Scottish Natural Heritage
Commissioned Report No. 982

Analyses of the fates of satellite tracked golden eagles in Scotland

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COMMISSIONED REPORT

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For further information on this report please contact:

Professor Des Thompson
Scottish Natural Heritage
Silvan House
231 Corstorphine Road
EDINBURGH
EH12 7AT
Telephone: 0131 316 2630
E-mail: des.thompson@snh.gov.uk

This report should be quoted as:

Whitfield, D.P. & Fielding, A.H. 2017. Analyses of the fates of satellite tracked golden eagles in Scotland. *Scottish Natural Heritage Commissioned Report No. 982.*

COMMISSIONED REPORT

Summary

Analyses of the fates of satellite tracked golden eagles in Scotland

Commissioned Report No. 982
Project No: 015542
Contractor: Natural Research
Year of publication: 2017

Keywords

Golden eagle; satellite tagging; Scotland; juvenile dispersal; wind farms; grouse moor; persecution; illegal killing.

Background

The Cabinet Secretary for Environment, Climate Change and Land Reform requested a thorough investigation of the fates of satellite tagged raptors, especially golden eagles. This report provides a major review of the movements and fates of golden eagles satellite tagged during 2004 - 2016.

Of 131 young eagles tracked, as many as 41 (31%) have disappeared (presumably died) under suspicious circumstances significantly connected with contemporaneous records of illegal persecution. These disappearances occurred mainly in six areas of the Highlands (predominantly in the central and eastern Highlands).

Some, but not all, areas managed as grouse moors were strongly associated with the disappearance of many of the tagged eagles.

Tagging revealed that the persecution of young eagles is suppressing the golden eagle population in the central and eastern Highlands, and hampering overall recovery from historic, widespread persecution.

Wind farms were not associated with any recorded golden eagle deaths, and there were very few records of tagged young golden eagles near wind farms.

Operations associated with tagging had no discernible adverse effects on the welfare, behaviour or survival of the birds.

Main findings

Purpose

1. This report addresses the question: is there a pattern of suspicious activity surrounding the ‘disappearance’ of many satellite tagged golden eagles?

Methods

2. The movements and fate of many raptors in Scotland are being studied through the use of satellite transmitters attached to birds. For golden eagles, tags were deployed between 2004 and 2016, with increasing activity in recent years, as transmitters have improved in reliability and ease of attachment. Studies are on-going on golden eagles, white-tailed eagles, ospreys, red kites, hen harriers, peregrines and kestrels. Many of these studies are undertaken by a range of individuals and organisations across the UK, and currently data are at varied stages of being prepared for publication.

3. This report details a comprehensive analysis of the fate of 131 satellite tagged golden eagles (tagged in the nest, and subsequently tracked).

4. Tag fates were cast into eight classes based on a combination of location data, transmitted engineering data and the results of searches for 'downed' birds or 'dropped' tags at and around the last transmissions' locations: Still Tracking; Died Natural; Stopped Malfunction; Battery Drained; Dropped Not Suspicious; Dropped Suspicious; Killed (found dead, most were poisoned); and Stopped No Malfunction.

5. Tag deployments are summarised by type, fate-class, year and region (NHZ) of deployment. Last fixes of potentially or known 'suspicious' tag fates are illustrated by calendar month. Potentially 'suspicious' tag fates almost entirely involved the 'stopped no malfunction' class of tag. These fates, involving many birds, were potentially suspicious because of sudden cessation of transmissions but also because no bird or its tag was discovered at or around the location of the last transmission(s).

6. Spatial maps summarise over half a million locations recorded to 15 January 2017 from the transmissions received from the tagged birds in Scotland. Grid references for final fixes of all tags which were not still transmitting as of that last date are presented.

Broad spatial patterns in the fates of tagged eagles

7. Tagged eagles ranged widely over most of upland Scotland (especially the Highlands). There was a broad association between last known fixes and the background density of utilisation from the tagged birds' locations. At a finer scale, however, it was apparent that several potentially suspicious tag fates were unusually concentrated.

8. A cluster analysis of the final locations of 'stopped no malfunction' and known 'killed' tagged birds fell into two broad areas: a broad 'Highland' grouping (four clusters) distinctly central-easterly and heavily populated with relatively concentrated clusters and many records; and a more westerly, looser grouping with four clusters.

9. Within these groupings, six broad geographical clusters were identified, with the most intense concentrations of potentially or actually 'suspicious' records in the central/eastern Highlands. **These clusters were indicative of an unusual concentration of potential or known suspicious final fixes from many tagged young eagles.** This was indicative of external human influences, as no other factor could account for such concentrations.

10. The final locations of these 'stopped no malfunction' and killed birds' tags were unexpectedly spatially connected, suggesting further a human influence. These 39 locations are referred to as 'stopped no malfunction last fixes' (snmlfs). There were up to 73 non-snmlf tags in these analyses.

11. Nearest neighbour distances (NNDs) were calculated between snmlfs and contrasted with NNDs for a 'virtual' set of last fixes drawn randomly from the locations of all tagged birds. Ten analyses were conducted, examining various alternative potential datasets to ensure that the results were robust.

12. The snmlfs were spatially clustered at up to five spatial scales in comparison to what was expected from randomly selected locations of last fixes. Thus, this clustering was not because birds spent more time in the areas where snmfls were recorded. The same results were apparent when the following were analysed: the snmlfs tags; the more reliable 70GPS/GSM tags; and when up to 20 of the 33 snmfls tags were assumed to have actually malfunctioned. Hence, even if many of the latter were undetected malfunctions (and so misclassified) the spatial clustering was still evident.

13. In marked contrast, for the non-suspicious tags there was no difference between their final fixes and randomly selected 'virtual last fixes'. This provided a robust test of the approach, but also provided further evidence that the snmfls were spatially associated and thereby suspicious.

14. The presence of clusters of snmlfs indicated localised activities that increased the probability that a tag would cease transmitting in those locations. The results strongly indicated that this was due to human influences operating primarily in six clusters, mostly in the central and eastern Highlands.

15. In answer to the question 'was there a suspicious pattern in the sudden failure to transmit for many tagged eagles?' The answer was: 'Yes'.

Reliability of different tags

16. Other research deploying the same MTI GPS PTT model tags had not found the same level of the 'stopped no malfunction' fate class as recorded in Scotland. A large sample from the USA for golden eagles classified a low rate (c. 2 %) of 'stopped no malfunction' fate (the comparable rate for Scotland was about 25 times higher), but for both the USA and Scotland there was a very similar (low) rate of definitely identified malfunction fate (c. 2 %).

17. The MTI GPS PTT tags which formed the backbone of the present project appeared to be intrinsically reliable, similarly so in Scotland and elsewhere, with a very low rate of unexpected malfunction.

18. An analysis of 'survival rates' of Scottish 70GPS/GSM tags revealed that 'stopped no malfunction' tags had relatively poor 'survival' compared to other tags, and was below the tag manufacturer's expected longevity of ≥ 3 years. Again, this was not consistent with sudden, failed tags suffering an undetected malfunction.

19. A few MTI GPS PTT tags classed as 'stopped no malfunction' may have been due to malfunction, but this number would appear to be very small, and not clustered. The results do not indicate a substantive contribution of 'tag reliability' to the scale and spatial pattern indicated by the many sudden, 'stopped no malfunction' tag fates in Scotland.

Inferences on human influences on the fate of tagged eagles

20. The results consistently point to a particularly high level of human-caused interference with tagged eagles in Scotland. The following six points are relevant to the human related fate of tagged eagles:

    a) Physical harm (e.g. lesions and inflammation) and contribution to further disease and possible death through ill-fitting harnesses have been recorded in 22% of 18 red kites in England. However, these results appear illustrative of a specific problem through failure of the normally stringent tagging procedures, than an indication of a generic widespread problem with the method when properly conducted. Post-mortems of 28 Scottish tagged raptors recorded no lesions or inflammations.

    b) Research in the USA has indicated that harness tagging of adult golden eagles can affect adults' behaviour, breeding success and survival; such problems were not detected in eagles tagged as nestlings.

    c) From post-tagging monitoring in Scotland, with trapping methods adapted to avoid nest sites and the breeding season, there was no evidence of any adverse effects on behaviour, territory occupation or breeding success in the few adult golden eagles recently satellite tagged.

    d) There was no evidence in the nest, or post-fledging and post-dispersal, of any adverse effects on the behaviour of a sample of nestling golden eagles satellite tagged in Scotland.

    e) 'Natural' survival rates of young satellite tagged eagles in Scotland were much higher than those estimated in the USA from ringing (banding) data. This critical result did not suggest any adverse impact of tagging on Scottish eagle survival after fledgling and dispersing.

    f) At least nine tagged birds have entered the breeding population, and the known age of recruitment was not different from observed untagged birds. This finding indicates no adverse consequence of tagging on this demographic parameter.

21. **Overall, we have found no evidence that satellite tagging of golden eagles in Scotland causes any harm to tagged birds, either physically, behaviourally, or demographically.**

Human factors investigated as potentially associated with the fate of golden eagles: wind farms and grouse moors

22. Previous results have strongly indicated that the source of the 'sudden no malfunction' fate was largely through human intervention. Two primary candidates were considered for this intervention: an association with wind farms or with grouse moor management.

23. We found no evidence that wind farms or activities associated with their operation accounted for losses of tagged eagles, or the disappearance of eagles with tags that suddenly stopped functioning.

24. In contrast, there were several indications that the management of grouse moors was associated with the locations of many of the tags which suddenly failed to function, and which subsequently disappeared along with the birds carrying them. A subset of areas

managed for driven shooting of grouse were associated with the suspicious disappearance of many birds, tags and their transmissions.

Associations between grouse moors, illegal persecution and the fates of tagged eagles

25. Previous research has indicated that persecution, largely through the killing of birds, was a major constraint on the Scottish golden eagle population in regions of Scotland where driven grouse moor predominated as the major land use.

26. We found several lines of evidence which pointed to the primary cause of the ‘stopped no malfunction’ tag fate being due to human intervention. We looked to see if the final fixes of these were closer to contemporaneous locations of persecution events than other tags’ final fixes were, where no suspicion was apparent.

27. Overall, the final fixes of tags which stopped working suddenly, with no malfunction, were significantly more likely to be closer to recent records of persecution events than were the final fixes of other tags which were not suspicious.

28. The final fixes of the many ‘stopped no malfunction’ tags were significantly associated with persecution records. Their sudden demise was evidently due in large part to people killing the tagged birds (and the disposal of the bird and its tag subsequently).

29. **Corroborative information points to the perpetrators of the persecution of tagged eagles being associated with some grouse moors in the central and eastern Highlands of Scotland.**

Consequences for golden eagle populations

30. For large raptors, such as the golden eagle, post-fledging survival rates are particularly influential in affecting their population dynamics and conservation status.

31. We estimated post-fledging survival rates of tagged nestlings due to natural losses and to other causes. One ‘other cause’ was the ‘stopped no malfunction’ tag fate, since several lines of evidence pointed to this being substantially due to human intervention (humans killing the tagged bird and destroying the tag), with persecution being the most likely cause.

32. For the 131 birds entered into analyses, there were 10 natural deaths, five birds killed, and 41 birds with a ‘stopped no malfunction’ fate.

33. Estimated natural survival rates (excluding other causes) were high, with approximately 88% of birds surviving to three years after tag deployment.

34. The impact of those birds known definitively to have been killed (that is, excluding suspected killings) was not statistically significant, but after about three years of tag deployment accounted for about a 9% difference in survival rate from the natural estimate.

35. As a likely cause of human-caused mortality, the ‘stopped no malfunction’ fate had a striking impact on estimated survival rates, with statistically significant differences from natural estimates (and natural + killed estimates). These differences first became significant at a time after tagging which equated approximately to when young tagged eagles dispersed from their parents’ territory.

36. By about three years after tagging the survival rate estimate for all causes (including definitive and putative persecution) had amounted to a halving of the estimated natural survival rate (88% natural versus 44% natural + other causes). The effect of ‘other causes’ of mortality on survival would be considerable.

37. Additionally, we generously assumed that 25% of birds which had a ‘stopped no malfunction’ tag fate did not die from human intervention but instead their tags had malfunctioned. Even then, there were still large and statistically significant effects on survival from an early age due to this putative, interventionist cause of death.

38. Our analyses were necessarily restricted by the nature of the data regarding definitive ‘fates’, including slight uncertainty on the fate of birds with no ‘stopped malfunction’ tags, and an assumption that any non-natural mortality was additive to natural (i.e. that a bird killed by a non-natural cause would not have died naturally later had it not been killed).

39. It was obvious, nevertheless, that human intervention had a significant negative effect on tagged birds’ survival and, more importantly, would have a substantial biological impact on eagle numbers in some areas, at least.

40. **It was apparent that satellite tagging of young golden eagles revealed that many young birds have probably been illegally killed in some parts of Scotland between 2004 and 2016, largely in the central and eastern Highlands. Such illegal killing potentially has consequences for the future golden eagle population’s trajectory within mainland Scotland. This is especially so in those regions where such killing continues to occur; many decades after such acts became illegal.**

41. Population modelling analyses were preliminary but illustrative, given that much further information will be available in the near future, and concentrated on the population consequences revealed by the project’s novel estimations of ‘natural’ survival rates on young (≤ 4 years old) eagles, and the influence on these rates through young eagles being killed (known and suspected).

42. The modelling showed that with the estimated ‘natural’ survival rates of young birds, even with relatively low productivity and relatively low adult survival rates, a Scottish golden eagle population was expected to grow, with a high probability of this outcome. This would enable much currently unoccupied habitat to be recolonised, greatly increasing the long-term security of the Scottish golden eagle population.

43. However, by contrast, the survival rates of young eagles which incorporated the non-natural causes of mortality showed that any prospect for a stable or increasing population became increasingly reliant on a relatively high reproductive output and high adult survival rate. This was borne out even after accounting for varying assumptions around the extent of the illegal killing involved in the ‘stopped no malfunction’ tags.

44. Since the 2003 National Survey of golden eagles, we conclude that many regions of Scotland away from the continued depressive effect of illegal killing of dispersing young birds have borne population expansion, or continued stability. Furthermore, we expect that there may have been some recovery in some parts of the central and eastern Highland regions where the eagle’s conservation status was previously unfavourable due largely to illegal persecution. However, these regions still yield evidence of continued illegal persecution, and so we do not expect recovery to the full capability of breeding birds.

45. Overall, we conclude that a relatively large number of the satellite tagged golden eagles were probably killed, mostly on or near <u>some</u> grouse moors where there is recent, independent evidence of illegal persecution.

46. This illegal killing has such a marked effect on the survival rates of the young birds that the potential capacity for the breeding golden eagle population continues to be suppressed around where this persecution largely occurs. In these parts, mainly in the central and eastern Highlands of Scotland, the prospects for recovery are poor.

For further information on this project contact:
Professor Des Thompson, Scottish Natural Heritage, Silvan House,
231 Corstorphine Road, Edinburgh, EH12 7AT.
Tel: 0131 316 2630 or des.thompson@snh.gov.uk
For further information on the SNH Research & Technical Support Programme contact:
Knowledge & Information Unit, Scottish Natural Heritage, Great Glen House, Inverness, IV3 8NW.
Tel: 01463 725000 or research@snh.gov.uk

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Acknowledgements

A large number of people have helped with this study. First thanks must go to Mike McGrady who first ‘brought’ satellite tagging of eagles to Scotland along with his unbounded enthusiasm for the species and a desire to understand its biology.

Ewan Weston (NR) has been indispensable to the study and it would not have been possible without his efforts in co-ordinating centralised reception and collation of all the data (not only NR ‘operated’ data), and for field work and many knowledgeable insights. The project owes a great debt of gratitude to Ewan.

Roy Dennis (HFW), Stuart Benn (RSPB) and Dave Anderson (FCS) co-ordinated ‘operated’ tagging data on behalf of their respective organisations, and willingly and rapidly provided co-operation through the provision of data and much other assistance. We were also helped by tagging efforts by Mike, Roy, Dave, and Ewan, along with Keith Brockie, Brian Etheridge, Justin Grant, and Duncan Orr-Ewing. We also acknowledge rapid, cooperative assistance from Dave Sexton and Roger Broad.

We hope that we won’t cause offence in being selective, but Justin Grant has been a universal and essential feature of much research on eagles in Scotland through his dedicated efforts, and in helping with the current project. Dave Anderson also deserves special thanks for his continued, tireless enthusiasm, substantial tagging efforts and his scrupulous time-consuming work on monitoring of any possible post-tagging effects; which he kindly allowed access to for this report.

Compared to many other countries, Scotland is blessed by having much voluntary expertise in the study of birds of prey through the Scottish Raptor Study Group membership. These members have assisted in supporting the tagging efforts in this project; and much more.

Emma Ahart and Peter Robson kindly arranged for permission to use data from tags which were funded by SSE (Scottish & Southern Energy) and SPR (Scottish Power Renewables), respectively. The tagging supported by SSE and managed by Emma and NR is part of wider study, funded by SSE, of the conservation and ecology of golden eagles in the Central Highlands Natural Heritage Zone (NHZ 10). Many other tags in the study were funded by SNH and we are grateful to Des Thompson and Chris Donald for sourcing funding and co-operation in using the transmitted data. Natural Research (NR) was also a primary funder of many tags and coordinated other funding sources: for this the NR Board and Pat Whitfield deserve respective recognition. Several individual tags were also funded by private donations; too many to list here, but this assistance was invaluable.

Elizabeth Sharp of SASA gave generously of her time, knowledge and efforts in the compilation of poisoning records, and was especially helpful, with Fiona Howie (SRUC), Hannah Orr (SRUC) and Elsie Ashworth (RSPB), in pulling together post-mortem records of harness tagged raptors in Scotland. Owen Selly (RSPB) collated and forwarded many post-mortem reports for white-tailed eagles undertaken by VLA Lasswade, for which we also thank Claire Smith and Rhian Evans. We are also grateful for assistance from staff at SAC Consulting Veterinary Services in Inverness. Ian Thomson (RSPB) was of indispensable assistance in collating a ‘persecution’ database which was subsequently vetted and checked (via NWCU, and SASA PAW criteria). Ian Thomson, Charlie Everitt and Andy Mavin (NWCU, Police Scotland), Daniel Hall and Karen Hunter (SG), and Andy Turner (SNH) were of great help in compiling and forwarding persecution records. We also thank Andy, Daniel and Karen, and especially Hugh Dignon (SG), for attending to other essential administrative matters.

Several international researchers responded with generosity in time and data, when their assistance on comparable unpublished data was requested at short notice. Todd Katzner (USGS) helped to facilitate access to the voluminous data from USA. Brian Millsap (USFWS) was of massive and vital assistance through providing the collated large dataset from USA, specifically attuned to our request, and further information on the excellent ongoing studies he is co-ordinating and leading on analysis; especially at a time when his other priorities were taking precedence. Thank you, Brian.

Jim Watson (Washington Department of Fish & Wildlife) also gave freely of his data; and of his considerable experience and scientific insights. It was a great pleasure and stimulation to correspond with such a knowledgeable scientist who has a vivid enthusiasm for discovering more about the golden eagle. We extend grateful thanks to Marie Pitts (Data Administrator) and Bryan Watts (Principal Investigator) of The Center for Conservation Biology, College of William & Mary and Virginia Commonwealth University, Williamsburg, VA, USA for promptly sending us data on fates for bald eagles tagged on the eastern USA seaboard. Torgeir Nygård (NINA) responded with typically good grace, cooperation and useful data on a sample of tagged golden eagles within his substantial experience from tagging many raptor species; despite the tight deadlines we were working to. Fabrizio Sergio (CSIC) was also, as ever, a great sounding board through his rare combination of intellect and scientific capability with a vast practical experience and knowledge of raptors in general; and tagging raptors in particular.

Paul Howey and the staff at Microwave Telemetry Inc. (MTI) helped in many ways, not only in providing background data on tag functionality, testing, expected longevities and research contacts, but also in providing an independent MTI examination of the engineering data from MTI-tagged birds from Scotland.

Thanks too, to Dave Leech and Jez Blackburn (BTO) for allowing us to include the current best practice document on tagging in an Annex.

An earlier draft of this report was much improved by reviews providing insights, comments and suggestions from Professors Miguel Ferrer, Robert Furness, Ian Newton and Des Thompson, for which we are especially grateful.

Finally, we thank our families for their forbearance in tolerating the long hours of absence and our one-track minds during this report's production.

1. INTRODUCTION

1.1 Background, impetus for the analyses and the project brief

Raptors in Scotland have been satellite tagged in recent years to support a range of conservation and scientific programmes. Detailed studies have been made of golden eagles *Aquila chrysaetos*, white-tailed eagles *Haliaeetus albicilla*, ospreys *Pandion haliaetus*, red kites *Milvus milvus* and hen harriers *Circus cyaneus*, with much of this coordinated by the Highland Foundation for Wildlife (HFW), Natural Research (NR), The Royal Society for the Protection of Birds (RSPB), Scottish Natural Heritage (SNH), and the Forestry Commission Scotland (FCS). Some of the work has been funded privately or by the renewable energy sector, and in recent years these parties have worked collaboratively, with work on golden eagles overseen by a group chaired by SNH. Much of this work is shared with researchers and collaborators abroad.

This report is an SNH Commissioned Report outcome from a Scottish Government request to investigate the disappearance of satellite tagged raptors in Scotland. The impetus is detailed in a quote from the Cabinet Secretary for Environment, Climate Change and Land Reform, Roseanna Cunningham MSP, in response to reports on the disappearance of satellite tagged golden eagles in the Scottish Highlands:

"The latest reports of satellite-tagged golden eagles disappearing on or near grouse moors are very disturbing and disappointing.
"That is why I have instructed officials to analyse the evidence from around 90 surviving and missing satellite-tagged eagles, to discover if there is a pattern of suspicious activity."

The Cabinet Secretary also subsequently requested that any suspicious patterns in 'disappearing' tagged hen harriers and red kites be included within the project brief. Appreciating the reasons for this request, after review we considered that there are currently insufficient data on harriers and kites for Scotland alone – and an analysis would be better including data from other parts of the UK. Moreover, for red kites, as the broad project purpose is hypothesized on identifying potential signs of 'suspicious activity' in Scotland (i.e. anthropogenic influences), then the SNH Commissioned Report 904 (Sansom *et al*. 2016) has recently re-examined this issue thoroughly.

The present report, therefore, is concerned solely with the golden eagle; a species which has not only been extensively studied in Scotland (e.g. Whitfield *et al*. 2008a, Watson 2010) but has been the subject of more satellite tagging in Scotland than any other bird. Indeed, the satellite tagging studies were devised and undertaken to build on previous research, primarily to gain insights into aspects of the species' biology which are difficult or impossible to study using other methods (e.g. Weston *et al*. 2013, Weston 2014). These aspects mostly involve the 'post-fledging dependence period', and subsequent 'juvenile dispersal' in the years between a bird leaving its parent's territory and it settling on its own breeding territory.

The primary aim of this report is encapsulated by the Cabinet Secretary's instruction; for analyses to examine if there was a pattern of suspicious activity surrounding the 'disappearance' of many satellite tagged golden eagles. Subsumed within and related to this primary aim there were several objectives/questions within the project brief which we addressed:

1. Is there a significant spatial pattern in tagged eagle 'losses'? Are losses greater in specific parts – regions or close-locations? Are they associated with a particular form of land use?

2. Are these losses greater than we might expect from observed movements (i.e. are more birds lost in some areas because there is a preference to be there)?
3. How reliable are the transmitters, and what is the expected lifespan?
4. Is there any evidence that the tags harm the birds or influence their behaviour?
5. What is the estimated loss of 'young-tagged' eagles to natural and other causes?
6. What impacts are the non-natural losses of eagles having on the population regionally and nationally?

1.2 Report structure

We have structured the report to address the above questions in a sequence which should follow logically; as described by sections outlined in the Contents.

1.2.1 Report section structure

Within each section, recognising that some readers may not wish to follow through on subsequent text and supporting information, we have presented an initial Summary header.

By way of maintaining transparency and providing full details, however, we have also endeavoured to provide all background information on full results of analyses. In some instances, where we judged that an analysis or a detailed set of results was directly relevant and was not too lengthy, we have included these as an Appendix to a section. In other instances we have provided section-referenced Annexes at the end of the report which can be navigated to by readers who wish to examine full workings or further details. All useable records from tagged eagles in Scotland were incorporated in the analyses undertaken to produce this report.

1.3 Golden eagle biology

There are many previous reviews describing the biology of the golden eagle, and in Scotland (e.g. McGrady 1997, Whitfield *et al*. 2008*a*, and notably Watson 2010). We do not repeat such background reviews in this report and we refer the reader to these other works and references therein. Similarly there are also several reviews of the history, research benefits and potential pitfalls of satellite tagging: such reviews are given by studies (and references therein) we cite later in this report (e.g. sections 6 and 7). Later in this report, we focus on potential pitfalls as they apply to tagging of golden eagles in Scotland, also referable to experiences abroad for this species, in section 7.

Some background on golden eagle biology nevertheless deserves brief re-iteration here, when this report is primarily concerned with potential effects and 'suspicious patterns' related to the period between young eagles fledging and their subsequent behaviour and ecology. The vast majority of tagged eagles in Scotland, and so reflecting the Cabinet Secretary's concern over suspicious disappearances of tagged individuals, refer to these young birds, and this period in the biology of golden eagles. The database refers primarily to these young birds which were tagged as nestlings to study their subsequent movement behaviour and ecology after fledging (e.g. Weston 2014). The Cabinet Secretary's concern and instruction relates to what happened to many of these birds after they were tagged as nestlings, when several apparently suddenly disappeared.

Essentially, as for many k-selected species which can potentially live for many years and have delayed maturity, the time between fledging and potential later settlement on a breeding territory can be lengthy for a golden eagle (e.g. Newton 1979): it usually takes around four years. After fledging, continued pre-dispersal dependency on the parental territory may involve a mere few weeks to many months, before dispersal away from their parents' (natal) territory (Weston *et al*. 2013, Weston 2014). Once in this juvenile dispersal period, young eagles may roam at considerable distance from their parental (natal) territory for several years (typically up to four years) shifting between temporarily settling in areas favourable for survival (food-rich areas) and periodic, or ongoing, explorations of potentially suitable breeding opportunities for later life (e.g. Weston 2014; see also Whitfield *et al.* 2009a, b). Such explorations often apparently involve returns to areas close to the birds' natal region (a natal philopatric 'pull'), increasing with but not restricted to age, likely seeking a potential breeding territory for later settlement.

The satellite tagging of many nestling golden eagles was undertaken to gain a greater understanding of the years between fledging and later settlement on a breeding territory (recruitment into the breeding population). It was during this period of 'roaming/nomadic' juvenile dispersal that the observation of many tagged eagles suddenly 'disappearing' occurred; which has prompted the Cabinet Secretary's concern and the commission of this report's analyses.

2. TAG METADATA

2.1 Summary

- This section is methodological and describes the methods used to tag birds and to collect and classify the transmitted data underpinning the study.
- Tags were deployed between 2004 and 2016 with increasing activity in later years, improved transmitter types and attachment method. A total of over 130 nestling golden eagles were tagged.
- Tag fates were cast into eight classes based on a combination of transmitted engineering data and the results of searches for "downed" birds or dropped tags at and around the last transmissions' locations: Still Tracking, Died Natural, Stopped Malfunction, Battery Drained, Dropped Not Suspicious, Dropped Suspicious, Killed, and Stopped No Malfunction.
- Tag deployments are summarised by type, operator, fate-class, year and region of deployment.
- Last fixes of potentially or known 'suspicious' tag fates are illustrated by calendar month. Potentially 'suspicious' tag fates almost entirely involved the "stopped no malfunction" class of tag.
- We emphasise how the potentially 'suspicious' tag fate (stopped no malfunction), involving many birds, was not only potentially suspicious because of sudden cessation of transmissions but also because no bird or its tag was discovered at or around the location of the last transmission(s).

2.2 Introduction

The fundamental basis for the report's analyses on young satellite tagged golden eagles rests on the raw data and how these were collected, and processed. This section describes the tag metadata used in the report, and how they were collected and classified so far as 'fate'. It also summarises where birds were tagged regionally, where their last records were recorded regionally, and a seasonal outline of when last transmissions from the eight tag fate classes were received.

2.3 Methods

2.3.1 Tag deployment methods

Nests were visited to fit transmitters to nestlings when the chicks were between approximately 50 - 70 days old, based on plumage. Golden eagles weighed between 3.4 and 5.0 kg at time of tagging and transmitter weights and harnesses were, in all cases, less than the 3 % lower recommended maximum of body weight (Phillips *et al*. 2003) and the higher recommendation of 4 % (Kenward 2001) (see also Sergio *et al*. 2015). Nests were visited and chicks fitted with transmitters under the appropriate licences granted by Scottish Natural Heritage (SNH) and the British Trust for Ornithology (BTO). Birds were tagged between 2004 and 2016.

All transmitters were fitted using a harness of 13 mm Teflon Ribbon (Bally Ribbon Mills, Bally, Pennsylvania). From 2004 - 2007 a breast strap design was used exclusively which incorporated two rubber tabs which caused several transmitters (unintentionally) to break and be dropped prematurely A further bird was fitted with this breast strap harness in 2008 and it was dropped in 2009 (this bird is now breeding). A total of 14 birds were tagged using this method, all but one (105GPS) with 80NS transmitters (see later for transmitter types).

Subsequently all birds were fitted with the crossover or 'X harness method'. The crossover design has been recently referred to as a "crossover wing harness" (Thaxter *et al*. 2016). The change in the harness design resulted in a reduction in the preponderance of dropped tags (see Results). Eagles were fitted with a breakaway feature within the harnesses by stitching with either cotton or linen thread at the central point over the sternum (Kenward 1987, 2001) intended to remain attached for the 3 - 5 year juvenile dispersal span of this species (Urios *et al*. 2007, Watson 2010) and manufacturer's expected transmitter lifespan.

An 'operator' organisation was deemed responsible for ordering tags from the manufacturer, their deployment; receipt of data and paying for data download costs. These operator organisations were the Forestry Commission Scotland (FCS), Highland Foundation for Wildlife (HFW), Natural Research (NR) and the Royal Society for the Protection of Birds (RSPB). As noted earlier (section 1.1) in recent years these parties have worked collaboratively, with work on golden eagles overseen by a group chaired by SNH.

Eight personnel were involved in tagging eagles, with two licensed personnel typically present at each tagging, in part to ensure cross-checks of harnesses, their fitting, and other features of deployment. While there was considerable cross-over in 'licensed tagger' personnel between operators, each operator organised its own team for tagging and its preparation (with the team also including personnel checking, at safe disturbance-free distances, the progress of a breeding attempt, to ensure that nestlings were at a suitable age for tagging).

2.3.2 Tag transmitter types

Five types of tags were deployed and used in analyses.

80NS – North Star transmitters, Argos only. These 80 g transmitters were (lithium) battery powered and manufacturer suggested a 3-5 year potential lifespan. Transmitters had a duty cycle that after several months the transmitters sent signals every 3-4 days. Even the best quality Argos locations are approximated c.150 m accuracy.

105GPS – Microwave Telemetry Inc. 105 g (lithium) battery powered GPS transmitters (LC4 PTTs). Transmitters took 1 GPS fix per day at 12 noon and transmitted every 10 days. Transmitters were suggested at 2.5 years battery life by the manufacturer.

70GPS – Microwave Telemetry Inc. 70 g solar powered GPS transmitters (PTTs). GPS fixes and transmissions cycles adjusted by pre-programmed fix rate and transmission schedule (duty cycle). Longevity of transmitters was suggested at ≥ 3 years by the manufacturer.

70GSM – Microwave Telemetry Inc. 70 g solar powered GPS/GSM transmitters (PTTs). Transmission is over the mobile phone (GSM) network but signal is especially good on birds wearing these tags. GPS fix rate is dependent on battery charge (dynamic adjusted fix rate dependent on battery charge from 1 per minute to 1 every 2 hours). Transmissions are attempted to mobile phone network twice daily. Longevity of transmitters was suggested at ≥ 3 years by the manufacturer.

95BTOGSM – 95 g GPS/GSM transmitters manufactured by BTO. Transmit via mobile phone (GSM) network. Several transmitters of a novel design were deployed in 2016 on golden eagles – some appear to be working well; for others it is too early to tell as transmissions are sporadic. These tags have been largely ignored in the analyses given how recently they were deployed and their prototypical nature.

In addition to these transmitters, six newly designed Cellular Tracking Technologies 95 - 100g GSM transmitters were fitted to golden eagles in 2009. All transmitters failed. Two gave intermittent data every few months. Problems were apparently due to a defective component. The working transmitters gave high resolution (approximately 15 minute interval) GPS fixes for a couple of days and then nothing for several months while the battery charged. These tags were totally unsuited to any analysis, but for completeness are noted here.

As well as transmitting location data and associated metrics (such as velocity and altitude), tags also transmitted numerous ‘engineering files’ documenting several metrics on the ‘status’ of the tags (these are described in great detail later in section 6: ‘Tag Reliability’). The data in the engineering files were critical to classifying tag fates. Notably, distinguishing between a tag which suddenly stopped transmitting with no prior warning (stopped no malfunction: see below) and a tag which had malfunctioned (evident from prior transmitted engineering data) either ‘prematurely’ or through reaching its manufactured longevity.

The spatial accuracy of locations from units featuring GPS (i.e. all but the 80NS tags) is given by Microwave Telemetry Inc. (MTI) as ± 18 m[1]. Accuracy for a (near-) stationary unit transmitting from the ground and in an open environment, as for typical golden eagle habitat, is even higher (± 10 m to ± 5 m)[2] than given by MTI for a (often rapidly) moving animal.

2.3.3 Classifying tag fates

Data from tags were temporally censored as of 15 January 2017: a cut-off date had to be set for ignoring any further incoming data from tags that were still transmitting so that analyses could proceed.

The fates of all tags were cast into eight classes, depending on the circumstances surrounding their final transmissions and results of searches at and around the last transmitted locations (see also section 6: ‘Tag Reliability’, on additional checks for key classes). These classes (in no particular order) were as follows:

1. **Still tracking**. Tags that were still transmitting as of 15 January 2017.

2. **Died natural**. A death was indicated from repeated transmissions at the same location (i.e. “drilling a hole in the map”) beyond expectations of the repeated use of a single overnight ‘roost site’. Subsequent searches of the locations discovered a corpse, with post-mortem examinations indicating that the bird had probably died naturally (e.g. broken wing, emaciation, evidence of a dispute with another eagle, tag transmitting from the sea/coastline with no external signs of injury). No suspicious circumstances of possible human intervention were involved in this class.

3. **Stopped malfunction**. Given by transmitted engineering files prior to no transmissions. Usually a battery problem or the end of its lifespan was evident (see section 6 for more details).

4. **Battery drained**. Given by transmitted engineering files prior to no transmissions. Evident almost exclusively for the few non-solar (integral lithium) battery tags. Note that this tag fate was combined with the previous malfunction fate in analyses as they are essentially the same outcome.

5. **Dropped not suspicious**. Tags that had been dropped through harness degradation or failure and subsequently recovered by searches from repeated transmissions at the dropped tag location.

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[1] http://www.microwavetelemetry.com/bird/solarArgosGPS.cfm

[2] http://www8.garmin.com/aboutGPS/
http://www.gps.gov/systems/gps/performance/accuracy/

6. **Dropped suspicious**. There was one single tag classed as such. This tag was discovered through continued transmissions at a single location. The tag and its harness were discovered below a presumed roost site (from previously transmitted records). The harness had been severed with a sharp implement and the tag itself had been stabbed with a thin sharp implement, although this did not prevent continued transmissions and discovery. The damage to the harness and tag were consistent with a human ‘implement’ (knife) and not an eagle’s bill.

7. **Killed**. There were four tags which continued transmitting at a specific location (“drilling a hole in the map”) and a search of the location discovered a dead bird which was then confirmed by post-mortem analyses as having been illegally poisoned. Another bird was assumed to have been killed (likely trapped and then the body clumsily disposed of). Prior to discovery of the corpse, this bird was stationery for a period (indicating that it had been ‘grounded’); then the transmissions revealed that it “travelled” at night before being discovered some days later many kilometres away by the side of a main road off a lay-bye: dead and with two broken near-severed legs. The final location of the bird’s corpse was in alien habitat for a golden eagle and in a place where no other transmissions from the bird or other golden eagles (from over half a million records) had been located. Our assumption that it was killed through human intervention seems legitimate.

8. **Stopped no malfunction**. Tags which abruptly stopped transmitting without any forewarning of imminent failure from prior transmitted engineering data. No bird or tag was discovered at the location of the last transmission or its environs. Even though, in some cases, there was transmitted evidence of a bird having ‘gone to ground’ before a search could be conducted (i.e. for a period the tag kept transmitting at a particular location). Despite such transmissions, in later searches no bird or tag was discovered at that location. For this class of tag fate, not only was there a sudden inexplicable cessation in transmissions (as per engineering data: see section 6) but also no tagged bird or its tag was discovered. In many or most cases this could potentially suggest, intrinsically, that evidence of the dead bird and its tag had been disposed of after the bird’s presumed death.

It is critical to appreciate that, bar the still tracking fate (obviously) and many of the stopped malfunction/battery drained fates, for every tag whose transmissions ceased these cessations were followed up by ground searches of the last known transmissions and their environs. These searches often involved considerable effort but were invaluable.

For example, although such searches discovered many dead eagles and/or tags, which could be assigned to natural deaths and dropped tags (see Results), the stopped no malfunction class involved not only the sudden unexpected cessation of transmissions but also the lack of any sign of the bird and/or its tag from where the last fixes transmitted (in some cases repeatedly from the same location, before a search could be seen as required and then organised). This is a critical basic finding when it comes to considering whether this stopped no malfunction tag fate was definitively ‘suspicious’ – it certainly warrants it being viewed as ‘potentially suspicious’.

Search times for ‘downed’ tags (including the stopped no malfunction fate) were not set because if a tag (with or without the bird) was found then the search stopped. Tags are expensive and so there was a financial motivation to recover a tag whenever possible so that they could be refurbished for redeployment. Also, for example, search times were partly related to the tag model; such that Argos-only tags (80NS) with much less spatial accuracy than GPS models (see above) required a wider area to be searched, and so more time. GPS tags provided highly accurate final fixes (see above) and so, depending on pre-programmed duty cycles, a much smaller area set the realm of the possible final location and a possible dead bird and/or its tag. And if a final set of fixes was repeatedly recorded at one location (even if the tag then suddenly stopped with no prior-transmitted signs of malfunction) then this too was indicative of a search area.

While we are loathe providing anecdotal information on specific instances, there were some cases where footprints and/or vehicle tracks and/or feathers were associated with the last fix locations of stopped no malfunction tags; even though no bird or its tag was discovered. Finally, we should also note that in recent years there has been a PAWS (Partnership for Action against Wildlife crime Scotland) protocol for searching for 'downed' satellite tagged birds involving Police Scotland (obliquely referred to in a letter of 26 March 2017 emailed to the Cabinet Secretary for the Environment, Climate Change and Land Reform (ECCLR) from the Convener of the ECCLR Committee).

The scavenging and removal and/or caching of a dead tagged eagle are possibilities, and this may interfere with the discovery of a 'downed' bird and its transmissions if the scavenger caches a carcass underground, for example. Several studies suggest, nevertheless, that scavengers tend to ignore carcasses of moderate-sized to large birds of prey, especially compared to carcasses of other birds (Barrios & Rodríguez 2004, Smallwood 2007, de Lucas *et al*. 2012, Urquhart *et al*. 2015; although see Smallwood *et al*. 2010). This may be because they are less palatable (Urquhart *et al*. 2015).

This possible confounding factor will not have been equitably distributed between land uses in Scotland, however, and will have been more influential away from land managed for driven shooting of grouse (see section 8). This is because management for driven grouse shooting is particularly associated with systematic and persistent removal of potential scavengers (notably the red fox *Vulpes vulpes*) (e.g. Hudson 1992). Hence, if this was a bias then it was less likely to explain the sudden disappearance of birds and their tags' transmissions on or near grouse moors (*cf* section 8).

2.3.4 Timing of last transmissions of potentially or known suspicious tag fates

A question posed by the project brief was when potentially or known 'suspicious' tag fates last transmitted temporally. Potentially or known 'suspicious' tag fates were taken as 'stopped no malfunction', 'dropped suspicious' and 'killed' (classes 8, 6 and 7, above, respectively), and we classed last transmissions of these classes by calendar month. Although finer temporal resolution was also requested, these would be inappropriate to present, at least for some tag types deployed, given transmission duty cycles.

2.4 Results

Location results from the many individual tags (up to 131) are illustrated in Annex 1. Also in Annex 1 are the grid references for the last known fixes of all tags which were not still transmitting as of 15 January 2017.

Summary results are presented in a number of tables which breakdown the various features within the tag metadata (Tables 2.1 – 2.6). To preserve confidential exact locations of tag locations (i.e. nest sites) we have used SNH's Natural Heritage Zone (NHZ) biogeographical classification of Scotland (Wrightham & Armstrong 1999, SNH 2000) (Figure 2.1). This was also the basis of a previous SNH commissioned report on a conservation framework for the golden eagle in Scotland (Whitfield *et al*. 2008a).

Tag deployment location, broken down by NHZ and tag type, is given in Table 2.1.

Tagging year, by NHZ where the tag originally deployed, the tag type and the 'operator' (data recipient) of the tag are given in Table 2.2.

Table 2.3 summarises the NHZs where tags' fates (final fixes) were recorded, split according to the eight tag fate classes.

Table 2.4 gives a breakdown of tags' class fate by the operator organisation, which also gave a broad proxy for the personnel deployed by operators in tagging birds according to the subsequent fate of these tagged birds. A summary of the eight classified fates according to the five tag models is presented in Table 2.5.

Last fixes of potentially or known 'suspicious' tag fates are illustrated by calendar month in Table 2.6.

2.5 Discussion

This section has summarised raw features of the tagging data used in subsequent analyses. Several features are evident. A good proportion of the tags (35 %) were still transmitting as of 15 January 2017 (the cut-off date for inclusion of data in analyses). The stopped no malfunction fate accounted for a relatively high proportion of the tag fates: 29 % of the total, or if the still tracking birds are excluded (since they have no 'end' fate, as yet) then it is 45 %. This on face value is a surprising proportion – nearly a half of all the tags, which had an end fate and were not still tracking, suddenly stopped transmitting. We should re-emphasise that the potentially 'suspicious' tag fate (stopped no malfunction), involving many birds, was not only potentially suspicious because of sudden cessation of transmissions but also because no bird or its tag was discovered at or around the location of the last transmission(s).

Many of the tags were deployed on nestlings in the Central Highlands (NHZ 10: Figure 2.1) and the Cairngorms Massif (NHZ 11). This was because of specific projects whose funders were especially interested in the biology of young eagles from these regions.

The obvious association between the battery drained tag fate and the operator (NR: Table 2.4) was because this tag fate involved the non-solar (integral lithium) battery models (80NS and 105GPS: Table 2.5) which were prevalent in the early years of the tagging studies, when NR was taking the operational lead in the research.

There was no apparent association between the operator (and so by broad proxy the team of taggers involved in deployment: see above) and potentially suspicious tag fates (the stopped no malfunction class) (Table 2.4). The stopped no malfunction fate was therefore not apparently associated with particular personnel who deployed the tag; or when the tag was deployed.

What was also revealing was that the stopped no malfunction fate did not obviously decline over the 2004 – 2016 study period, despite the fact that technological advances in satellite tag design and functional-reliability increased: a recently deployed tag model for which there were many tags still transmitting (70GPS: see Table 2.5) still had a high rate of the stopped no malfunction fate.

There was no pattern by month as to when potentially or known suspicious tag fates stopped transmitting (Table 2.6).

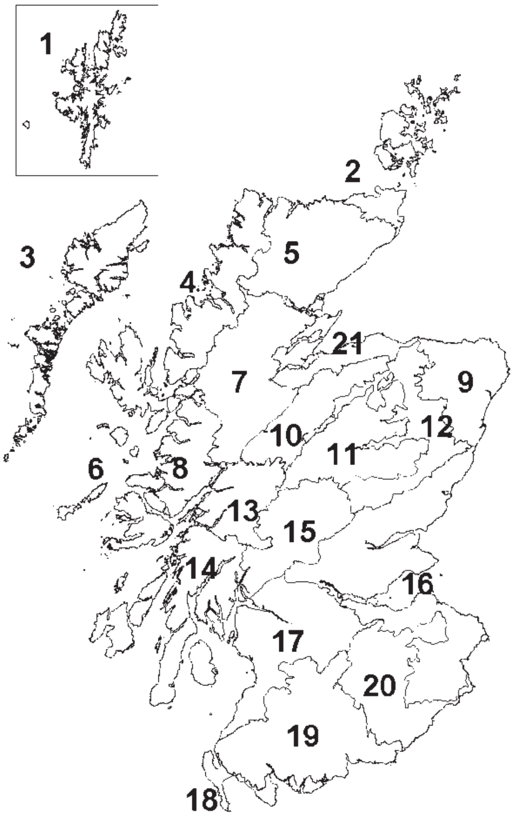

Figure 2.1. Biogeographic zones of Scotland, termed Natural Heritage Zones (NHZs), developed by Scottish Natural Heritage. 1 = Shetland, 2 = North Caithness and Orkney, 3 = Western Isles, 4 = North West Seaboard, 5 = The Peatlands of Caithness and Sutherland, 6 = Western Seaboard, 7 = Northern Highlands, 8 = Western Highlands, 9 = North East Coastal Plain, 10 = Central Highlands, 11 = Cairngorms Massif, 12 = North East Glens, 13 = Lochaber, 14 = Argyll West and Islands, 15 = Breadalbane and East Argyll, 16 = Eastern Lowlands, 17 = West Central Belt, 18 = Wigtown Machairs and Outer Solway, 19 = Western Southern Uplands and Inner Solway, 20 = Border Hills, 21 = Moray Firth.

Table 2.1. Tag type by NHZ where tag originally deployed.

NHZ	**70GPS**	**70GSM**	**80NS**	**95BTOGSM**	**105GPS**	**All**
Argyll West and Islands	5	5	2	1	5	18
Breadalbane and East Argyll	4	2	4	2	4	16
Cairngorms Massif	28		3		5	36
Central Highlands	18	5				23
Lochaber	1					1
North East Glens	1			2		3
North West Seaboard	5				1	6
Northern Highlands	2				1	3
Peatlands of Caithness & Sutherland	5				1	6
Western Isles	2		5		4	11
Western Seaboard	5					5
Western Southern Uplands & Inner Solway	1	1		1		3
All	**77**	**13**	**14**	**6**	**21**	**131**

Table 2.2. Tag year by NHZ where tag originally deployed, the tag type and the 'operator' of the tag (FCS = Forestry Commission Scotland, NR = Natural Research, HFW = Highland Foundation for Wildlife, RSPB = The Royal Society for the Protection of Birds, SSE = Scottish & Southern Energy).

NHZ	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**All**
Argyll West and Islands			1		2	1	2	1	4	1	2	2	2	18
Breadalbane and East Argyll		1	3	1	2			1	1	1	2	1	3	16
Cairngorms Massif			1	3	4	3	8	3	4	5	2	3		36
Central Highlands							4	2	2		1	9	5	23
Lochaber											1			1
North East Glens									1				2	3
North West Seaboard						1	1	3		1				6

NHZ	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**All**
Northern Highlands							1				1	1		3
Peatlands of Caithness & Sutherland							4				1	1		6
Western Isles	1				3	3	1			3				11
Western Seaboard									1	2	1	1		5
Western Southern Uplands & Inner Solway							1					1	1	3

Tag Type	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**All**
70GPS				1	2		17	9	13	12	8	15		77
70GSM											2	4	7	13
80NS	1	1	5	2	3	2								14
95BTOGSM													6	6
105GPS				1	6	6	5	1		1	1			21

Operator	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**All**
FCS											2	4	8	14
NR	1	1	5	3	9	8	10	2	6	8	2	1		56
HFW				1	2		9	7	3	1	4	3		30
RSPB							3	1	4	4	3	1		16
SSE/NR												10	5	15
All	**1**	**1**	**5**	**4**	**11**	**8**	**22**	**10**	**13**	**13**	**11**	**19**	**13**	**131**

Table 2.3. Outcome (tag fate class) by NHZ where a tag was deployed originally.

NHZ	**Still tracking**	**Died - natural**	**Dropped - not suspicious**	**Stopped - malfunction**	**Battery drained**	**Dropped - suspicious**	**Killed**	**Stopped - no malfunction**	**All**
Argyll West and Islands	6	3	3		2		1	3	18
Breadalbane and East Argyll	5		4		1		1	5	16
Cairngorms Massif	8	1	2	5	1	1	2	16	36
Central Highlands	13		3				1	6	23
Lochaber	1								1
North East Glens	2							1	3
North West Seaboard	2	1	1	1				1	6
Northern Highlands	1		1					1	3
The Peatlands of Caithness and Sutherland	1	2	3						6
Western Isles	3	2	1		3			2	11
Western Seaboard	2							3	5
Western Southern Uplands and Inner Solway	2							1	3
Total	**46**	**9**	**18**	**6**	**7**	**1**	**5**	**39**	**131**

Table 2.4. Summary of tag fate by operator. Note that the total differs from previous Tables (2.1 – 2.3) because we could not ascertain the precise deployment location of four early tags (three 80NS and one 105GPS).

	Operator					
Tag fate	**FCS**	**NR**	**HFW**	**RSPB**	**SSE/NR**	**All**
Battery drained		7				7
Died - natural		7	2	1		10
Dropped - not suspicious		10	8			18
Still tracking	12	9	8	3	14	46
Stopped - malfunction		5	1			6
Dropped - suspicious			1			1
Killed		1	2	2		5
Stopped - no malfunction	2	21	8	10	1	42
All	**14**	**60**	**30**	**16**	**15**	**135**

Table 2.5. Summary of tag fate by tag model.

	Tag model					
Tag fate	**105GPS**	**70GPS**	**70GSM**	**80NS**	**95BTOGSM**	**All**
Battery drained	6			1		7
Died - natural	4	5		1		10
Dropped - not suspicious	3	9		6		18
Still tracking	1	28	11		6	46
Stopped - malfunction	4	1		1		6
Dropped - suspicious		1				1
Killed	1	4				5
Stopped - no malfunction	3	29	2	8		42
All	**22**	**77**	**13**	**17**	**6**	**135**

Table 2.6. Month of final fix by tag model, for potentially or known suspicious tag fates.

105GPS						Month							
Class	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**All**
Killed			1										1
Stopped - no malfunction				1	1				1				3
All			**1**	**1**	**1**				**1**				**4**

70GPS/GSM													
Class	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**All**
Dropped - suspicious			1										1
Killed			1		1		1				1		4
Stopped - no malfunction	2	4	1		3	3	1		3	7	5	1	30
All	**2**	**4**	**3**		**4**	**3**	**2**		**3**	**7**	**6**	**1**	**35**

80NS													
Class	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**All**
Stopped - no malfunction	1	1		1				2	2			1	8

ALL													
Class	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**All**
Dropped - suspicious			1										1
Killed			2		1		1				1		5
Stopped - no malfunction	3	5	1	2	4	3	1	2	6	7	5	2	41
All	**3**	**5**	**4**	**2**	**5**	**3**	**2**	**2**	**6**	**7**	**6**	**2**	**47**

3. LOCATION DENSITIES

3.1 Summary

- In this section we summarise, via spatial mapping, the large number (over half a million) of locations that had been recorded to 15 January 2017 from the transmissions received from the scores of golden eagles tagged in Scotland.
- Tagged eagles ranged widely and most of the uplands of Scotland (especially the Highlands) were used by one or more tagged birds.
- There was a very broad superficial indication of an association between last known fixes and the background density of utilisation from the tagged birds' locations. This would be expected. At a finer scale, however, it was apparent that several potentially 'suspicious' tag fates may have been unusually concentrated.

3.2 Introduction

A key question for the present project was to examine if the final fixes of several tags which suddenly stopped transmitting (stopped no malfunction) were in a 'suspicious' pattern.

It would be unwise to base a spatial analysis of satellite tag losses (sudden no malfunction tags) on only their last known locations. This is because the density of tags' location records can be very variable spatially depending on where nestlings were tagged and to where they subsequently dispersed. Consequently it is reasonable to assume that if tags suddenly failed at random then they were more likely to fail (from whatever cause) in areas where there were more location records (areas which eagles used more frequently).

As a first step towards the need for such spatial analyses that incorporate background usage and to document, broadly, the locations used by the tagged sample of golden eagles, in this section we illustrate simply the full set of the locations which the tagged eagles used and all of the last fixes of tags. (Tag-specific data are provided in Annex 1.)

3.3 Methods

All locations and final fixes were entered into a GIS. Density maps (number of locations per 4 km^2) were produced for 504,295 satellite tracked locations (20 point quantile scale with each class holding 5% of the observations going from red (low density) to green (high density).

3.4 Results

Figure 3.1 presents a density map of tag location records (n = 504,295: all records) minus any duplicates as would occur from repeated use of a roost site within a day (for example), up to 15 January 2017.

It was clear that there were some high density regions of use with no last known fixes and some low density regions of use with one or more last known fixes. This was particularly true if the map of last known fixes was restricted to tags that failed with no obvious malfunction, were fitted to birds that were killed or fitted to a tag that was dropped under suspicious circumstances (Figure 3.2).

3.5 Discussion

There was a very broad superficial indication of an association between last known fixes and the background density of utilisation from the tagged birds' locations (Figure 3.1). This would be expected. At a finer scale, however (Figure 3.2), it was apparent that several potentially 'suspicious' tag fates may have been unusually concentrated.

What was broadly evident (Figure 3.1) was that the many tagged eagles stuck quite rigidly to the uplands of Scotland (e.g. Ratcliffe & Thompson 1998). Figure 3.1 effectively illustrated the distribution of the Scottish uplands, albeit with thinner records in some of the Hebridean islands and the Southern Uplands which probably at least partially resulted from where nestling eagles were tagged. There were very few records of tagged birds utilising the lowlands and the sharp Highland Boundary Fault was particularly evident.

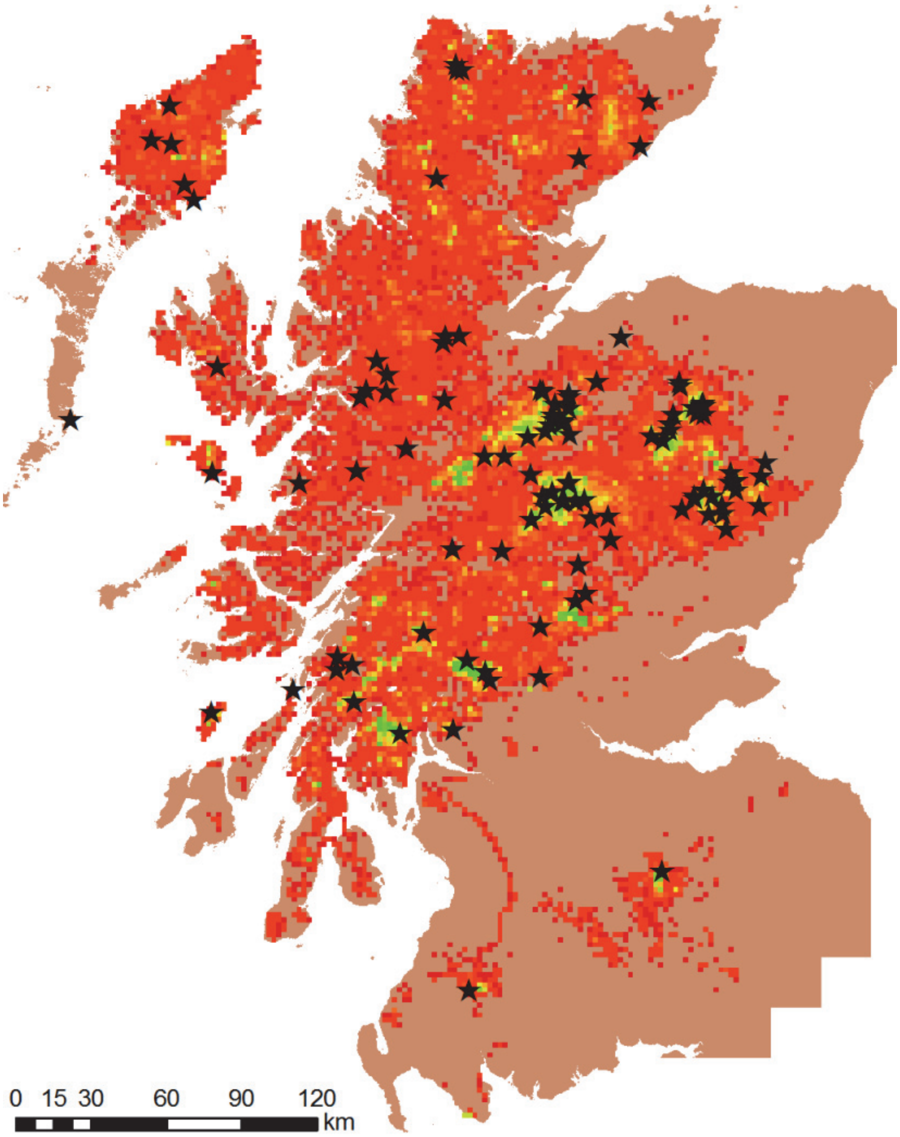

Figure 3.1. Density map (number of locations per 4 km^2) of 504,295 satellite tracked locations (20 point quantile scale with each class holding 5 % of the observations going from red (low density) to green (high density). Stars indicate last known fixes for each tag including those that were still operational (still tracking) at 15 January 2017.

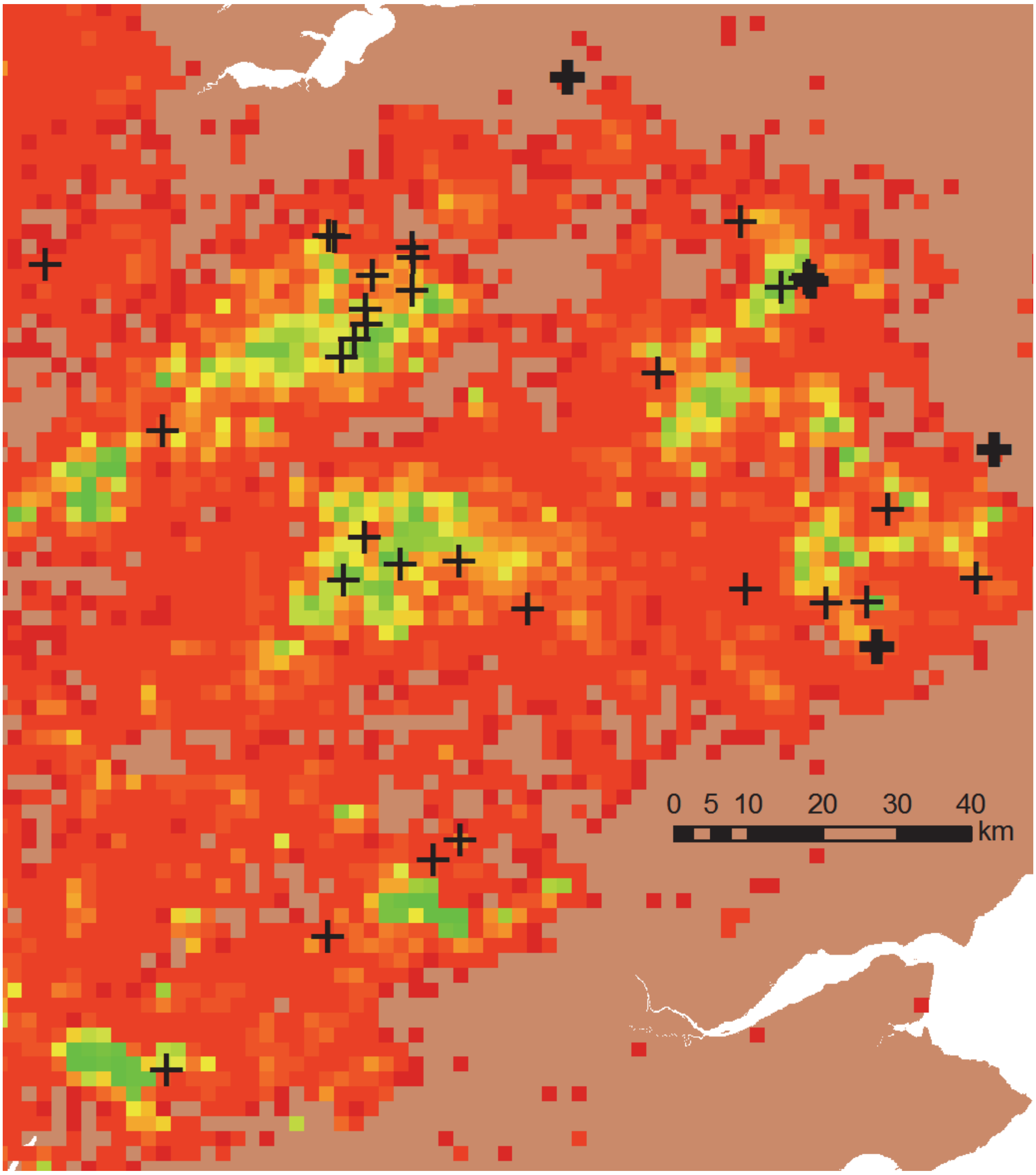

Figure 3.2. See Figure 3.1 for legend. Plus (+) symbols indicate last known fixes for tags that stopped transmitting with no apparent malfunction, bold plus (+ emboldened) symbols mark the last transmitted locations for some satellite tracked birds that were killed.

4. CLUSTER ANALYSIS OF LAST FIXES OF POTENTIALLY AND KNOWN ‘SUSPICIOUS’ TAGS

4.1 Summary

- A hierarchical cluster analysis of the final locations of potentially (stopped no malfunction) and known (killed birds) ‘suspicious’ tags was undertaken to provide an initial examination of any obvious clustering in their locations. Any marked clustering should be synonymous with the final locations being indicated as suspicious (indicative of an external anthropogenic influence) because there was no substantive intrinsic (tag-based) reason why they should be markedly clustered.
- Broadly there were two major groupings at the highest geographical scale. A broad ‘Highland’ grouping (four clusters) was distinctly central-easterly and heavily populated with relatively concentrated clusters and many records. A broad more westerly grouping was far weaker even though it too had four clusters (but included two singular outliers in the western mainland and the Inner Hebrides).
- Six broad geographical clusters could be identified within these major groupings, differing in the intensity of clustering: there were two outliers in 33 records (single member ‘clusters’) on Colonsay (cluster 7: stopped no malfunction) and near Loch Morar (cluster 3: killed).
- The most intense concentrations of potentially or actually ‘suspicious’ records were in the central/eastern Highlands.
- Simplistically, based on a) minimum convex polygons connecting the outer limits of all the several thousands of tagged birds’ locations when alive and b) from a previous section (3: Location Densities) these six clusters appeared indicative of an unusual concentration of potential or known suspicious final fixes from many tagged young eagles in six areas. Such suspicion would indicate the influence of an external anthropogenic influence on the final locations of the stopped no malfunction tags.
- As these indications were simplistic but potentially revealing of a spatial pattern which would suggest that many tagged eagles were killed in particular locations, then further more rigorous investigations were justified (as in section 5: Spatial Analyses, which follows).

4.2 Background and Methods

A hierarchical cluster analysis of the final locations of potentially and known ‘suspicious’ tags was undertaken to provide an initial examination of any obvious clustering in their locations. Any marked clustering should be synonymous with the final locations being indicated as suspicious (and indicative of an external anthropogenic influence). This was, in large part, because there was no substantive intrinsic (tag-based) reason why they should be markedly clustered. If these tags’ final fixes were connected spatially and if their pattern was geographically non-random this indicates that they were, indeed, suspicious, and would point to an external influence affecting their end fate.

The analysis used the R hclust package (Core Team 2016) with a Euclidean distance measure between records’ final X and Y coordinates and incorporating complete linkage clustering. This analysis included not only final records for ‘stopped no malfunction’ tagged birds (excluding the older 80NS tags) but also records where it was known that satellite tagged birds had been killed and one record where a dropped tag was apparently the result of human intervention (‘dropped suspicious’ class): the latter tag was discovered with a cleanly cut harness and the actual tag had been stabbed with a sharp thin implement.

In setting up the R hclust analysis, eight clusters was, *a posteriori*, considered to be the optimum number of clusters that minimised the creation of large ‘inflated’ clusters but also prevented the creation of many single member clusters. This was based on an examination of the dendrogram (Figure 4.1).

A national minimum convex polygon (MCP) was created to encompass the outer limits of all locational records of satellite tagged birds in Scotland: this gave a crude description of the spatial limits within which clusters could occur and thereby provided a coarse spatial context, within the broadest area of birds' 'use' (see the dark green area: Figure 4.2).

Another MCP was derived to encompass the outer limits of end points (final fixes) of 'no malfunction', 'killed' and 'dropped suspicious' tag fates. This second MCP thereby gave a broad outer limit to the records based on potential 'suspicious' tag fate (n = 33, stopped no malfunction) or known 'suspicious' tag fates (n = 5, killed; + n = 1, dropped suspicious), and is shown in light green in Figure 4.2.

4.3 Results

In interpreting the results of these analyses we urge the reader to view the colour-coded dendrogram shown in Figure 4.1, in combination with the spatial mapping of these results; which also includes the two MCP polygons and how these MCPs were derived (Figure 4.2).

Broadly there were two major groupings at the highest geographical scale. One main 'Highland' grouping, involved clusters 2, 4, 5 & 6 (Figure 4.1); and a secondary weaker grouping involved clusters 1, 3, 7 & 8 (Figure 4.1), which included two outliers: one on Colonsay and another in the vicinity of Loch Morar, Lochaber (Figure 4.2). The broad 'Highland' grouping was distinctly central-easterly and heavily populated with relatively concentrated clusters and many records, whereas the broad more westerly grouping was far weaker (see Figure 4.1, 4.2) and influenced by a couple of single outliers.

Consequently, on a finer geographical scale, concentrations of potentially or actually 'suspicious' records were in the central/eastern Highlands, with: cluster 2 (red label) had 11 members in an area of 119.3 km^2, clusters 4 (turquoise label) and 6 (grey label) both had seven members but in much larger areas (494.1 and 401.5 km^2 respectively). Cluster 4, in particular, is large spatially because of the inclusion of a record some distance northwest of most of the cluster members.

Within the 'Highland' grouping, there were four clusters of actual or potentially suspicious tag fates (in highest to lowest order of clustering metric including number of members: Figure 4.1, 4.2):

- Cluster 2 (red label): 'northern Monadhliaths ("Strathdearn")';
- Cluster 6 (grey label): 'Angus Glens/south Aberdeenshire';
- Cluster 4 (turquoise label): 'east Grampians/Aberdeenshire; including Ladder Hills (main cluster)';
- Cluster 5 (blue label): 'central/southern Grampians, Gaick Forest to Glen Tilt'.

The other grouping was dominated by two weaker clusters (in highest to lowest on clustering metric: Figure. 4.1, 4.2):

- Cluster 1 (purple label): 'upper Tay/Forth';
- Cluster 8 (green label): 'south Loch Ness'.

As noted previously, there were two outliers (single member 'clusters') on Colonsay (cluster 7: stopped no malfunction) and near Loch Morar (cluster 3: killed).

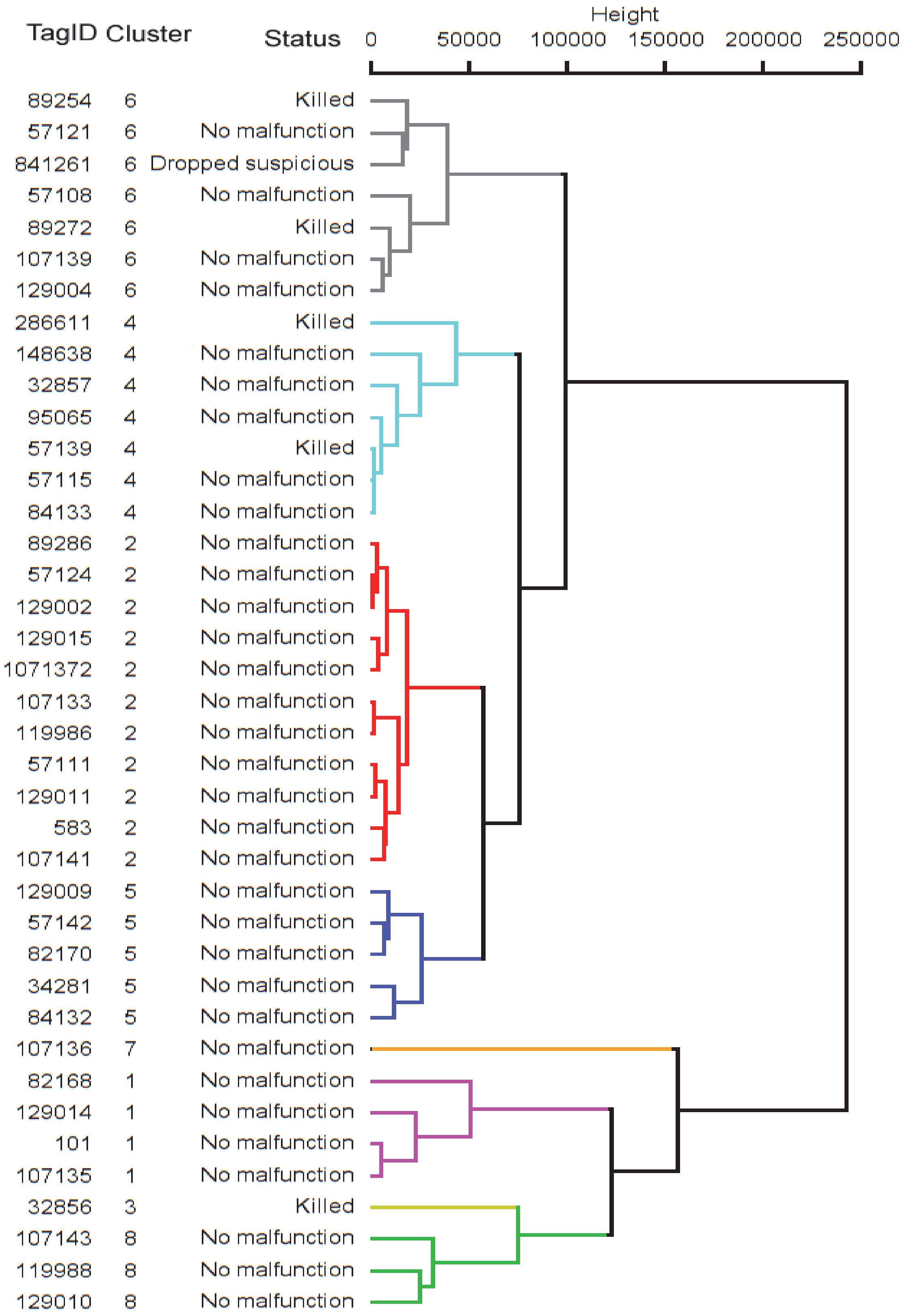

Figure 4.1. Dendrogram illustrating Euclidean distances between final X and Y coordinates with complete linkage clustering. Coding colours also refer to Figure 4.2: for spatial mapping of records.

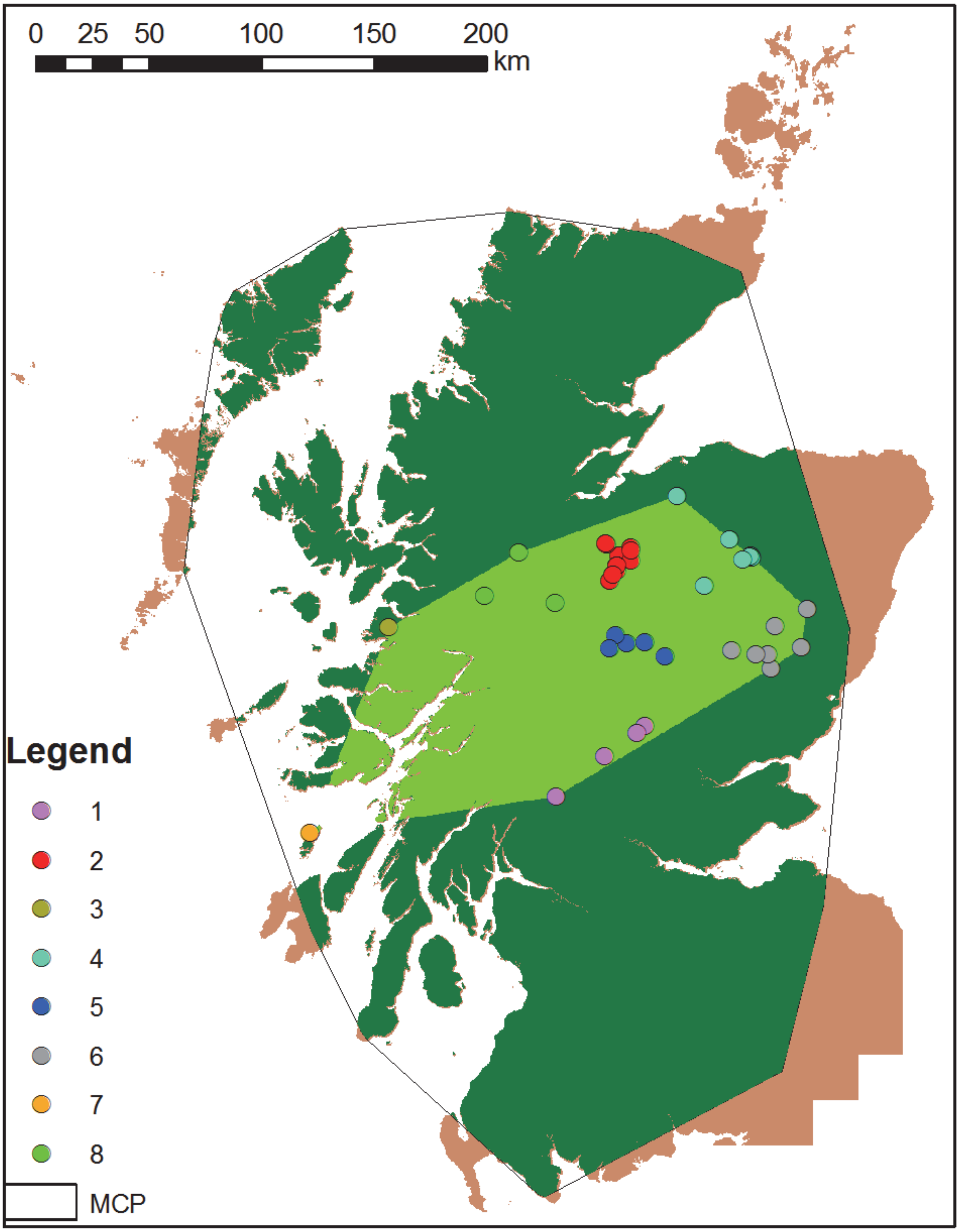

Figure 4.2. Cluster map of the final locations of the potentially and known suspicious tag fates. Points are labelled using the same colour scheme as in Figure 4.1. The dark green area shows the minimum convex polygon (MCP) enclosing all tag location records and the light green polygon shows the MCP enclosing the final locations of the potentially and known suspicious tag fates. Contains Ordnance Survey data © Crown copyright and database right 2010.

4.4 Discussion and conclusions

Spatial clustering of the potentially and known ‘suspicious’ final fixes was especially obvious in the ‘Highland’ grouping of clusters, which were distinctly central-easterly and heavily populated with relatively concentrated clusters and many records. Of course, these clusters could have been because the tagged birds spent more time in the environs of the final fixes. Hence, it could be considered possible (for the predominant stopped no malfunction tag fate class, anyway), albeit highly unlikely, that they could suddenly stop transmitting and then disappear in these locations because tagged birds spent far more time in these areas.

Simplistically, this possibility was eliminated by the observation that the national MCP enveloping the outer limits of all tagged birds’ locations (dark green: Figure 4.2) was markedly larger than both the identified clusters and the MCP enveloping the outer limits of potentially and known ‘suspicious’ final fixes (light green: Figure 4.2). It appeared that although the tagged eagles ranged widely across the uplands of Scotland, the potentially and known ‘suspicious’ final fixes were far more restricted spatially. This would suggest that the final fixes of these tags were, indeed, suspicious and likely due to a systematic geographically-limited external (human-based) influence (notably the ‘Highland’ grouping). The large majority of these final fixes were subject to a high degree of GPS accuracy (section 2, Tag Metadata: ± 18 m to ± 5 m accuracy) which gave confidence in the spatial coincidences of clusters on final fixes.

Moreover, in the earlier section 3 (Location Densities), it was also subjectively illustrated that the final fixes were not obviously spatially related to where young tagged eagles spent most of their time. There were several areas of intensive use where potentially and known ‘suspicious’ final fixes did not occur.

Given the crudity of MCPs and the simple mapping of location densities, however, more sophisticated analyses were justified and warranted to examine this possibility in more detail. The next section describes such analyses.

5. SPATIAL PATTERN ANALYSES

5.1 Summary

- In this section we examine whether the final locations of the stopped no malfunction tags (and killed birds) were unexpectedly spatially connected. Such an unexpected spatial connection would indicate an external (anthropogenic) influence and so, definitive suspicion pointing to the prospect of a spatially systematic killing of tagged young birds associated with particular regions. For brevity these locations are referred to hereafter in this section as stopped no malfunction last fixes (snmlfs) since this was the substantial tag fate (33 of 39: five birds were killed and one tag was 'dropped' suspiciously). There were up to 73 non-snmlf tags in these analyses.
- The approach was to calculate the nearest neighbour distances (NNDs: up to and including the 5th NND) between snmlfs and contrast them with NNDs for a 'virtual' set of last fixes drawn randomly from the locations of all tags. This approach allowed us to compensate for the non-random distribution of all tag locations. A difference in NNDs from that expected from a random pattern would indicate that the snmfls were spatially clustered beyond what was expected from where tagged birds were recorded overall.
- Essentially, 10 analyses were conducted, examining various alternative datasets to ensure that the results were robust. These involved re-running the basic snmfls v random analysis by: excluding the five known killed and one 'dropped suspicious' tags (i.e. considering only stopped no malfunction tags); considering only the 70GPS/GSM tags (i.e. excluding the 105GPS tags); and allowing for the possibility that up to 20 of the 33 stopped no malfunction tags had actually malfunctioned but not detected as such. This gave eight analyses. The final two involved an examination of whether the final fixes of the non-suspicious (non-snmfls) tags were different from a 'virtual' random set of final fixes, for all tag models and for only 70GPS/GSM tags.
- The snmlfs were spatially clustered at up to five spatial scales in comparison to what was expected from randomly selected locations from all tagged birds i.e. last fixes of the potentially and known suspicious tags were clustered and not because birds spent more time in the areas where snmfls were recorded.
- The same result was apparent when only the stopped no malfunction tags were analysed.
- The same result was apparent when only the 70GPS/GSM tags were analysed.
- The same result was apparent when up to 20 of the 33 stopped no malfunction tags were assumed to have actually malfunctioned (and so were assumed as not 'potentially suspicious'). Hence, even if many of the stopped no malfunction tags were misidentified the spatial clustering was still evident.
- In marked contrast, for the non-suspicious tags (non-snmlfs) – both for all tags and only 70GPS/GSM tags – there was no difference between their final fixes and randomly selected 'virtual last fixes'. This provided a test of the approach but also provided further evidence that the snmfls (including the stopped no malfunction tags) were indeed spatially associated and thereby suspicious.
- The presence of clusters of snmlfs was indicative of localised processes that increased the probability that a tag would cease transmitting in those locations. The results strongly indicated that the fate of the stopped no malfunction tags was due to external (anthropogenic) source(s) operating primarily in six clusters mostly in the central and eastern Highlands.
- In crudely answering a key question of the project brief: was there a suspicious pattern in the sudden failure to transmit for many tagged eagles? The answer was an unequivocal 'Yes'.

5.2 Introduction

An overarching and critical objective of the project was to determine if the final fixes of the many stopped no malfunction tags were suspicious and thereby indicative of an external human influence (such as people killing the birds and then destroying and disposing of the bird and its tag). We should reiterate that there is fundamentally an inherent element of 'suspicion' in the stopped no malfunction tag fate classification. This is because not only did these many birds' tags suddenly stop transmitting without any prior transmitted warning of imminent failure (see 'Tag Reliability' section) but also that the bird and/or its tag was not discovered during later searches of the location and the environs around the last transmitted fixes. In several other tag fate classes (e.g. natural death, dropped tag not suspicious) many bird carcasses and/or their dropped tags were re-located and discovered by such searches (see section 2, Tag Metadata).

So the stopped no malfunction tag fate is not only mysterious as to why a previously perfectly functioning tag should suddenly stop transmitting but also that there was no later sign of the bird or its tag in the area around the last transmission.

In this section we examine whether the final locations of the stopped no malfunction tags were no different from what might be expected if there was an innocuous explanation for their distribution across the Scottish landscape. If, however, these final locations were unexpectedly spatially connected this would indicate an external (anthropogenic) influence and, so definitive suspicion pointing to the prospect of a spatially systematic killing of tagged young birds. This section thereby addresses the primary question posed by the project's brief.

Earlier we showed by 'Cluster Analysis' (section 4) that there was a spatial pattern in the final fixes of these potentially or known suspicious tag fates which pointed to an anthropogenic causality for the many tags which stopped transmitting suddenly. This simple exploratory analysis, however, could not thoroughly address some related possibilities as to how the clustering of many potentially suspicious tag fates may have occurred (even if some such possibilities may be logically remote).

In this section we thoroughly consider several alternative possibilities to examine the clustering of potentially or known suspicious final fixes, by addressing the following questions (after each question we subsequently show in bold predictions based on the overarching objective and its associated hypothetical expectations):

1. Were the locations of last fixes of the potentially and known suspicious tags spatially connected (superficially indicating an external human influence) because tagged eagles spent more time in those locations? **If the last fixes of potentially and known suspicious tags were more spatially connected than expected from randomly selected prior locations of all tagged birds, then their geographical connectivity was not a simple and inevitable consequence of tagged birds spending more time in the area of the 'suspicious' last fixes.**
2. Were the last fixes of potentially and known suspicious tags similar to the last fixes of other (non-suspicious) tags whose fates were not potentially or known to be suspicious? **If the final fixes of other (non-suspicious) tags were as expected from the usage of all tagged birds then this would point further to the non-random nature of the potentially or known suspicious tag final fixes.**
3. Were the last fixes of the potentially and known suspicious tags due to a particular tag model, and so, perhaps (e.g.), differing reliability between tag models? **If re-run analyses removed a tag model (which included tags classed as potentially or known suspicious) and the results showed a non-random (unexpected) spatial**

connection between final fixes of the potentially and known suspicious tags, then any influence of a tag model could be discounted.

4. Were several of the stopped no malfunction tags mis-classified and so they had actually malfunctioned? We accept that there was no intrinsic reason as to why tags may suddenly malfunction in particular geographical areas. If it was assumed, nevertheless, that several of the tag fates had been mis-classified from potentially suspicious (stopped no malfunction) to not potentially suspicious (stopped malfunction): after this re-classification, was there still a spatial connection between the last fixes of the stopped no malfunction tags? **If there was a spatial connection between the putative or known suspicious tags' last fixes after many stopped no malfunction tag fates were re-classified as having malfunctioned, then this would indicate that such potential mis-classification was not influential.**
5. Did including known killed birds affect the analyses so far as results for the stopped no malfunction tag fate? **If removing known killed birds from the analyses did not affect the results then it would indicate that the results were also applicable only to the potentially suspicious stopped no malfunction tags.**

To address all of these various possibilities required a large set of analyses and presentation of many alternative results.

5.3 Methods

5.3.1 Data

The starting point for these analyses was primarily the locations of last known fixes from tags off young eagles that ceased transmitting data with no prior indication that there was a technological problem with the tag (stopped no malfunction tags): a potentially 'suspicious' tag fate. We also initially included five tags fitted to birds known to have been killed plus one bird where the tag was 'dropped' in suspicious circumstances (known to be 'suspicious': see earlier 'Cluster Analysis'). 80NS tags were excluded from all analyses in this section due to inconsistent availability of their non-GPS data between tagging and final fixes, and their lower level of fix accuracy (see section 2, Tag Metadata).

For brevity, even though the tags included those where birds were killed (n = 5) or were suspected of being killed (n = 1), these locations are referred to hereafter in this section as stopped no malfunction last fixes (snmlfs) since this was the substantial tag fate (33 of 39). We also used all final fix location data from all other tags and all of the tens of thousands of recorded locations from all tagged birds prior to their end fate classification.

5.3.2 Basic approach

Analyses of spatial patterns in point locations are essentially area or distance based. Area based analyses of pattern are very dependent of the scale of the analysis and are generally considered inferior to the distance based approaches. We used a distance based point pattern analysis method based on nearest neighbour distances (NNDs, Figure 5.1). The concept is simple. The NND from an event is the Euclidean distance to the nearest similar event, in this case the nearest snmlf. It is possible to extend this approach to include the 2nd, 3rd...nth nearest neighbours. We calculated distances up to the 5th nearest neighbour, so as to examine potential relationships at several spatial scales and to avoid the possibility that results could have been biased by a simple, single short-scale approach from 1st NND alone. Calculating distances up to the 5th nearest neighbour allowed the results to indicate if the snmlfs were spatially connected from a local level through to a regional or supra-regional level.

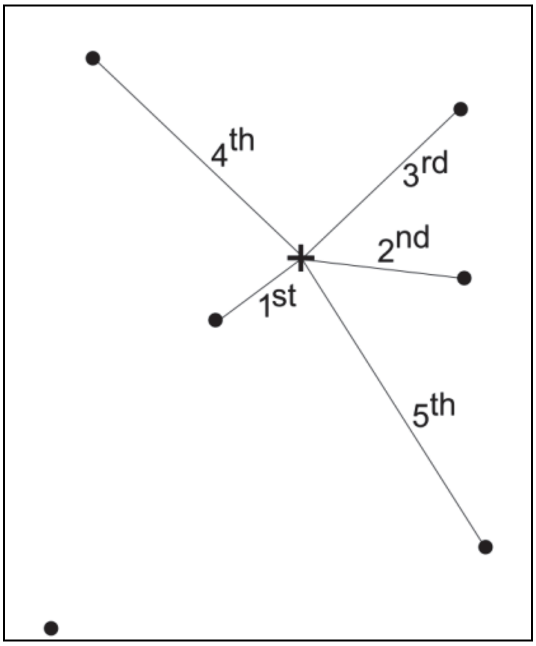

Figure 5.1. Nearest neighbour distances (NNDs) to a location (+) from similar events (•) illustrating the 1st to 5th NND approach to examine multiple spatial scales of association between the same location records for the snmlfs and the randomly selected locations drawn from all tagged birds' locations.

5.3.3 Calculating expected (random) NNDs from all locations

The ratio of the observed NND to the expected NND can be used as an indicator of spatial pattern. The expected mean NND of a random distribution of points is 0.5/square root(*n*/*A*), where *n* is the number of data points (39 snmlfs) and *A* is the Area (97,095,747,156m^2 for a minimum convex polygon covering the locations from all tags). A ratio of 1 suggests a random distribution whilst a ratio <1 indicates a pattern that exhibits aggregation or clustering. If the ratio is >1, the trend is towards dispersion. There are significance tests in the literature to determine if the departure from a ratio of 1 is significant but they depend on assigning values to the area or assume a rectangular boundary and it is known that the test statistics are sensitive to changes in the study area (Boots and Getis, 1988). The golden eagle location data are almost all on land which makes the area calculation difficult and a rectangular boundary, that included all data points, would include a large area of sea. There are also complications arising from the distribution of tagged birds, they are not evenly spread across the Scottish landscape and it is reasonable to assume that tag failures would be concentrated in regions with the highest densities of tagged birds. Although we calculate the ratio of the observed NND to the expected NND our main analyses used a different approach that relied on re-sampling the data.

A sample of NNDs can be summarised by their average; the median was preferred to the mean because a mean NND would be heavily influenced by very small or large NNDs.

If the spatial pattern of snmlfs was different from random this would imply that they were spaced in either a regular or an aggregated pattern. If there was any aggregation of the snmlfs this will reduce the median NND compared to a random pattern. However, if tags stopped at random, with no external influences, the observed median NND was unlikely to be in the tail of the distribution of all possible median NNDs sampled from the data. Under those circumstances it should not be possible to differentiate between the actual pattern of snmlfs and those generated by creating virtual failures at some point in a tag's locational history (i.e. a randomly selected value from a tag's location records).

The presence of a non-random pattern in the snmlfs can be identified if the snmlf median NND is compared to what would be expected if tags failed at random. The expected median NND arising from random tag failures can be estimated by randomly sampling locations from the tags and assuming that these random locations represented a normal, but virtual, tag failure. However, a simple random sample of the tag locations would be unreliable because of large differences in the tags' operational periods. Consequently, sampling was weighted so that the probability that a tag is included in a random sample of tags was proportional to the number of days for which there were records for that tag. Thus, a tag with records from 1,000 days was much more likely to be included in a sample than a tag with only 50 days of records [3]. Secondly, it was assumed that the probability of a tag failing increased with the length of time that it had been operating. The algorithm used to deal with this assumption is described in Appendix 5.1.

5.3.4 Accounting for undetected malfunctions

Even if there was an anthropogenic cause for some snmlfs it is possible that other failures identified as snmlfs might be the result of undetected tag failures, although the engineering diagnostic information for the tags or other investigations did not indicate likely failure (section 6: Tag Reliability). The impact of failing to recognise that some snmlfs were indeed simple failures of the tags was analysed by assuming that between 1 and 20 of the 39 snmlfs was an undetected tag failure. (Note that this was considerably higher than any other indication from studies using the same or similar tags: see 'Tag Reliability' section).

Because we had no information about which specific snmlfs might be tag failures, a sampling procedure was used. It was impossible to include an exhaustive permutation of all combinations of tag failures once the number of undetected failures was greater than three. For example, with four undetected failures there were 82,251 permutations of 35 failures from 39 tags and for 5 failures it was 575,757.

The approach used was as follows. Assume that there are *S* snmlfs and *F* undetected tag failures. A random sample of *S-F* tags can be drawn, without replacement, from the list of *S* snmlfs. This reduced sample becomes the new set of snmlfs used in the analyses. Samples are obtained without replacement because sampling with replacement is likely to result in the same snmlf being included more than once and this would produce a NND of 0 that would bias the analyses by reducing the NND. Simultaneously, a random sample of *S-F* tags is selected from which *S-F* random, virtual tag failure locations are selected using the algorithms described previously. Median NNDs are found for each sample. This sampling is repeated *N* times to obtain two samples of *N* NNDs whose medians can be compared using a Mann Whitney test. The Mann Whitney test, like all other statistical tests, becomes more powerful as the sample size increases and the effect size for a given power will fall with increasing values of *N*. In order to avoid identifying very small differences in median NNDs as significant a series of tests were run to determine the minimum value of *N* needed to achieve a power of 0.95 (if there is a difference in the median NNDs it will be detected 95 times out of a 100). The rationale by which a sample size of 86 was selected is described in Appendix 5.2.

5.3.5 Exclusion of killed birds

While the number of killed birds in the snmlfs was relatively small, to examine any influence of their inclusion (and so thereby examine only the spatial pattern of stopped no malfunction tag final fixes) analyses were re-run excluding the killed birds from the snmlf data. Hence, two snmlf data sets were used in all analyses. The first included tags fitted to birds known to

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[3] The Days field is the number of days between a tag's last and first records and daysum is sum of Days over all tags. Therefore, days/daysum is the proportion of tracked days allocated to a particular tag and proportion of all record days allocated to a particular tag is its value for Days/daysum.

have been killed and the second excluded the tags fitted to the killed birds. Analyses were undertaken for all tag types (excluding the older 80NS tags) and for all tag types except the 105GPS tags (i.e. using the 70GPS/GSM tags).

Overall, these re-runs with different datasets resulted in eight analyses that are summarised in Table 5.1.

5.3.6 Spatial patterns in non-suspicious tag

A final pair of analyses was undertaken as a test of the method used. Data from 112 tags (all tag types except 80NS) were available from 39 snmlf tags and 73 others. If the analyses were repeated but using the pattern of last fixes from the 73 non-snmlf tags there was no reason to assume that were would be a pattern. The absence of a pattern would indicate that the last fixes of the non-suspicious tags were random with respect to the areas used by birds.

All analyses were undertaken using R (R Core Team, 2016 Version 3.3.2) and, in order to ensure the transparency of the analyses, each spatial point pattern analysis is produced as a separate R-Studio R Markdown document (RStudio Team, 2015, Version 1.0.136) in Annex 2.

Table 5.1. Summary of the ten analyses (1 – 10) of spatial patterns in the tag end points.

All tag types		
	No undetected tag failures	1-20 undetected tag failures
All snmlfs	1	5
snmlfs excluding tags fitted to birds known to have been killed	2	6
snmlfs from tags not suspected of anthropogenic disturbance	9	
Excluding the 105 GPS Tags		
	No undetected tag failures	1-20 undetected tag failures
All snmlfs	3	7
snmlfs excluding tags fitted to birds known to have been killed	4	8
snmlfs from tags not suspected of anthropogenic disturbance	10	

5.4 Results

5.4.1 NND ratios

The observed mean 1st NND for the 39 snmlfs was 12,056 m. The sampling area of the MCP covering the locations from all tags was 97,095,747,156 m^2 or 68,015,875,000 m^2 if sea is excluded. Consequently, the expected mean NND is 24,948 m (0.5/sqrt(39/97,095,747,156)) or 20,881 m if the sea is excluded. The ratios of the observed mean NND to the expected mean NND were 0.483 (12,056/24,948) or 0.577 after excluding the sea. Since both were considerably less than one this suggested that the snmlfs were aggregated. Indeed, a cluster analysis of the snmlfs (section 4 – Cluster Analysis) suggested six main clusters and two outliers. It is perhaps unsurprising that the snmlfs were clustered since there were considerably higher densities of tag location records in some regions (section 3 – Location Densities). However, it was clear from the point density map that there were regions of Scotland with a high density of tag records but no snmlfs. The snmlfs were not spread evenly throughout the high density regions.

5.4.2 NND spatial point pattern re-sampling analyses

The results are summarised in Tables 5.2 and 5.3. One analysis from each table is described in detail. The full results for all ten spatial point pattern analyses, plus the R code used to produce the results, are in Annex 2.

Table 5.2 Summary of the spatial point analyses assuming no undetected tag failures. The table is split into ranks and p-values. The rank is the position of the actual snmlf statistic with respect to the 5,000 simulations. The rank is converted to a p-value on the right hand side of the table. The table is further split depending if all tags (analyses 1 & 2 in Table 5.1) or all tags excluding the 105GPS tags (analyses 3 & 4 in Table 5.1) were included and whether tags fitted to birds known to have been killed are included. Non-snmlf refers to analyses 9-10 from Table 5.1. p values >5% are highlighted in bold italics.

		Ranks						**p values**					
	Tags	**No 105GPS**			**All**			**No 105GPS**			**All**		
	Killed	**Yes**	**No**	**Yes Non-snmlf**	**Yes**	**No**	**Yes Non-snmlf**	**Yes**	**No**	**Yes Non-snmlf**	**Yes**	**No**	**Yes Non-snmlf**
	NND												
Minimum	1	7	2	2944	6	4	289	0.1	0.0	***58.9***	0.1	0.1	***5.8***
	2	30	225	1711	35	205	2438	0.6	4.5	***34.2***	0.7	4.1	***48.8***
	3	70	43	4839	72	34	4016	1.4	0.9	***96.8***	1.4	0.7	***80.3***
	4	79	43	4844	79	38	4508	1.6	0.9	***96.9***	1.6	0.8	***90.2***
	5	139	70	4798	128	69	4706	2.8	1.4	***96.0***	2.6	1.4	***94.1***
1st Quartile	1	3	1	1690	15	5	2287	0.1	0.0	***33.8***	0.3	0.1	***45.7***
	2	10	7	3046	13	5	2267	0.2	0.1	***60.9***	0.3	0.1	***45.3***
	3	2	15	4846	2	5	4034	0.0	0.3	***96.9***	0.0	0.1	***80.7***
	4	83	31	4745	41	13	3860	1.7	0.6	***94.9***	0.8	0.3	***77.2***
	5	16	10	4595	15	2	4503	0.3	0.2	***91.9***	0.3	0.0	***90.1***
Median	1	20	2	2689	22	7	2796	0.4	0.0	***53.8***	0.4	0.1	***55.9***
	2	8	22	1395	2	2	1495	0.2	0.4	***27.9***	0.0	0.0	***29.9***
	3	57	129	4040	4	1	2171	1.1	2.6	***80.8***	0.1	0.0	***43.4***
	4	199	724	4509	9	67	2962	4.0	***14.5***	***90.2***	0.2	1.3	***59.2***
	5	791	485	4638	46	262	4599	***15.8***	***9.7***	***92.8***	0.9	***5.2***	***92.0***
Mean	1	5	2	2689	22	7	2796	0.1	0.0	***53.8***	0.4	0.1	***55.9***
	2	1	1	1781	1	1	464	0.0	0.0	***35.6***	0.0	0.0	***9.3***
	3	1	2	4624	1	1	2399	0.0	0.0	***92.5***	0.0	0.0	***48.0***
	4	1	1	4475	1	1	2995	0.0	0.0	***89.5***	0.0	0.0	***59.9***
	5	1	1	4164	1	1	4468	0.0	0.0	***83.3***	0.0	0.0	***89.4***
3rd Quartile	1	47	2	3991	218	6	3572	0.9	0.0	***79.8***	4.4	0.1	***71.4***
	2	2	1	1618	9	2	619	0.0	0.0	***32.4***	0.2	0.0	***12.4***
	3	4	1	4130	3	2	1125	0.1	0.0	***82.6***	0.1	0.0	***22.5***
	4	3	4	3435	1	2	2051	0.1	0.1	***68.7***	0.0	0.0	***41.0***
	5	1	6	2081	1	4	1408	0.0	0.1	***41.6***	0.0	0.1	***28.2***
Maximum	1	4721	4636	1727	2274	3978	2262	***94.4***	***92.7***	***34.5***	***45.5***	***79.6***	***45.2***
	2	4156	3848	1219	2338	4268	2037	***83.1***	***77.0***	***24.4***	***46.8***	***85.4***	***40.7***
	3	4536	4311	747	3476	3509	1041	***90.7***	***86.2***	***14.9***	***69.5***	***70.2***	***20.8***
	4	4175	3835	2456	2682	4114	3665	***83.5***	***76.7***	***49.1***	***53.6***	***82.3***	***73.3***
	5	3729	3398	1499	3688	3529	2546	***74.6***	***68.0***	***30.0***	***73.8***	***70.6***	***50.9***

Analysis 1 (Table 5.1) involved all snmfls and no assumed undetected tag failures. The full details of this analysis are in Appendix 5.3. Figure 5.1 shows the location of the NND statistics from the snmlfs in the distributions of the sampled (random) NND statistics.

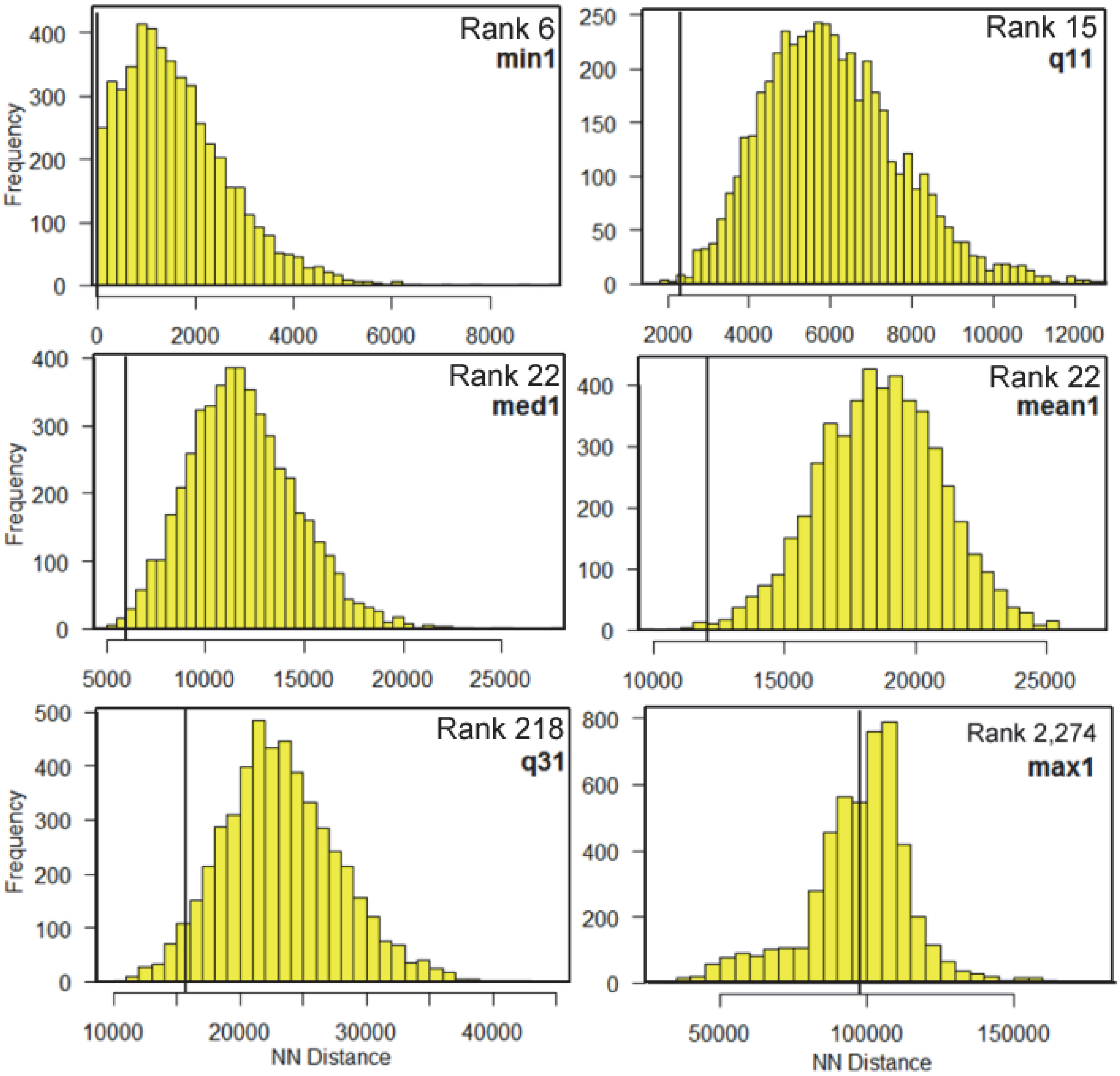


Figure 5.2. Frequency distributions of six statistics for the first NNDs derived from 5,000 samples of tags. The vertical bar marks the position of the snmlf statistic and its rank is shown in the upper right of each plot.

The rank values of all of the statistics for the 1st NND metrics, except the maximum NND, were all in the lower 2.5% of the distribution of median NNDs suggesting that it was unlikely that the spatial point pattern of the snmlfs was random, supporting the interpretation of the ratio of NNDs (Figure 5.2). There was no reason to expect that the maximum NND would be at the low end of the distribution even if most of the snmlfs are aggregated given that one of them is on Colonsay in the Inner Hebrides. It was not until the 5th NNDs were examined that the median snmlf NND was not in the lower tail, suggesting that the clusters of snmlfs were perhaps made up of fewer than five cases.

5.4.3 Analyses excluding killed birds, and 105GPS tags

Analysis 2 repeated analysis 1 (all snmfls) but excluded tags fitted to birds known to have been killed (and so used only stopped no malfunction tags). Analysis 3 excluded the

105GPS tags (so only 70 GPS/GSM tags); and analysis 4 repeated analysis 3 but additionally excluded killed birds. The interpretation of a significant clustering of the snmlfs in analysis 1 was supported by the other three analyses (i.e. analyses 2, 3 & 4 in Table 5.1) (Annex 2).

5.4.4 Analyses of final fixes of non-suspicious tags

When the analyses were repeated but using the last known fixes of tags that were not thought to have a suspicious termination (non-snmfls: analyses 9 & 10 in Table 5.1) there was no evidence that their spatial point pattern was different from random. This was evident for whether all tags or just 70GPS/GSM tags were used (analysis 9 & 10: Table 5.1) (Annex 2).

5.4.5 Analyses assuming that snmfls included up to 20 malfunctioned tags

The spatial point pattern analyses were extended to include the assumption that between 1 and 20 (more than 50%) of the snmlfs were undetected failures of the tag that could not be recognised from the tag's engineering data. The results of these analyses (analyses 5 to 8 in Table 5.1) are in Table 5.3, Figure 5.3 and Annex 2. As an illustration of the results the outcomes from the analysis excluding the 105GPS tags and tags fitted to birds known to have been killed are examined in more detail.

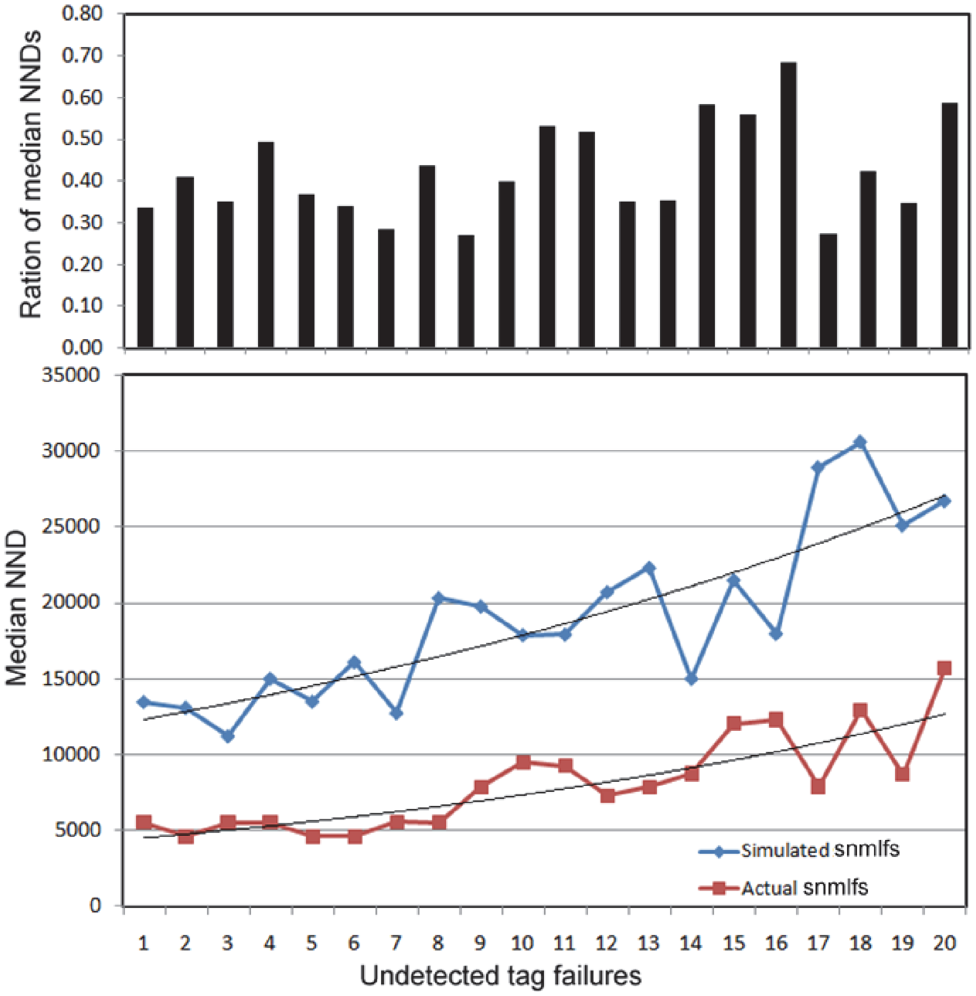


Figure 5.3. Median NNDs for simulated and actual snmlfs as the number of undetected tags failures increases. The upper bar chart shows the ratio of the median NNDs (actual/simulated).

The p values from the Mann Whitney for all values of undetected failures are low (maximum 1%). These results stand despite identifying the minimum sample size that would deliver the desired statistical power. This is important because if we had used a large sample, for example 1,000, the effect size would have been very small and we could have been identifying small differences in medians as highly significant. The difference in medians is apparent in Annex 2 and Figure 5.3.

As shown in Figure 5.3, there were consistently large differences in the median NNDs consistent with the small Mann Whitney p-values. Also, as expected, the median NNDs increased as the number of undetected tag failures increased. There was no trend in the ratio of median NNDs.

Irrespective of the tag types included in the analyses the p values were consistently small when tags fitted to killed birds were excluded. When all birds were included there were some larger p values but only one >5% and there was no trend evident in the p values.

Table 5.3. p values from Mann Whitney tests of equality of median NNDs. P values are given for the 1st to 5th NND and for 1-20 undetected tag failures amongst the 39 snmlfs. Values are given for four combinations of tag type and the inclusion/exclusion of tags fitted to birds known to have been killed. The pink cell highlights a p value > 0.05. The median NNDs from these analyses are in Annex 2.

	Including Killed						**Excluding Killed**				
All tags											
failed	1	2	3	4	5	failed	1	2	3	4	5
1	0.00	0.68	0.42	0.43	0.03	1	0.00	0.00	0.01	0.00	0.00
2	0.01	0.82	0.63	0.01	0.33	2	0.00	0.01	0.00	2.02	0.00
3	2.63	0.00	0.00	0.14	5.23	3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.02	4	0.00	0.00	0.00	0.00	0.00
5	0.18	0.27	0.00	0.10	0.87	5	0.00	0.01	0.00	0.00	0.01
6	0.06	0.00	0.07	0.00	0.02	6	0.00	0.02	0.00	0.00	0.00
7	0.01	0.01	0.00	0.00	0.01	7	0.00	0.00	0.00	0.00	0.00
8	0.07	0.00	0.86	3.37	0.09	8	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	4.47	0.22	0.62	9	0.00	0.00	0.00	0.00	0.00
10	0.28	0.00	0.00	0.00	0.00	10	0.00	0.00	0.00	0.00	0.00
11	0.01	0.01	0.00	0.11	0.56	11	0.00	0.00	0.00	0.00	0.01
12	0.00	0.00	1.51	0.00	0.40	12	0.02	0.00	0.01	0.00	2.17
13	0.13	0.00	0.02	0.01	0.00	13	0.00	0.00	0.00	0.01	0.00
14	0.86	0.00	0.01	0.02	2.59	14	0.03	0.04	0.00	0.00	0.01
15	0.27	0.15	0.06	0.00	0.05	15	0.00	0.26	0.01	0.06	0.00
16	0.01	0.09	1.01	0.00	4.53	16	0.01	0.00	0.02	0.00	0.00
17	0.01	0.00	0.15	0.00	0.00	17	0.08	0.00	0.00	0.34	0.00
18	0.00	0.32	1.12	0.01	0.00	18	0.00	0.00	0.23	0.45	0.00
19	0.11	0.00	1.91	0.00	1.21	19	0.01	0.00	0.00	0.00	0.00
20	0.09	0.00	0.10	0.00	0.05	20	0.00	0.00	0.12	0.00	0.01
Excluding 105GPS tags											
failed	1	2	3	4	5	failed	1	2	3	4	5
1	0.00	0.01	0.02	2.59	0.00	1	0.01	0.00	0.00	0.00	0.00
2	0.00	0.00	1.86	0.05	0.42	2	0.00	0.00	0.04	0.00	0.00
3	0.05	4.57	0.00	0.00	0.00	3	0.00	0.00	0.00	0.03	0.00
4	0.00	0.00	0.00	0.56	0.00	4	0.00	0.00	0.00	0.00	0.00

Including Killed						Excluding Killed					
5	0.00	0.00	0.51	0.00	0.00	5	0.00	0.00	0.00	0.00	0.03
6	0.00	0.00	0.00	0.00	0.00	6	0.00	0.00	0.00	0.03	0.00
7	0.10	0.03	0.00	0.00	0.00	7	0.14	0.00	0.02	0.00	0.00
8	0.06	0.00	1.04	0.00	0.00	8	0.00	0.01	0.01	0.00	0.00
9	0.00	0.01	0.00	0.02	0.00	9	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	10	0.03	0.00	0.00	0.00	0.00
11	0.00	0.10	0.05	0.00	4.00	11	0.00	0.00	0.00	0.00	0.00
12	0.00	0.01	0.00	0.01	0.17	12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.06	0.00	0.01	0.00	13	0.00	0.08	0.00	0.01	0.00
14	0.00	0.00	0.00	0.14	0.00	14	0.01	0.00	0.01	0.00	0.00
15	0.00	1.75	0.00	0.00	0.11	15	0.04	0.00	0.00	0.00	0.05
16	0.00	0.00	0.02	0.00	0.00	16	1.00	0.70	0.00	0.13	0.00
17	0.00	0.00	0.00	0.00	0.00	17	0.00	0.00	0.00	0.00	0.01
18	0.01	0.00	0.01	0.04	0.03	18	0.00	0.00	2.45	0.00	0.01
19	1.40	0.13	0.00	0.00	0.04	19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	2.82	20	0.00	0.00	0.00	0.29	0.00

In summary, the results from analyses 5 - 8 (Table 5.1) were consistent with those from analyses 1 - 4 (Table 5.1) and indicated that the snmfls, the final fixes of only stopped no malfunction tags or only 70GPS/GSM tags were spatially clustered even when up to 20 stopped no malfunction tags were assumed to have malfunctioned.

Annex 2 contains details of the spatial analyses.

5.5 Discussion and conclusions

The results involving the snmfls were consistent and showed that snmlfs were spatially clustered at up to five spatial scales in comparison to what was expected from randomly selected locations from all tagged birds i.e. last fixes of the potentially and known suspicious tags were clustered and not because birds spent more time in the areas where snmfls were recorded.

The same result was apparent when only the stopped no malfunction tags were analysed; or when only the 70GPS/GSM tags were analysed. The same result was also apparent when up to 20 of the 33 stopped no malfunction tags were assumed to have actually malfunctioned (and so were assumed as not ‘potentially suspicious’). Hence, even if many of the stopped no malfunction tags were misclassified the spatial clustering was still evident.

In marked contrast, for the non-suspicious tags (non-snmlfs) – both for all tags and only 70GPS/GSM tags – there was no difference between their final fixes and randomly selected ‘virtual last fixes’. This provided a test of the approach, which was passed, but also provided further evidence that the snmfls (and also only the stopped no malfunction tags) were indeed spatially associated and thereby suspicious.

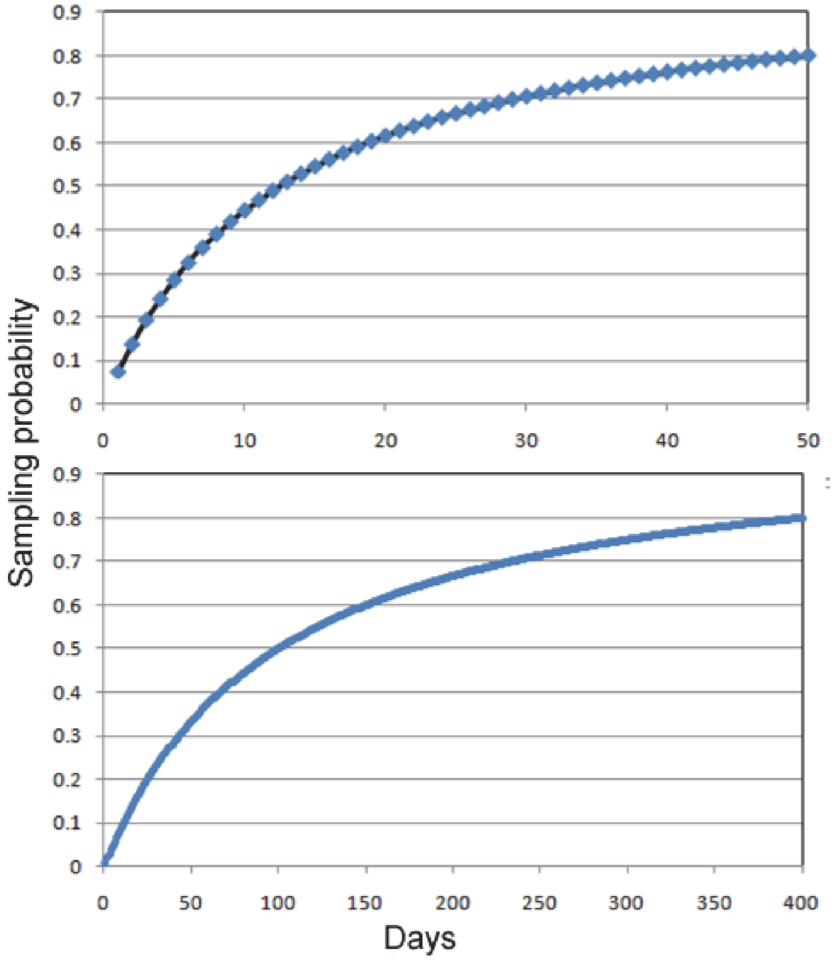
The conclusion that must be drawn from these spatial point analyses is that it was highly improbable that a random selection of tag failures would produce the observed aggregated spatial pattern and the presence of clusters of snmlfs was suggestive of localised processes that increased the probability that a tag would cease transmitting in those locations. This was apparent no matter which set of data was considered as subsets of the snmfls, and held even if some of the snmlfs were not the result of anthropogenic actions. The presence of clusters of snmlfs was indicative of localised processes that increased the probability that a tag would cease transmitting in those locations. That the unsuspicious non-snmlfs were no different to what would be expected from the locations which had been used by tagged eagles was additionally revealing.

As illustrated elsewhere in this report (Location Densities: section 3) there were several areas with relatively high use by young golden eagles where there were no snmfls. The results in the present section strongly indicated, together with the Cluster Analysis (section 4), that the fate of the stopped no malfunction tags was due to external (anthropogenic) source(s) operating primarily in six clusters mostly in the central and eastern Highlands.

In crudely answering a key question of the project brief: was there a suspicious pattern in the sudden failure to transmit for many tagged eagles? Yes.

Appendix 5.1. Tag time weighted sampling algorithm

Each day in a tag's record is assigned a sampling probability based on a "Plateau" curve[4]: *probability=ax/(b+x)*. Using values of *a* =1 and *b*=total number of record days/4 seems to produce a suitable sampling curve. The equation used here is *sampling probability = day number/(day number + total number of days/4).* Two sampling probability curve examples are shown for 50 and 400 days of tags records.



Appendix 5.2. Determining the appropriate sample size

Two sets of 1,000 random samples of n = 39 (the total number of snmlf for all tags excluding the 80NS and those fitted to adult birds) locations were drawn (sampling with replacement). Set 1 contained locations of simulated snmlfs, set 2 comprised locations drawn from the actual snmlf. NNDs (1st to the 5th NN) were calculated for each sample of 39 NNDs. Means and standard deviations were obtained for the two sets of 1,000 random samples (Mean = 20,093m, sd = 24,285m for the simulated snmlfs and a mean of 12,056m, sd =17,502m for the actual snmlfs). A lognormal distribution was a good approximation of the empirical frequency distributions of these two samples of medians (Figure A5.1). The simulated mean NND of 20,093 m is similar to that expected (20,881 m) for a random distribution of 39 points (Results 5.4.1).

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[4] See http://onlinelibrary.wiley.com/doi/10.1002/9780470126714.app4/pdf

20,000 random NNDs were generated using each pair of statistics using the dLogNormal function in Poptools V 3.2 (Hood, 2010). The empirical (drawn from the real tag location data) and randomly generated (by Poptools) frequency distributions for the simulated snmlfs are shown in Figure A5.1. The simulated frequency distribution is a good approximation of the empirical frequency distribution.

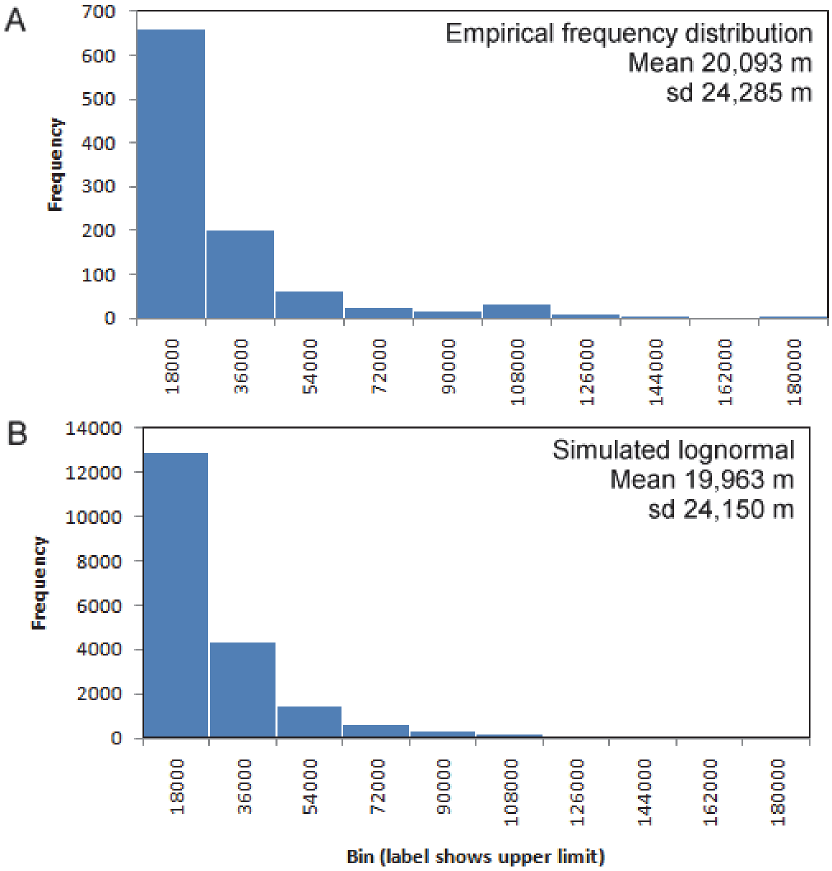

Figure A5.1. Frequency distributions of the median NNDs for samples of 39 locations. A is the empirical frequency distribution of samples drawn from the tag location data. B is a random sample generated using the dLogNormal function in Poptools with the mean and sd of set A.

The two samples of 20,000 NNDs were imported into R and randomly sampled with sample sizes varying from of 30 – 100. This was repeated 1,000 times for each sample size. 1,000 Mann Whitney tests were carried out and the number of times that $p<0.05$ was counted and stored. For example, when a sample size of 30 was used, 30 values were drawn from the two sets of 20,000 values. The medians of these two samples of 30 values were compared using a Mann Whitney test. This was repeated a further 999 times and then the sample size was increased to 31. This continued until the sample size was 100.

The standard deviation and the running mean of actual snmlfs stabilised once the sample size was approximately 80. For the simulated data the sample sizes were larger before they stabilised (Figure A5.2).

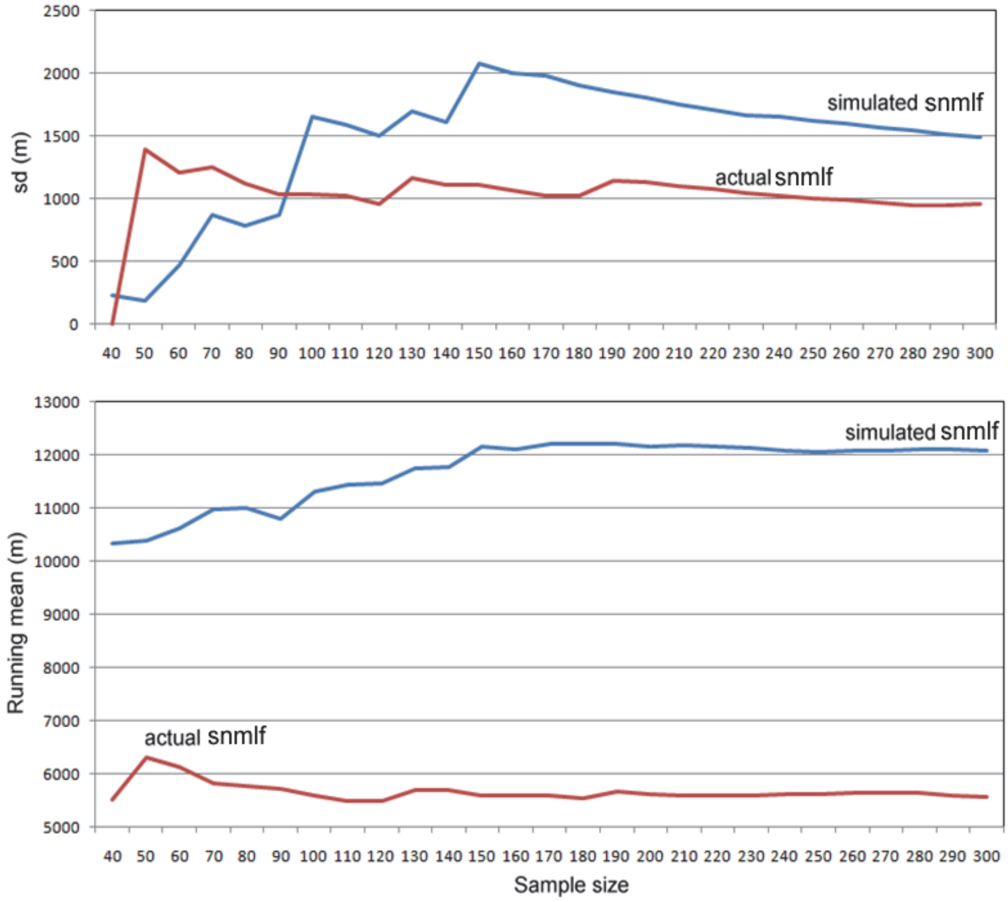

Figure A5.2. The standard deviations and means of median NNDs from samples of 39 locations in relation to the number of repeat random samples taken.

A sample size of 86 repeat samples was needed to achieve a power of 0.95 for a Mann Whitney test comparing median NNDs of two samples of 36 locations drawn from simulated data (Figure A5.3).

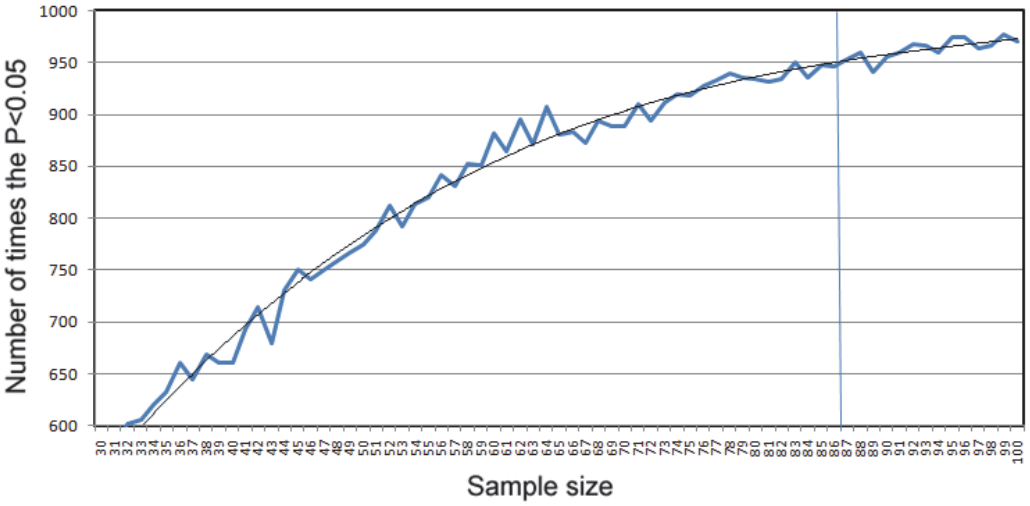

Figure A5.3. Power (number of times p<0.05 in 1,000 trials) of a Mann Whitney test to compare median NNDs. The plot shows the actual (blue) and fitted trajectory of the power (black) in relation to the sample size (number of repeat samples).

Appendix 5.3.

Median NNDs used in the Mann Whitney tests of equality of median NNDs (Table 5.2). Median NNDs are given for the 1st to 5th NND and for 1-20 undetected tag failures amongst the 39 real and simulated snmlfs. Values are given for four combinations of tag type and inclusion/exclusion of tags fitted to birds known to have been killed.

	All tags										**No 105GPS**									
All tags	**Simulated median NNDs**					**Actual snmlf NNDs**					**Simulated median NNDs**					**Actual snmlf NNDs**				
failed	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
1	12297	10848	11617	10472	13004	4602	6103	5519	6190	6017	11856	9356	9529	10676	12030	4602	5060	4602	7034	5060
2	13199	13365	13693	12934	11503	5568	6017	6393	6190	6292	12924	12528	10180	11168	9370	4602	5519	7939	5060	6190
3	13112	13754	10873	10035	10321	6848	5798	5519	5855	6017	10612	10563	12846	12563	13235	5519	7878	4602	5519	4602
4	13045	16970	12855	15721	11497	6017	5519	5519	6190	6017	13950	13695	9179	9823	9936	6747	5060	5519	5519	5519
5	11524	11183	10167	12808	12314	5941	7908	6017	7136	8543	16493	16900	13344	13531	17410	5798	5519	7908	5519	5060
6	9356	14708	14868	13605	14942	5519	7303	6292	6190	6393	19151	12878	12471	16485	20353	4602	5519	5519	6190	7034
7	15292	12623	11955	19571	14475	6017	4602	5519	6190	7939	13232	12031	15000	15447	19903	7279	5519	5865	5674	4602
8	12410	14614	15230	10265	13199	6393	6017	10988	6124	6292	12536	17382	14350	15193	18355	7303	5798	8499	5519	6028
9	16989	16176	12708	10922	13291	7908	7064	7939	5768	7939	15823	14488	14911	13434	13961	5060	7878	5519	7548	6124
10	12925	11606	14590	19925	16632	7908	4599	6017	7908	5741	13003	16235	14678	13544	17743	7591	6190	4599	5865	7982
11	15348	14769	13801	14206	13943	6103	6292	5519	7908	8499	19499	14133	14763	11468	11622	7550	7878	7939	4602	10803
12	19288	16807	12720	21508	12384	7939	6393	9060	7591	6017	13260	16655	20572	15025	16150	6190	7878	6028	7878	10024
13	12470	12524	16758	15100	14064	6393	5874	6848	7581	6103	18370	16203	16770	15744	12495	6190	9256	5692	6028	5519
14	12462	18117	13500	19716	13763	11077	6701	6557	7982	9839	20500	19613	20292	16251	20259	7939	5798	7939	7908	4602
15	14632	18843	17366	18901	16055	10988	6965	8499	6190	10293	17525	13458	21210	19701	15771	5568	7300	7908	11223	10988
16	18450	17139	12610	19253	15344	7878	8025	9676	6393	11077	14012	15022	12901	19420	18041	7878	5519	6991	5732	5961
17	18453	21909	16698	15522	20493	7878	6103	8499	6991	6190	20578	21695	17506	18645	17815	7908	5961	6949	6704	7878
18	17499	16539	13226	18742	14846	7012	7303	7982	10803	6103	19493	16698	17487	18177	20509	11276	7878	7908	7878	11276
19	15808	15009	17956	15251	16762	7716	6017	11534	9266	12603	16209	16471	20603	18141	17548	12813	10024	7878	7621	10552
20	19086	19079	15743	21379	20859	11276	7908	10823	8543	11276	24308	24001	27766	29296	23212	10045	11582	11132	7939	16007
No Killed failed	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	12858	14093	13139	11975	12561	5519	4602	6017	5060	5519	13483	18257	10841	12681	11944	5519	4602	4602	4602	5519
2	14434	14271	13237	14100	13892	5768	6205	5519	9159	5519	13097	15941	12549	13055	13111	4602	5519	5519	5519	4599
3	14736	14211	14536	14542	16843	5568	5741	7908	5768	6393	11225	14677	13164	13423	17763	5519	4600	5060	6698	4599
4	15575	14424	14898	11945	15272	5519	4602	5941	5060	6017	15013	13252	16685	14465	17584	5519	4602	5060	4602	7878
5	16078	11632	14746	14445	15444	5519	5519	5941	5519	7209	13499	15948	16926	16403	11544	4602	4602	7878	4602	7878
6	14818	17563	16585	12543	16663	4599	7982	4602	4252	5519	16109	17012	19683	12525	14963	4599	4602	7878	5519	5519
7	17292	14127	15687	12585	16492	5060	5519	5519	6017	6017	12744	19599	12413	15898	17750	5568	6747	5519	7878	6949

8	15009	13506	16021	17036	18405	5732	4599	5519	6848	6393	20325	16220	15858	19721	14300	5519	7878	7908	5519	7878
9	16854	15451	16877	16475	18400	7548	6393	7951	4602	5060	19778	16133	16079	16332	18061	7878	7303	4602	5519	7878
10	25852	20316	18059	17485	15718	10640	7939	6205	5865	5865	17890	23691	21802	19040	25061	9506	5732	5519	7591	7295
11	16263	14928	15839	14949	14384	6205	5798	6037	7136	6205	17925	26191	18034	19635	18456	9278	7279	7591	10988	6541
12	16325	17357	14734	18121	12406	7939	7908	7008	10293	6991	20726	17851	19254	21016	20248	7295	6584	7548	6916	7878
13	16014	16390	19545	22662	16554	5674	9159	6536	10988	5798	22312	15782	18584	17443	15252	7878	7908	6638	8025	6972
14	15254	14056	23920	17857	17923	9159	7279	7303	7300	10988	15011	17305	18102	18559	20248	8748	7982	7591	5519	5961
15	20819	21008	19499	14018	22865	6393	11132	7982	9116	7878	21513	19309	24270	18813	15808	12044	5519	5568	6680	9755
16	24317	23700	16973	17427	21487	10803	6225	7982	6017	9116	17974	17351	20252	20027	22524	12303	10803	7591	15098	7908
17	16533	18879	18110	19787	22706	10293	7939	8705	10988	10389	28930	23197	24489	20107	22812	7908	7548	8025	7982	10988
18	21806	18889	16048	19784	25105	8709	10213	10988	12195	11276	30627	33101	17666	31174	26304	12925	12263	11166	12813	11276
19	23752	24018	25896	24065	23040	11510	8459	8025	11573	7939	25115	22441	25735	23644	25237	8705	13955	11132	13574	10958
20	20844	21471	24021	28629	18952	7982	11276	11573	10823	8025	26724	35358	34194	26528	31679	15706	10805	10988	15096	12813

6. TAG RELIABILITY

6.1 Summary

- Earlier in this report spatial analyses have indicated spatial clustering of the substantial majority of final fixes of stopped no malfunction tags (snmfl data). This, in itself, has indicated a "suspicious pattern" as regards the primary objective of the project, because it substantially indicated that an external anthropogenic influence was behind the sudden cessation of transmissions of many of these tags (and also, as well as the spatial patterns, suspicion was intrinsically confirmed by an absence of the bird carrying the transmitting tag, or its tag, when searched for at and around the last fix).
- On these results, therefore, there is little reason to suppose that an 'internal' process due to the tag's construction/performance/reliability could substantially explain this pattern because this would require not only that tags should suddenly stop transmitting in areas where tags transmitted well-enough previously, but also that the sudden cessation of transmissions should also result in the absence of any bird or its tag at or near the final fix location. [To examine directly such a set of results would have had to invoke some kind of "Bermuda Triangle" type of hypothesis, which we could not responsibly invoke, never mind try to test.]
- As described earlier, many birds and/or their tags have been recovered because when a tag has been dropped or a bird has died and its corpse has not been interfered with around death, then transmitted signals (and the subsequent recovery) all point to a cause of the tag fate and/or or the bird's fate. These transmitted signals, and this subsequent follow-up to recover the bird and/or tag are wholly different in nature to the stopped no malfunction fate.
- Nevertheless, as per the project's objectives, in this section we have examined several further aspects of 'tag reliability'. This is an issue which seldom appears in the published literature and so we solicited data on 'reliability' from a range of other researchers who have deployed the same type of tags elsewhere.
- From Scottish data, we describe how, from transmitted engineering data, a 'malfunction' tag was identified: we show examples of the distinguishing processes applied to GPS tags (using comparable LC4 tag transmissions) from transmitted engineering data.
- Several cross-checks and validation procedures were undertaken and are summarized, to examine if our stopped no malfunction class was robust (as against the stop malfunction class ≈ "premature failure" ≈ "unreliable tag") for the primary data source for the present study – MTI 70GPS (PTT) tags, as well as MTI 105GPS LC4 tags.
- These checks included sending a 'blind' sample of engineering data for 10 randomly selected 70GPS (PTT) tags to the manufacturer (MTI) for checking on 'fate': the results of these checks agreed with our core classification for the sample; an absence of malfunction. Other forwarded data on LC4 (internal lithium battery) tags were also confirmed as some tags having met with battery failure: coincident with our findings.
- As a result of the cross-check and validation procedures, we were confident that our MTI GPS PTT tag fate classifications were robust on available engineering data. These showed a very low stopped malfunction rate; and a high stopped no malfunction rate: these were the primary data behind our earlier conclusion of 'suspicious' patterns in the sudden failure of transmissions and coincident lack of tag or dead bird at or around the last fix.
- Other solicited research deploying the same MTI GPS PTT model tag had not found the same level of the stopped no malfunction fate class as recorded in Scotland: the Scottish classification rate was relatively high. In particular, a large sample from the USA for golden eagles classified a low rate (c. 2 %) of stopped no malfunction fate (the comparable rate for Scotland was about 25 times higher) but for both the USA and Scotland there was a very similar (low) rate of malfunction fate (c. 2 %).

- Other researchers, nevertheless, also worked in study areas where some persecution (killing) of birds was also occurring, and so this could have been (or was) involved as a ‘suspicious’ explanation for the sudden stop class. Even so, it was revealing that the stopped no malfunction fate was higher in Scotland than anywhere else.
- That this result was anomalous for Scotland, indicating a particularly high level of external human-caused interference, was highlighted by how similarly low the rates of tag malfunction were across all studies.
- In other words, the MTI GPS PTT tags which formed the backbone of the present project appeared to be intrinsically reliable, similarly in Scotland and elsewhere, with a very low rate of unexpected malfunction.
- An analysis of “survival rates” of Scottish 70GPS/GSM tags revealed that stopped no malfunction tags had relatively poor survival compared to other tags and was below the tag manufacturer’s expected longevity of ≥ 3 y. This again was not consistent with sudden failed tags being due to undetected malfunction.
- Data from bald eagle tags had the next-nearest highest rate of stopped no malfunction rate in solicited data (albeit less than half the comparable rate for Scottish golden eagle tags). Stopped no malfunction tags had higher survival rate (greater duration) than comparable Scottish tags, suggesting a greater likelihood of undetected or unreported malfunction than for the Scottish golden eagles. This further illustrated the disparity between the likely cause of sudden failure rates of Scottish tags and those recorded elsewhere.
- We conclude that some number of the many MTI GPS PTT tags classed as stopped no malfunction may have been due to malfunction, but this number would appear to be small.
- Apart from the intrinsic lack of any responsible hypothetical basis on why the observed spatial patterns of sudden tag failure last fixes could be explained on a ‘tag reliability’ basis, the results of this section do not indicate a substantive contribution of ‘tag reliability’ to the scale and spatial pattern indicated by the many sudden no malfunction tag fates in Scotland.
- Rather, the several results consistently pointed to a particularly high level of human-caused interference on tagged eagles in parts of Scotland.

6.2 Introduction

An objective of the project was to consider the reliability of the transmitters deployed. This objective refers primarily to the possibility that the stopped no malfunction (snm) fate may have been caused by (undetected) sudden internal ‘catastrophic’ cessation of the tag’s functions, and this may have a bearing on spatial analyses for such tag fates. That these are sudden is reference to a lack of any prior transmitted engineering data (including battery failure and/or sporadic/truncated GPS locations); such failures have been classed differently under a stopped malfunction fate.

Classification of tag fates is critical to the project’s objectives especially on classification of tags’ stopped no malfunction fate, as final locations of these tags are fundamental to addressing the primary objective posed by the project brief. This is especially relevant to comparing the stopped no malfunction class with the stopped malfunction class, because ‘reliability’ infers that the stopped no malfunction tags have, actually malfunctioned (without detection); or that their fate may have otherwise been misclassified.

As noted earlier in this report, for example, for all tags that were not still tracking at the end of the data collection period, the locations and surrounding areas of all final fixes were searched, for evidence of either a tag, a dead bird and/or a dead bird + attached tag. Notably, for the tags classed as stopped no malfunction, despite searches around the last known fix location, no tag or (dead) bird was found, indicating that the sudden cessation of transmissions was probably not due to the tagged bird dying at the last fix location. Such searches add a secondary level of evidence that the sudden stop in transmissions is probably not from a natural death of the tagged bird, or a dropped tag.

This is because in this scenario of a natural death (as confirmed by other researchers and publications e.g. McIntyre et al. 2006, Klaassen *et al.* 2014, Nygård *et al*. 2016) the transmitted data (alone) are usually different. Typically a naturally dead tagged bird (or a killed bird which is not removed/destroyed along with the tag) “drills a hole in the map” by continuing to transmit repeatedly over a prolonged period at the same location. A search can potentially discover the dead bird (and tag): several were found in the present Scottish study. Similarly a dropped tag “drills a hole in the map” and a search can recover the tag at the location: several such tags were found in the present study by searches.

There was a possibility for recently deployed tags, however, notably the predominant Microwave Telemetry Inc. (MTI) GPS PTT (Platform Terminal Transmission) tags involved in this Scottish project, that the stopped no malfunction tag fates were the result of an undetected malfunction and that no dead bird was found at the final fix of stopped no malfunction tags because the tags had actually stopped working (malfunctioned) and so the bird was still alive but with a non-functioning tag.

To examine such a possibility this section describes several additional tag diagnostic checks for the possibility that tag fates could have been mis-classified on tag functional state when transmissions were terminated. First, as background, we describe the features and processes behind classifying tags as having malfunctioned; and the most obvious factors that may cause a sudden trauma for a sudden malfunction, otherwise. Second, we outline the three validation processes behind the classifications; including submitting data to MTI for ‘blind’ checking of our core classification of the tags’ functioning by their chief engineer. Third, we present plots derived from transmitted engineering files which illustrate how key tag fates on function (‘reliability’) were ascertained from such data.

Next, there is little in the published literature on raptors for the rates of unexpected (sudden no malfunction) and malfunction rates of satellite tags which can indicate their ‘reliability’ (Klaassen et al. 2014, for an exception). Hence we solicited unpublished data from a number of researchers known to be using the same or similar MTI PTT tags on golden eagles, or similar species, to examine if the stopped no malfunction and stopped malfunction rates were the same as in Scotland. Any differences or similarity could indicate if the findings from Scotland were unusual (a high level of stopped no malfunction tag fates), and thereby further test the possibility that the data from Scotland were thereby ‘suspicious’. This possibility would be supported also if the rate of stopped malfunction fate was similar across studies.
An objective of the project was to consider the reliability of the transmitters deployed. This objective refers primarily to the possibility that the stopped no malfunction (snm) fate may have been caused by (undetected) sudden internal ‘catastrophic’ cessation of the tag’s functions, and this may have a bearing on spatial analyses for such tag fates. That these are sudden is reference to a lack of any prior transmitted engineering data (including battery failure and/or sporadic/truncated GPS locations); such failures have been classed differently under a stopped malfunction fate.

Classification of tag fates is critical to the project’s objectives especially on classification of tags’ stopped no malfunction fate, as final locations of these tags are fundamental to addressing the primary objective posed by the project brief. This is especially relevant to comparing the stopped no malfunction class with the stopped malfunction class, because ‘reliability’ infers that the stopped no malfunction tags have, actually malfunctioned (without detection); or that their fate may have otherwise been misclassified.

As noted earlier in this report, for example, for all tags that were not still tracking at the end of the data collection period, the locations and surrounding areas of all final fixes were searched, for evidence of either a tag, a dead bird and/or a dead bird + attached tag. Notably, for the tags classed as stopped no malfunction, despite searches around the last known fix location, no tag or (dead) bird was found, indicating that the sudden cessation of transmissions was probably not due to the tagged bird dying at the last fix location. Such searches add a secondary level of evidence that the sudden stop in transmissions is probably not from a natural death of the tagged bird, or a dropped tag.

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There was a possibility for recently deployed tags, however, notably the predominant Microwave Telemetry Inc. (MTI) GPS PTT (Platform Terminal Transmission) tags involved in this Scottish project, that the stopped no malfunction tag fates were the result of an undetected malfunction and that no dead bird was found at the final fix of stopped no malfunction tags because the tags had actually stopped working (malfunctioned) and so the bird was still alive but with a non-functioning tag.

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Finally, we also examined the ‘survival’ rate of 70GPS PTT tags (not birds’ survival) from Scottish data to further elucidate how likely the stopped no malfunction rate was possibly due to malfunction, on the basis that tag failure rate was more likely as the tag aged after deployment and that (according to the manufacturer) tags should typically continue to function for at least 3 y (manufacturer’s tested minimum for built-in tag longevity). Further suspicion would be cast on sudden tag failures in Scotland if sudden failure data from elsewhere revealed such tags transmitted for longer and closer to the manufactured longevity.

6.3 Checks and validation of Scottish tag fates

6.3.1 Transmitted engineering data: distinguishing a ‘malfunction’ tag

Tags transmit many diagnostic ‘engineering’ data, as well as locations (and data on other metrics associated with the location), which basically involve transmissions of internal monitoring of several of the tags’ key functions and states.

In the majority of cases it is apparent that the state of the battery is often the primary indication of imminent malfunction (which, can, obviously include the tag reaching its operational lifespan inherent in the component part(s)) but obvious disruption in GPS fixing performance can be a related or separate feature (see also Klaassen *et al.*, 2014).

When a GPS PTT reaches its operational lifespan, the battery is usually the first component to show its age. For a GPS PTT, the first signs of this would be seen from transmitted messages of “low voltage”, “battery drain” and “no fix”. These are also evident from transmitted changes in the metrics of the time taken to acquire a GPS fix, hours from a reset to gain a fix, and hours from a previous GPS fix.

For combined GPS/Argos tags (i.e. the large majority of the tags deployed in Scotland) the GPS receiver has a higher voltage threshold requirement than the Argos transmitter. If the GPS PTT is not maintaining a high enough charge to activate the GPS receiver, “low voltage” will be recorded in place of the GPS location data for that hour. If the GPS PTT has a high enough charge to activate the GPS receiver at the scheduled hour, but the voltage falls below that threshold value before a fix is locked, the GPS PTT records “battery drain” in place of that hour’s location data. It also gives an indication of how quickly the battery drained. If the GPS PTT’s battery voltage is sufficient to keep the receiver on for the full two minutes allotted for fix acquisition, but is unable to lock up a fix, “no fix” is recorded in place of that hour’s location data. As the GPS PTT’s battery starts to peter out, not only will this be evident from the battery voltage transmissions, but also from an increasing number of “battery drain” transmitted messages due to the decreased battery capacity.

The transmitted engineering messages are “snap shots” of the GPS PTT’s condition on the transmission day. The battery voltage readings in the engineering data reflect the voltage at the time of transmission. If the engineering data are showing full battery charge, but GPS messages are showing battery drains (particularly quick battery drains) this can be an indication of reduced battery capacity. Repeated messages across several scheduled transmission days in this regard can therefore also indicate a declining capacity for function which can assist in interpretation of a final cessation of any transmissions.

As the GPS receiver gets toward the end of its operational life, or is otherwise suffering from a battery voltage problem, it has greater difficulty in locking up fixes (e.g. transmitted data on time taken to acquire a GPS fix), and also results in more “no fix” messages. However, even if the GPS receiver failed it would not prevent transmission to Argos (due to different battery voltage threshold requirements – see above). The GPS PTT would continue to transmit Argos messages as long as the battery voltage is above the threshold required for transmission. Sudden unexpected fluctuations in the temperature sensor may also be indicative of a possible imminent failure.

In other words, if the internal components are having problem(s) in functioning, there are many transmitted data which can indicate such problem(s) either in isolation or in combination. If these continue over a period of scheduled transmission days and before the cessation of any transmissions then this indicates that the tag has ‘stopped malfunction’.

By contrast, if there are no messages of these many indicative problems transmitted before the sudden cessation of any transmission then the tag has stopped no malfunction. A point to be noted here is that in the sudden stopped no malfunction class there is an absence of several pre-transmitted metrics which could indicate a problem with the tag itself.

External factors can suddenly stop a PTT from working. Damage that creates a breach in a PTT's external housing will let in moisture, which will corrode the electronics. In this situation, there is usually no warning from transmitted engineering data. Similarly if the housing and electronics are broken with hard external force, there is no warning from transmitted data.

So far as transmitted engineering data, the stopped-no malfunction fate class should be most similar to the 'still tracking' fate class. The critical difference being that the still tracking tags were still functional at the end of the data collection period but the stopped-no malfunction tags suddenly became non-functional before the end of the of the data collection period. We allude to this similarity later in this section ('Example plots of four diagnostic engineering data features').

6.3.2 Validation exercises for the stopped no malfunction fate class

The critical classification of the stopped no malfunction fate (as opposed to the stopped-malfunction fate) was cross-checked by way of several independent examinations of engineering data:

1. Initial data collation and classification into tag fates was coordinated from contributory data-holders by the contributors and through collation by Ewan Weston after examination of engineering file transmissions.
2. A secondary independent validation of these fates, including checking the sudden no malfunction fate for GPS (70GPS and 70GSM) tags and LC4 (105GPS) tags, was undertaken by the report authors with access to the same engineering files. The results of the first two exercises were in agreement across all tags which had engineering files on the stop no malfunction and stop malfunction fates. The summary of all tag fates have been presented elsewhere in this report (section 2). Illustrative examples of temporal plots of four diagnostic features from tags' engineering files from LC4 tags are presented later in this section ('Example plots of diagnostic engineering data').
3. A tertiary exercise on validation/checking was undertaken by submitting a random sample of engineering data (and raw unparsed files) from several tags to MTI for their chief engineer to check, so far as signs of malfunction. This sample included several LC4 (105GPS) and 10 70g GPS PTT tags This sample was 'blind' to MTI because MTI was unaware how the previous two exercises had classified tag fate on the examples forwarded.

Attention via the tertiary exercise was focused on MTI tags because the large majority of tags deployed on Scottish golden eagles were from this manufacturer[5], and MTI tags formed the substantial majority of the 'stopped no malfunction class' and were predominantly behind the spatial analyses, described earlier, examining any fundamental 'suspicious' pattern. MTI were requested to concentrate on the 70g GPS PTT tags because these were the most common in the project.

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[5] This report is not the place to compare the reliability of different tag manufacturers' products but it was apparent from several sources of data (and several practitioners' unpublished experience, as communicated to us) that MTI are highly respected on their tags' reliability and in designing minimal aerodynamic effects. (This reputation, and direct experience, was why most of the satellite tags deployed on Scottish eagles were MTI tags.)

6.3.3 MTI ‘blind’ checks of Scottish tags’ engineering data

For their solar battery Argos/GPS PTT tags and GPS/GSM tags, MTI provide 1 y limited warranty of non-failure and, based on pre-delivery testing, a 3 y minimal expectation of lifespan on component parts – with (see above) the battery being the most likely component to fail after this time. MTI consider that transmitter failure due to electronics is extremely rare and the transmitters are subject to extensive tests during manufacturing. MTI view the 70g GPS PTTs and their GSM equivalents as their most robust transmitters and these devices have redundancies built in; for instance they have two solar arrays which are totally independent of each other.

A random sample of engineering data for 10 70GPS PTT tags were examined ‘blind’ (i.e. MTI did not know our tag fate classifications) by the MTI chief engineer and in none of the tags was any malfunction prior to transmission cessation discovered. Our classified ‘fates’ of the 10 tags were: stopped no malfunction (n = 6), died natural (n = 1), dropped not suspicious (n = 1), killed (n = 1) and still tracking (n = 1). Collectively, therefore, our assessment was that none of these tags had malfunctioned: MTI’s independent assessment was in agreement.

Incidentally, MTI noted subjectively that “…*several of the LC4 PTTs* [105GPS] *showed clear signs of the batteries winding down*” which was the case from our assessment (see earlier).

6.3.4 Example plots of four diagnostic engineering data features

Plots of four diagnostic features are shown below for five 105 g MTI (LC4) tags as examples of how tag fate was assessed. The four diagnostic features are GPS fix time (hours); Hours from a reset; Hours from a GPS fix, and Battery Voltage. These are data that are transmitted by the tag as ‘engineering’ files which accompany the location records. Note that: 1) this suite of data illustrates the need for several transmitted diagnostics to be considered together; and 2) as described above there are other transmitted data which allow further discrimination of a tag’s internal status.

For the four diagnostic features, the example plots presented below show the mean record surrounding the day of transmitted data (black dots): days are numbered from the first transmission date (i.e. date of tag deployment on a nestling). A smoothed line on these averages is given by the blue line and a less smooth curve is also shown in grey shading (span = ± 0.5, around the [blue] line average).

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For the four diagnostic features (Figures 6.1-6.5), the example plots presented below show the mean record surrounding the day of transmitted data (black dots): days are numbered from the first transmission date (i.e. date of tag deployment on a nestling). A loess smoothed line (span = 0.5).on these averages is given by the blue line and credible limits are shown in grey shading.

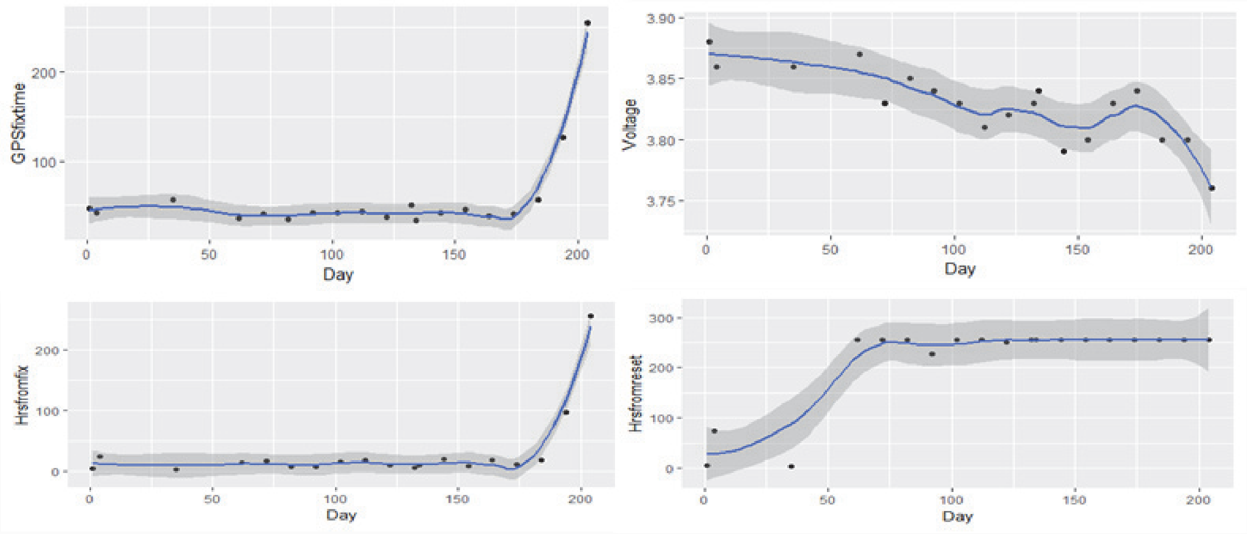

Figure 6.1. TagID = 94838 Stopped with a malfunction. There was apparently a problem in the tag acquiring GPS signals, most likely related to a decline in the battery’s voltage to a level where the capacity for the tag to connect to GPS transmitters/receivers could not be powered.

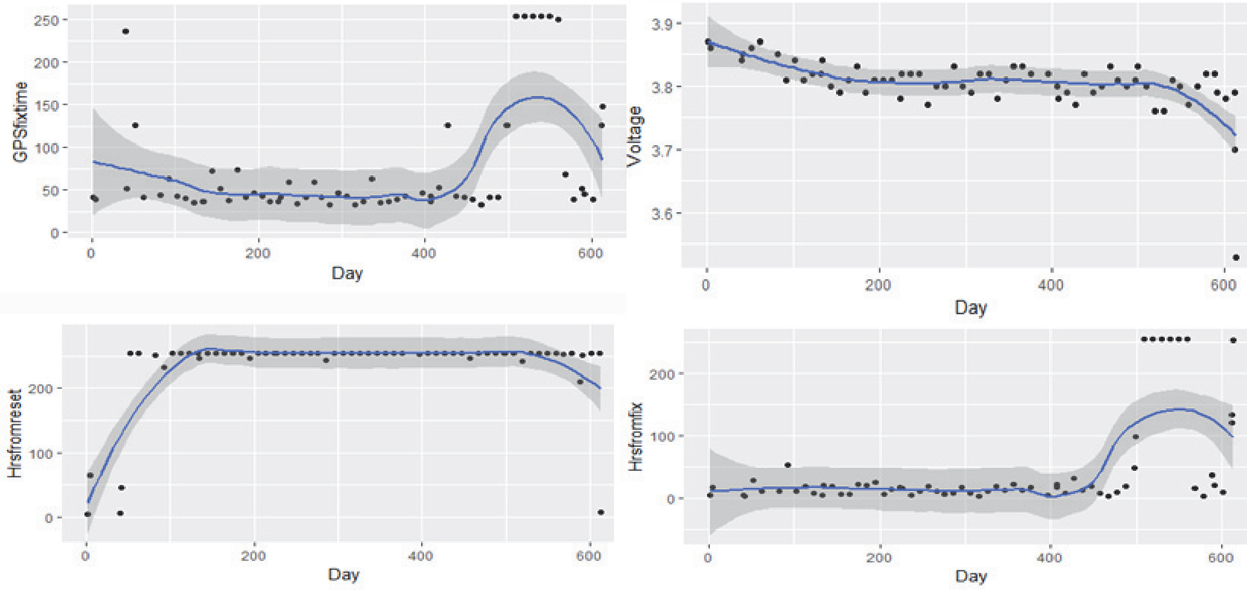

Figure 6.2. TagID = 94840 Stopped with a malfunction. There was an indication of a problem with the battery, with a decline in voltage before the last transmitted records; reflected also in other engineering diagnostics.

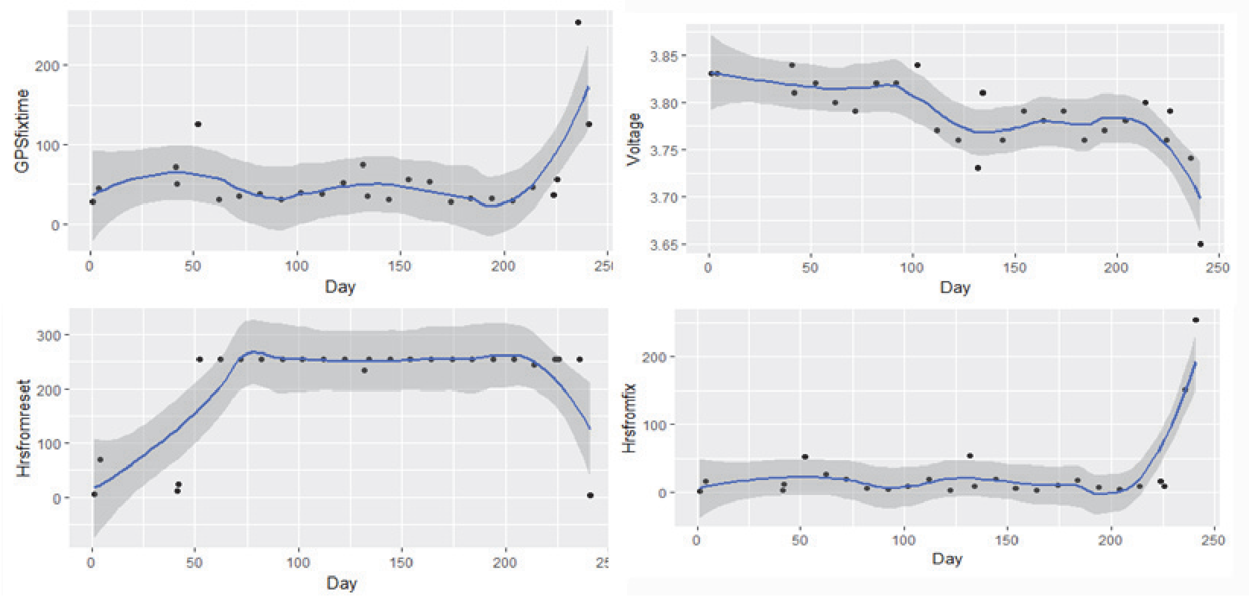

Figure 6.3. TagID = 94841 Stopped with a malfunction. There was an indication that there was a problem acquiring GPS signals. The time to obtain a GPS fix and the time since the last fix increased markedly before transmission ceased. The battery voltage also appears to have been dropping rapidly; which was probably the cause of the tag's difficulty in gaining GPS fixes in the final few days.

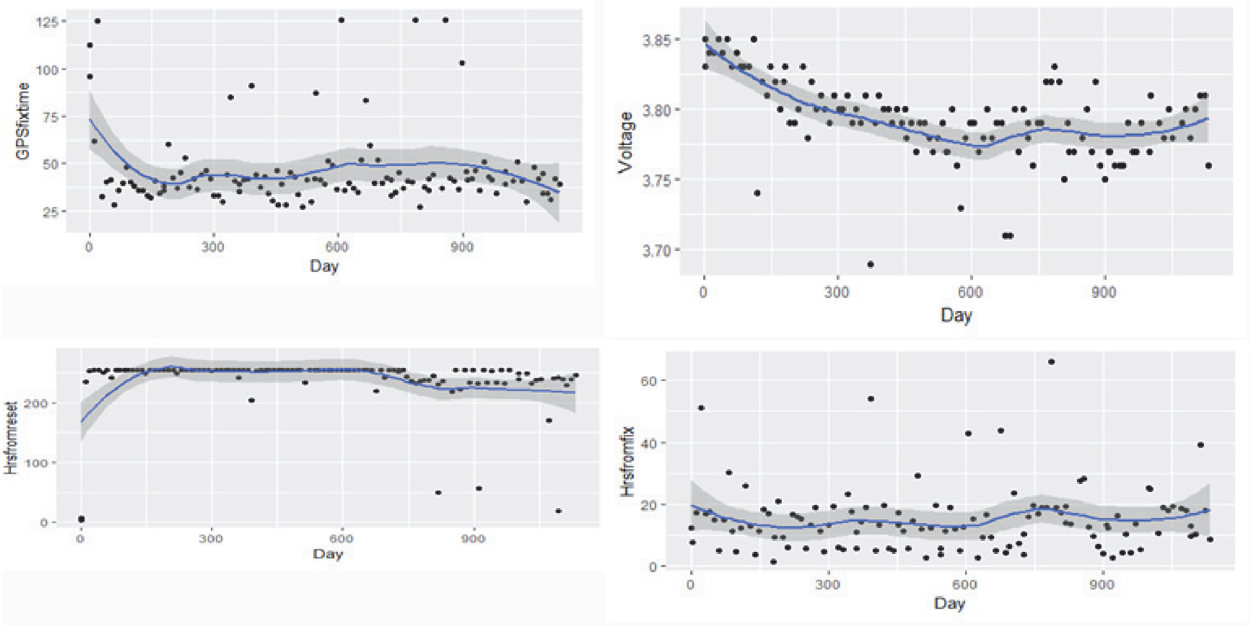

Figure 6.4. TagID = 328582 Still tracking. At the end of the data collection period this tag was still transmitting data. Note the absence of common features with the malfunction tags (TagIDs = 984840, 94841) in the end-point ('final days') data, but the similarity in end-point data with the stopped no malfunction tag (TagID 32857). The latter similarity in four diagnostic engineering files serves to emphasize that transmission data were essentially the same, but that they suddenly stopped (inexplicably on engineering data) for the stopped no malfunction tag (TagID 32857). Thereby further illustrating the 'no malfunction' classification for tags such as TagID 32857.

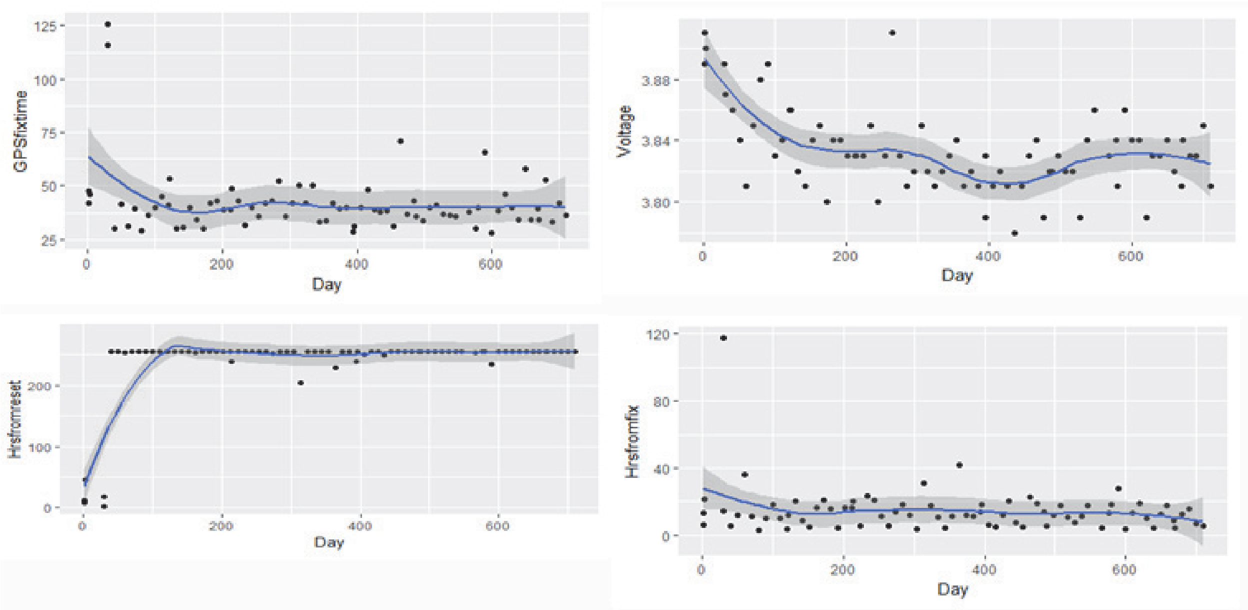

Figure 6.5. TagID 32857 Stopped with no malfunction. There is no indication of an impending transmitted problem in any of the four diagnostic features hence its status as stopped-no malfunction. Note: 1) that the end-point data for this tag are very similar to the 'still tracking' tag (TagID = 328582), with the exception that unlike the 'still tracking' tag, this tag prematurely and suddenly stopped transmitting, and 2) these end-point ('final days') data are very different to the 'malfunction' tag data examples (TagIDs = 94838, 984840, 94841).

A random sample of engineering data for 10 70GPS PTT tags were forwarded to and examined 'blind' (i.e. MTI did not know our tag fate classifications) by the MTI chief engineer and in none of the tags was any malfunction prior to transmission cessation discovered. Our classified 'fates' of the 10 tags were: stopped no malfunction (n = 6), died natural (n = 1), dropped not suspicious (n = 1), killed (n = 1) and still tracking (n = 1). Collectively, therefore, our assessment was that none of these tags had malfunctioned: MTI's independent assessment was in agreement.

6.4 Rates of no malfunction and malfunction from other studies

Our next approach to examine the tag reliability objective was to review other studies' experience of reliability for the same tag models (primarily MTI PTT tags) used on Scottish golden eagles. This approach was based on the hypothetical assumption that a stopped no malfunction fate can result from either an undetected malfunction (which other analyses suggest is unlikely) or an external human-based destruction of the tag. If other studies, using the same tag models have a lower rate of stopped no malfunction then this would suggest further that in Scotland there was a greater propensity for humans to destroy tags. This conclusion would be particularly emphasized if the malfunction rates were the same or similar across studies, indicating a common level of background tag reliability.

Hence, greater rates of sudden tag failure (sudden no malfunction) ≈ greater likelihood of external influence on causing sudden catastrophic tag failure: specifically a greater human-based destruction of birds and tags, and removing evidence of destruction. Moreover, similarity in stopped malfunction rate ≈ likely similarity in tag reliability; further suggesting greater rates of sudden tag failure were not due to reliability.

Several researchers were solicited to provide data on tag fates to provide comparisons with the Scottish data for golden eagles: our requests included the classification system we had used for Scottish data so as best to maintain comparability where possible. Our primary interest was in Microwave Telemetry Inc. (MTI) tags comparable or the same as those mostly used on golden eagles in Scotland.

6.4.1 USA data for golden eagle

Summary fate data were generously supplied by Brian Millsap and colleagues at the U.S. Fish and Wildlife Service, co-ordinating data from many studies and researchers, for 708 satellite tags deployed on golden eagles in the USA from 1997 to 2016. These data have been collated as part of a wide ranging and exceptionally detailed USA project outlined provisionally by USFWS (2016). These are the most comprehensive data which allow a comparison with the reliability of tags deployed in Scotland, as they are a large sample and explicitly responded with comparable classes to those we have used in the present project.

These USA data included several tag models from several manufacturers, including North Star (NS), MTI, Cellular Tracking Technologies (CTT), Sirtrack, Telonics and Vectronics Aerospace. In Scotland, tags from three of these manufacturers have been used: CTT, NS and MTI.

A small number of prototype CTT tags (solar, cellular/GSM reception/transmission) were purchased for deployment on birds in Scotland, but failed immediately through a design failure from this (at the time) start-up company, and so have not featured in any of the Scottish analyses in this report. This basic initial failure in prototype design was obviously not just a Scottish experience, but also for the USA (data forwarded by B. Millsap) and researchers in Europe (M. Delgado, *pers.comm.*). CTT subsequently redesigned their GSM tags which have met with more success on reliability (data forwarded by B. Millsap); but as these were not used in Scotland they are not considered further. Few NS tags were deployed in either study, and so findings from MTI tags bear most relevance and comparison with the Scottish dataset.

Overall, however, for the USA data across <u>all</u> tag models and years it was reported that only 19 of 708 tag fates were classed as sudden malfunction/suspicious (2.7 %). This is conspicuously below the rate for the same tag fate in Scotland – which was 29.0 % overall (n = 131) or 44.7 % (n = 85) if ‘still tracking’ fates were excluded (given that very few of the USA tags were still tracking: see below).

6.4.1.1 MTI solar GPS PTT tags

It should be noted that few (10 of 389: 2.6 %) tags were still tracking in the USA dataset for MTI solar GPS PTT tags. This is noteworthy because for the Scottish dataset there were proportionately more still tracking (28/77 = 36.4 %) and so the possibility of ‘alternative fates’ (which could happen in the future) was higher for the Scottish tags. This means that the raw Scottish data may underestimate the proportions of alternative fates (such as stopped no malfunction ≈ sudden malfunction/suspicious) relative to the USA data. Hence, for example, if the rate of the stopped no malfunction fate is higher in Scotland data than in USA data, then it could potentially be even higher once final tag outcomes were comparable temporally. Summary statistics for the USA data on key metrics of sudden malfunction/suspicious (≈ stopped no malfunction) and battery fail (≈ stopped malfunction) are given in Table 6.1.

Table 6.1. Summary statistics from a data collation of MTI solar GPS PTT tags deployed on golden eagles in the USA, 1997 – 2016, for fates classed as 'sudden malfunction/suspicious' and 'battery fail' (data courtesy of B. Millsap on behalf of many collaborators). Age of bird gives the age of the bird when tagged: Age 1 includes birds tagged as nestlings through to individuals up to one year of age; through to Age 5 which includes birds at least five years old.

Age of bird	**Tags deployed**	**Sudden malfunction/suspicious**		**Battery fail**	
	n	n	%	n	%
1	254	3	1.2	5	2.0
2	7	0	0	0	0
3	2	0	0	0	0
4	14	1	7.1	0	0
5	112	5	4.5	3	2.7
Total	**389**	**9**	**2.3**	**8**	**2.1**

For the eight MTI tags classed as battery fail fates (2.1 % of all deployed tags), the range in tag lifespan (from attachment to failure) was 47 – 405 d (median 232 d). These are below the MTI stated manufactured lifespan (3 y: see above) and seem to be genuine malfunctions, inexplicable from manufacturing tests.

6.4.2 Washington State, USA, data for golden eagle

We are very grateful to Jim Watson for supplying data, and associated commentary, on 70g MTI GPS PTT tags which were deployed on 46 golden eagles in northwest USA (20 on juveniles/nestlings, and 26 on adults). At the time of communication, 17 were still transmitting (6 juveniles, 11 adults). Three tags were stopped no malfunction (after a mean of 12 months; it was suspected the birds had been shot) and two were stopped malfunction due to expired batteries at 95 months and 73 months (birds were still alive). Twenty four tags were recovered when they were stationary on the ground and continued to transmit for several weeks and up to several months, including five birds which had been shot or probably shot.

6.4.3 Norway and Sweden data for golden eagle

Summary data were kindly supplied by Torgeir Nygård for 32 golden eagles tagged with MTI units as nestlings in north Norway and Sweden, and none was still tracking when communicated (see also Nygård *et al.*, 2016). There were three 95g Argos PTT 100, 13 105g GPS LC4, and 16 70g MTI GPS PTT. At least four birds (12.5 %) were killed and an attempt was made for the evidence to be removed or hidden in three instances. Overall six tags had a stopped no malfunction fate (18.8 %), and four tags (three 70GPS) had a stopped malfunction fate (battery drain: after 6.6, 6.4. 6.4 and 5.0 y) (12.5 %). Hence, the stopped malfunction tags were apparently a battery lifespan issue, not an unexpected malfunction. For the 16 70GPS tags three were stopped no malfunction (18.8 %) and three were stopped malfunction (due to battery lifespan) (18.8 %).

6.4.4 Delaware Bay, USA, data for bald eagle

Summary bald eagle *Haliaaetus leucocephalus* (n = 83) and golden eagle (n = 2) MTI transmitter lifespan data were generously supplied by The Center for Conservation Biology (CCB, 2016) for 68 70GPS tags and 17 70GSM tags. Thirteen of the 17 70GSM tags were still transmitting and so this model is not considered further. Six of the 70GPS tags were still transmitting, and for the other 62 70GPS tags 15 (24.2 %) could be classed as signal stopped (≈ stopped no malfunction). There were four tags which could be classed as battery failure (6.5 %) but all were apparently due to the battery reaching its inherent lifespan (failure after 4.2, 4.7, 7.9 and 8.6 y).

6.4.5 Klaassen et al. (2014)

Klaassen *et al*. (2014) studied 69 migratory adult raptors: osprey *Pandion haliaetus* (n =18), marsh harrier *Circus aeruginosus* (n = 17) and Montagu's harrier *Circus pygargus* (n = 34), mostly in Sweden and in The Netherlands using three MTI tag models ("Argos PTT-100, solar Argos PTT-100, solar Argos/GPS PTT-100"). At least one of these tag models was used in Scotland on golden eagles. It is difficult to be certain on how many of these tags were used on which species by Klaassen *et al*. (2014) when details were lacking.

Klaassen *et a*l. (2014) also used slightly different classification criteria for tag fates to those we and others have used, which may be at least in part because different tags (and so different transmission data) were involved and that it was difficult (as for The Center for Conservation Biology 2016) to search the final fix locations for many birds. Klaassen *et al.* (2014) described the fate classification of 64 tags/birds (though not broken down by tag type or species).

The first two classes of fates (probable or confirmed transmission failure, n = 13) probably involved our stopped malfunction fate through transmitted signs of imminent failure. Unfortunately for this project's purposes, the authors did not distinguish the age of the tags in these 13 records, when this can indicate whether a specific tag failure (malfunction) was more likely expected or unexpected on the minimum expected tag lifespan given by the manufacturer's extensive pre-sale tests (see McIntyre et al. 2006, and data above).

A high number of fates (n = 41) were classed by Klaassen *et al*. (2014) as "probable death of a bird". This included both abrupt loss of transmissions (akin to our stopped no malfunction class) and continuous transmissions from the same location with no movement (akin to a dead 'grounded' bird or a dropped transmitter). Although Klaassen *et al.* (2014) could not, understandably (given the inter-continental nature of their study), check the latter presumed fates on the ground they noted that through additional marking of birds, very few birds apparently dropped their transmitters. They also acknowledged, however, that the abrupt loss of transmissions in some tags may not have been due to a death but to an undetected malfunction. They considered that such undetected malfunctions were probably very few.

We could derive a crude stopped malfunction rate across three species from the information presented by Klaassen *et al*. (2014) as 18 of 64 = 20.3 %. This estimate does not indicate how many malfunctioning tags were expected based on the age of the tags and MTI's given 'predicted minimal tag lifespan' based on their testing. We could not derive a stopped no malfunction fate rate based on the data presented in Klaassen *et al.* (2014).

Elsewhere[6], Raymond Klaassen noted that 67 Montagu's harriers had been tagged in six European countries. It was also noted, after referring also to ospreys and marsh harriers, that a stopped malfunction (sm) rate was 6 % and a stopped no malfunction (snm) rate was 14 %. It was unclear if these statements referred to harriers alone and/or to the other species. We did not have the opportunity to verify these claims, unfortunately, because our priorities were with golden eagles and similar species; but have referred (as above) to Klaassen *et al.* (2014) where, at least, the stated malfunction rate was much higher (c. 20 %) than c. 6 %. That said; 14 % for snm and 6 % for sm would not be inconsistent with our findings from tagged golden and bald eagles away from Scotland (Table 6.2).

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[6] http://www.rspb.org.uk/community/ourwork/skydancer/b/skydancer/archive/2016/09/23/guest-blog-mortality-in-montagu-39-s-harriers-as-revealed-by-satellite-tracking.aspx

6.4.6 Broad comparisons between other data and equivalent Scottish data

To contrast the broad 'headline' rates of stopped no malfunction and malfunction fates recorded by the solicited studies and this Scottish study, we restricted the various data to include only a comparable MTI GPS PTT tag model. We also removed the possible distortive effect, under the need for a like-for-like comparison, of still transmitting tags because this tag class varied by preponderance generally and time in operation individually. We also did not include the results of Klaassen *et al.* (2014) for the several reasons of incompatibility and uncertainty described above.

The summary results of these comparisons for stopped no malfunction and malfunction fate rates are presented in Table 6.2.

These results illustrated that other researchers deploying the same MTI GPS PTT model tag did not find the same level of the stopped no malfunction fate class as was recorded in Scotland: the Scottish classification rate was relatively high (Table 6.2). In particular, a large sample from the USA for golden eagles classified a low rate (c. 2 %) of stopped no malfunction fate (the comparable rate for Scotland was about 25 times higher) but for both the USA and Scotland there was a very similar (low) rate of malfunction fate (c. 2 %).

Table 6.2. Summary of the results for the percentages of stopped no malfunction fates and stopped malfunction fates from several studies using MTI GPS PTT tags. Still tracking birds were not included. GE = golden eagle, and BE = bald eagle. Figures in parentheses give alternative estimates (see Table notes).

Source	n	% stopped no malfunction	% stopped malfunction
USFWS (GE)	379	2.4	2.2
J. Watson (GE)	29	10.3* (0)	0** (6.9)
T. Nygård (GE)	16	18.8	0*** (18.8)
CCB (BE)	62	24.2	0**** (6.5)
Scotland (GE)	49	59.1	2.0

**Due to three individuals where there was a strong suspicion that the birds had been shot and the carcasses and tags removed and destroyed: five other birds were known to have been shot or probably shot.*

***Two 'malfunctions' were apparently due to inherent expiration of battery performance on birds still alive at 6.1 and 7.9 y after deployment, well beyond the expected lifespan indicated by MTI from manufacturing tests (3 y) – hence arguably not 'malfunction'. Whereas all of eight of the USFWS stopped malfunction tags expired before 1.1 y, as did the single Scottish stopped malfunction tag.*

****All three 'malfunctions' were apparently due to inherent expiration of battery performance.*

***** All four 'malfunctions' were apparently due to inherent expiration of battery performance*

Other researchers, nevertheless, also worked in study areas where some persecution (killing) of eagles was also occurring, and so this could have been (or was) involved as a 'suspicious' explanation for the sudden stop no malfunction class in other studies. Even so, it was revealing that the stopped no malfunction fate was far higher in Scotland than anywhere else.

That this result was anomalous for Scotland, suggesting a particularly high level of external human-caused interference to create a high stopped no malfunction rate, was also highlighted by how similarly low the rates of tag malfunction were across all studies, including Scotland. The common low baseline rate of malfunctioning tags thereby suggested further that the cross-study differences in the stop no malfunction rates were not substantially due to differences in tag reliability.

6.5 ‘Survival rates’ of 70GPS/GSM tags for Scottish golden eagles

6.5.1 Introduction

We also examined the ‘survival’ rate of 70GPS/GSM PTT tags from Scottish data to elucidate further how likely the stopped no malfunction rate was possibly due to malfunction, on the basis that tag failure rate is more likely as the tag ages after deployment and that (according to the manufacturer) tags should typically continue to function for at least 3 y (the manufacturer’s tested minimum for built-in tag longevity). If stopped no malfunction tags were mis-classified and were actually malfunctioned tags then we would expect that they should have relatively longer survival than other tags. Alternatively, if stopped no malfunction tags had relatively low survival (duration of operation) then this would indicate a lower likelihood that they had actually malfunctioned.

As was illustrated earlier (Table 6.2), the data from bald eagle tags (The Center for Conservation Biology 2016) had the next-nearest highest rate of stopped no malfunction rate in solicited data (albeit less than half the comparable rate for Scottish golden eagle tags). We investigated whether the duration of stopped no malfunction tags differed between the data for USA bald eagle and Scottish golden eagle. This may cast light on whether there was any indication of a difference in possible misclassification of tags (i.e. stopped no malfunction was actually malfunction) on the premise that the likelihood of a malfunction increase with tag age.

6.5.2 Methods

6.5.2.1 Tag ‘survival’

Two tag survival analyses were undertaken in R (R version 3.3.2) using the survminer package (Kassambara & Kosinski (2016), version 0.2.4) with different definitions of censored observations. The survminer package calculates Kaplan-Meier estimates of survival. In the first analysis all tags except those which had malfunctioned were censored (and it was assumed that stopped no malfunction tags had actually malfunctioned). In the second analysis the 30 stopped no malfunction tags were removed from the analysis.

In addition to looking at wholesale removal of stopped no malfunction tags, we also examined the effect of removing a proportion of stopped no malfunction tags. The computational problem with this approach is the number of removal permutations (e.g. for 10 removals there are 30,045,015 permutations). Inevitably this means that a sampling approach must be used for all except the removal of one (30 permutations), two (435 permutations) or three (4,060 permutations) stopped no malfunction tags. Once the number of removals is >3 the number of permutations becomes too large to undertake an exhaustive search of all 30 million+ possible permutations of 20 tags from 30 stopped no malfunction tags. A sampling procedure had to be used instead.

The data file was organised so that the first 30 rows were the stopped no malfunction tags. A random sample of 10 values was drawn from a 1:33 set and those rows were removed from the data set prior to calculating the survival estimate. This was repeated 1,000 times and the survival results were summarised by the mean and range of three statistics.

6.5.2.2 Stopped no malfunction tag duration of operation: bald eagle USA v golden eagle Scotland

Simple descriptive statistics were derived from both data sets on time to fail after deployment for 70 GPS/GSM tags.

6.5.3 Results

6.5.3.1 Tag 'survival'

For all tags the median survival period (duration) was 1035 days after deployment (c. 2.8 y) (n tags = 89, n events = 41, 95 % LCL = 678, 95 % UCL n/a) (Figure 6.6a). All but one of the stopped no malfunction tags had a survival period (duration) which was less than the median for all tags and which was less than the manufacturer's 3 y minimum estimated longevity. After excluding the 30 stopped no malfunction tags the median survival period (duration) was 1889 days after deployment (c. 5.2 y) (n tags = 59, n events = 11, 95 % LCL = 1629, 95 % UCL n/a) (Figure 6.6b).

Excluding between one and three stopped no malfunction tags, made relatively little difference to tag survival rates: even for three removals the effect was an increase of less than 5% in the median tag survival period.

For ten removals the number of events changed from 41 to 31 and there was a large effect of removing any of ten of the 30 stopped no malfunction tags. The effect was a 33% increase in the median tag survival period, see Table 6.3 (metric is days since deployment):

Table 6.3. Statistics (days since deployment) after converting 10 stopped no malfunction tags to stopped with malfunction tags.

	mean	**se**	**median**
min.	1340.1	123.6	1326
max.	1361.2	130.9	1443
mean	1349.8	127.2	1379
no removals	1214.6	115.8	1035

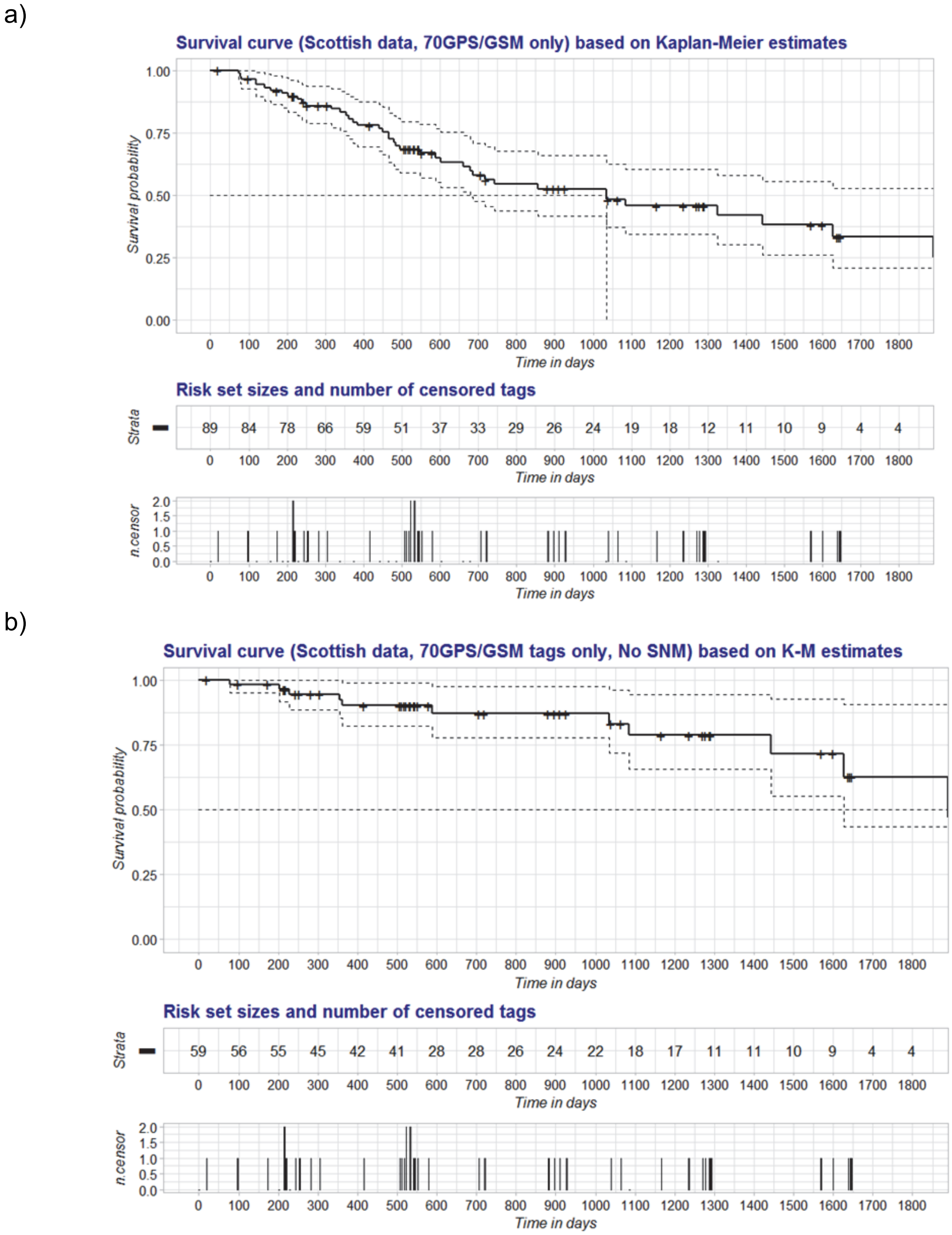

Figure 6.6. Survival plots for tag function duration produced using the survminer package (Kassambara & Kosinski, 2016). Upper plot is tag survival probability against day with 95 % UCL and 95 % LCL (dotted lines). Plus (+) symbols indicate censored events (tags still operating on that day). Horizontal and vertical dotted lines show medians. The lower plots show the number of tags per 100 day time block and the number of censored events per day. a) Shows results for all 70 GPS/GSM tags, and b) shows results with the stopped no malfunction tags removed.

6.5.3.2 Stopped no malfunction tag duration of operation: bald eagle USA v golden eagle Scotland

The Scottish golden eagle stopped no malfunction tags failed much earlier than the USA bald eagle tags (Table 6.4).

Table 6.4. Descriptive statistics for the time between deployment and failure of MTI 70GPS/GSM stopped no malfunction tags for bald eagle (BE) in USA and golden eagle (GE) in Scotland.

Data source	n	mean days	sd days	median days	median years
BE (USA)	15	1197.0	496.7	1341	3.7
GE (Scotland)	30	497.2	301.6	465.5	1.3

Relative to the threshold of 3 y as the minimum expected tag lifespan as guided by MTI, the stopped no malfunction Scottish golden eagle tags were more likely to fail this threshold than were the USA bald eagle tags: 97 % (29 of 30) and 33 % (5 of 15) did not pass the threshold, respectively.

6.5.4 Summary

Removing stopped no malfunction tags from the Scottish database had the effect of increasing the average tag survival time. This was because all but one of the stopped no malfunction tags had a survival period that was less than the median for all tags. (Birds carrying stopped no malfunction tags disappeared when relatively young.) All but one of the 30 stopped no malfunction tags had a survival period (duration) which was less than the median for all tags and which was less than the manufacturer’s 3 y minimum estimated longevity.

A sample of bald eagle tags deployed in the eastern USA had a higher rate of stopped no malfunction fate than for golden eagle tags in the USA; a rate (24 %) that was still well below that for Scottish golden eagles (59 %), nevertheless. The stopped no malfunction bald eagle tags lasted longer than the Scottish golden eagle tags: 67 % bald eagle tags lasted longer than 3 y, whereas only 3 % Scottish golden eagle tags lasted longer than 3 y. Based simply on stopped no malfunction tag lifespan, and the MTI 3 y lifespan guideline, then there was little chance that the Scottish tags may have actually malfunctioned, whereas several of the bald eagle tags may have malfunctioned. It would follow that this would further emphasise how unexpected (i.e. ‘suspicious’) was the high rate of sudden tag failures in Scottish golden eagles.

6.6 Conclusions

Our main conclusion is that the relatively high level of sudden no malfunction tag outcomes for Scottish golden eagles is unusual and is probably only minimally related to technological failures due to tag design or reliability.

This adds yet more weight to the spatial analyses (section 5) in strongly indicating that an external anthropogenic influence is the most likely explanation of the sudden no malfunction tag fate; at least for a major proportion of the final fix locations.

The earlier spatial analyses indicated with strong evidence that this external influence is spatially connected and largely limited to parts of Scotland. The several results in the present section consistently also pointed to a particularly high level of human-caused interference on tagged eagles in Scotland.

7. POTENTIALLY ADVERSE EFFECTS OF SATELLITE TAGGING

7.1 Summary

- Physical harm (e.g. lesions and inflammation) and contribution to further disease and possible death through ill-fitting harnesses were recorded in 22 % of 18 red kites in England. These results appear to be more illustrative of a specific problem (person who tagged the birds[*]) through failure of the normally stringent tagging procedures, than an indication of a generic widespread problem with the method when properly conducted. For example, we summarise post-mortems of 28 harness tagged raptors in Scotland (including nine golden eagles and 14 white-tailed eagles) which found no such evidence of physical harm; and this effect has been rarely reported or experienced elsewhere.
- Research in the USA (published and unpublished) has indicated that harness tagging of adult golden eagles can affect adults' behaviour, breeding success and survival. These findings have instigated increased attention to practices, the experience and training of tagging personnel, and consideration of other marking methods. Such problems do not relate to birds harness tagged as nestlings in the USA.
- From post-tagging monitoring in Scotland, with trapping methods adapted to avoid nest sites and the breeding season, there was no evidence of any adverse effects on behaviour, territory occupation or breeding success in the few adult golden eagles recently satellite tagged. Sample size was small, although potential incipient discrepancy with USA experience may relate to tagging protocols, legislative and procedural oversight, methods, and experience of personnel.
- There was no evidence in the nest, or post-fledging and post-dispersal periods, of any adverse effects on the behaviour of a sample of nestling golden eagles satellite tagged in Scotland. (Birds tagged as nestlings formed the basis of the present project, and USA experience of adverse effects do not relate to birds tagged at this age.)
- 'Natural' survival rates of young satellite tagged eagles in Scotland were much higher than those estimated in the USA from ringing (banding) data. Despite several caveats that should be considered in the comparison, this critical result did not suggest any adverse impact of tagging on Scottish eagle survival after fledgling and dispersing, for this vital demographic rate.
- At least eight tagged birds have entered the breeding population and the known age of recruitment was not different to observations of untagged birds. This finding does not suggest any adverse consequence of tagging on this demographic rate.
- On available information, we have found no substantive evidence that the satellite tagging of golden eagles in Scotland has caused any substantial 'harm' to the tagged birds, either physically, behaviourally, or demographically.
- We cannot say that there have been no mistakes in tagging Scottish eagles; mistakes are probably inevitable in any marking scheme. Definitively, however, it is inconceivable that the spatial pattern of the last fixes of the stopped no malfunction tags (described earlier in this report) could be explained by any possible 'harm' to the tagged birds. Any (at worst negligible) harm caused by the tagging of golden eagles cannot possibly explain the 'suspicious' pattern of the numerous tags which suddenly stopped with no malfunction.
- This is, in part, because there is no reason why any 'harmed' tagged birds should suddenly stop transmitting in geographical clusters (as observed) <u>and</u> that their bodies (and tags) should disappear (as observed). Moreover there were numerous stopped no malfunction tags, and there is no evidence from this section's review for tagging causing such a level of 'harm' to Scottish golden eagles, anyway.
- It is essential to continue to maintain the high legislative and procedural standards for best practice in satellite tagging of all raptors: these standards involve continued

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[*] See Corrigendum on p. 70.

feedback for any opportunity to learn and improve. It is always possible that occasionally a mistake is made, or that the bird itself will have an unexpected accident that affects its tag. In considering such possible mistakes it is important that these are put in a wider context: in our quantified assessment of the available evidence to date any such mistakes are probably rare and have not apparently affected the key vital rates of the tagged birds (and so the wider population).

7.2 Introduction

An important objective of the project was to examine if satellite tagging of golden eagles was causing the birds harm. In addressing this objective we have considered a range of potentially harmful factors:

1. Harnesses causing physical harm;
2. Adverse behavioural effects;
3. Adverse demographic effects, including survival and age of first breeding;
4. Tagging practice: we touch on this only briefly because a review of best practice was beyond our remit.

7.3 Harnesses causing physical harm

7.3.1 Peniche et al. (2011)[*]

Peniche *et al*. (2011) documented four cases (of 18 carcasses examined: 22 %) of lesions and moderate to severe inflammation which were caused by the harness on VHF (radio) tagged red kites *Milvus milvus* in England. The birds with lesions had been tagged for longer than the other 14 birds examined, and the injuries (and associated disease) were likely involved in at least some of the four birds' deaths.

As noted by Peniche *et al.* (2011) there was only one previous report of such an issue in the literature at the time (a paper on owls in 1992) with no contemporary reports, given how knowledge and practices would have improved since 1992. Kenward (2001), however, warns of the potential physical problems of harnesses if not fitted properly. Since Peniche et al. (2011) we are aware of one paper which has recorded similar physical harm in one saker falcon *Falco cherrug*, tagged in Mongolia (Dixon *et al*. 2016).

It is apparent from scrutiny of Peniche *et al.* (2011), though not stated or examined by Peniche *et al.* (2011) that the identified problem of poor fitting of harnesses occurred in one red kite release site area (North Yorkshire), and was likely to be attributable to one person improperly fitting harnesses. Moreover, the harness attachment illustrated by Peniche *et al.* (2011: Figure 1) has not been used on GPS/GSM/VHF tagged golden eagles and white-tailed eagles in Scotland, for example. Such differences can be influential in designing 'best practice' (e.g. Kenward 2001).

Subjectively, but revealingly, considering the thousands of raptors which have been harness tagged in the USA and in Europe, from our contacts with other researchers who are involved in this work and routinely recover and post-mortem dead tagged birds, none could recall this potential problem occurring in any studies they and colleagues were involved with (e.g. James Watson *pers. comm.*, Fabrizio Sergio *pers. comm.*). Without decrying the obvious importance of the research, Peniche *et al.* (2011) may be an example of studies which find an 'effect' being more likely to report the effect than studies which find 'no effect' (e.g. Møller & Jennions 2001, Fanelli 2012, Parker *et al.* 2016).

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[*] See Corrigendum on p. 70.

To provide some quantified context from Scotland on the possible scale of the problem documented by Peniche *et al*. (2011) we sought data on post-mortem examinations on harness tagged raptors from relevant approved institutions which handle such work.

7.3.2 Post-mortem data from harness tagged birds in Scotland

Data were solicited from post-mortem (PM) examinations of harness tagged raptor carcasses in Scotland. PMs were conducted by Science and Advice for Scottish Agriculture (SASA), Scottish Agricultural College/Scotland's Rural College (SAC/SRUC) Veterinary Services, and/or VLA (Veterinary Laboratories Agency) Lasswade. In several cases carcasses passed between more than one laboratory for examination and reporting. There were several named personnel (n = 8) who had attached the tag to the bird that was later subject to a PM, none of whom were involved in tagging red kites in Yorkshire.

In several cases the carcass had disintegrated or decomposed so that any epidermal or sub-dermal lesions or inflammations could not have been recorded. The results of the PM data supplied are summarised in Table 7.1.

Table 7.1. Summary of the received numbers of post-mortems (PMs) of harness tagged raptors in Scotland, by species; broken down further by how many carcasses examined were sufficiently fresh to discover any lesions or inflammation at harness contact points (e.g. Peniche et al. 2011), and the number of PMs which recorded such lesions or abrasions likely due to the harness.

Species	**PMs of harness tagged bird**	**Fresh carcass of tagged bird**	**PMs recording lesions/abrasions**
Golden eagle	9	9	0
White-tailed eagle	16	14	0
Red kite	14	1	0
Hen harrier	7	3	0
Buzzard	1	1	0
Total	**47**	**28**	**0**

None of the PMs from 28 fresh carcasses of tagged birds revealed any signs of lesions, abrasions or inflammation due to the harness. These results, across a range of species including golden eagle, indicated that there was no evidence from Scotland to support the findings of Peniche *et al.* (2011).

7.3.3 Conclusions

While the results of Peniche *et al.* (2011) give cause for concern, they appear to be unusual. Putting on harnesses is a skilful exercise which requires considerable training and experience (e.g. Kenward 2001, Sergio *et al.* 2015). It seems most likely that their results were attributable to one person who improperly tagged the birds for which problems were recorded in subsequent PMs. What this study best illustrates, therefore, is not that harness tagging of raptors will lead inevitably to birds suffering direct physical harm but rather that tagging of raptors is a skilled practice and that when not undertaken properly it can cause the bird physical harm.

7.4 Review of adverse behavioural and demographic effects of satellite tagging

There have been many studies of the effects of satellite tagging of birds, including several raptors (for reviews see Kenward 2001, Barron *et al*. 2010, Sergio *et al*. 2015, Harmata 2016, and references therein). Any reactions to tags may differ for a number of mutually inclusive reasons, such as species or individual or age of birds, experience of the tagging personnel, and type of harness. Many older studies are also possibly not wholly relevant to modern practices when technology and methods/materials have improved subsequently (often as a result of these earlier studies); and personnel and the knowledge-base have become more experienced and improved, respectively.

While here we have concentrated on reviewing studies of golden eagles, it is worth highlighting first the research of Sergio *et al*. (2015) because it is recent, and the most comprehensive and exemplary evaluation of a harness tagged raptor, the black kite *Milvus migrans*. Sergio *et al*. (2015) studied 110 harness tagged individuals (mostly tagged as adults) using the same harness attachment procedures as those recently used in Scotland (F. Sergio *pers. comm.*) and with the same basic tag model design as most recent golden eagle tags (MTI Argos/GPS PTT) with a tag mass that was slightly higher (c. 4 % of body mass) than for golden eagles in Scotland (< 3 %: e.g. Weston *et al.* 2013). Sergio *et al*. (2015), utilising a large control of non-harness tagged birds, found no detectable difference between tagged and control individuals in survival probability, longevity, recruitment, age of first breeding, reproductive performance and timing of breeding. Tagged and untagged kites also behaved similarly in fights over food and in provisioning rates of young.

By contrast, there have been several studies which have reported adverse effects of harness tagging of adult golden eagles, from the USA and Scotland. The Scottish study (Gregory *et al*. 2003) documented how, when adult birds were trapped at the nest during the height of the summer, then their use of nest sites changed and their breeding success declined thereafter. This result, as noted by the authors, may have been as much a reflection of the locations and times when birds were caught, as opposed to or as well as the tagging *per se*.

In the USA, Marzluff *et al.* (1997) noted that in some years with harsh environmental conditions tagged territorial eagles appeared to have reduced breeding success. Stahlecker *et al.* (2015) has recorded increased preening and attention to harnesses in adult eagles, and possible reduced survival. As a result of published (and, likely, unpublished) concern over harness tagging adult golden eagles in the USA, Harmata (2016) undertook a study which used tail-mounted tags as an alternative method. This method was short-lived in application (duration of tags staying on birds) and did not have comparable adverse effects on the measured vital demographic rates, although several birds did remove or ‘play with’ the tail-mounted tags.

Evidence for adverse effects on adult eagles from the USA is not just restricted to published studies, as there is similar unpublished information (J. Watson *pers. comm.*, USFWS 2013) which indicates that adult golden eagles may react adversely to being harness tagged, on behavioural and vital demographic rates (notably breeding success and survival). J. Watson (*pers. comm.*) has communicated, for example, that there appear to be two extremes in response when territorial adults are tagged in USA: from birds which repeatedly bite at the harness (see also Stahlecker *et al*. 2015) and do not nest or fail early; to other birds which ignore the harness and breed as before tag deployment.

Such experience appears to be commonplace and has led to a review of practices, including birds trapped on migration (USFWS 2013). Given the USA legal status of golden eagles and plethora of wind farms or proposed wind farms which may affect them, there have been a large number of studies which have involved trapping adult and/or migrating birds for tagging (USFWS 2013). Concern over possible adverse effects has caused a recommended moratorium on such practices (USFWS 2013): in part it would seem because this rush-to-study may have resulted in standards and oversight on personnel’s qualified experience slipping. In common with views from other experienced practitioners (e.g. Kenward 2001, Sergio *et al*. 2015) it is likely that the experience and skill of practitioners is key to successful tagging of adult eagles in the USA (J. Watson *pers. comm.*). In part, however, it is also possible that other issues in the USA, unrelated to personnel, deserve further attention or a revision of methods (Harmata 2016).

It should be reiterated, nonetheless, that there have been no studies indicating such problems for golden eagles tagged as nestlings in the USA either published or (J. Watson *pers. comm.*) unpublished.

While the present project is concerned primarily with 'harm' to birds tagged as nestlings, and no substantive evidence has come to light from the USA for such birds, we have compiled the available unpublished data on post-tagging monitoring of recently tagged adult golden eagles in Scotland (and tagged nestlings) courtesy of David Anderson; which follows.

7.5 Post-tagging monitoring of adult golden eagles in Scotland

7.5.1 Methods

Trail cameras have been deployed at several locations to record the presence and activity of golden eagles at carcasses which have been placed as 'bait' to trap and tag adult golden eagles. These activities were typically undertaken over five to six months within the non-breeding season (September through to February) (*cf* Gregory *et al.* 2003); exact dates being dependent on the weather conditions and monitoring of the state of any breeding attempt on the relevant presumed territory. Locations were at least 2 km (and up to 8 – 10 km) from, and out of line of sight, of the nearest eagle nest site (*cf* Gregory *et al.* 2003). Each location was typically checked at least every 10 days when the state of the carcass was evaluated (and replaced/supplemented as necessary) and the SD card in the camera removed and replaced. Cameras were programmed to record either stills or a mixed alternation between stills and 30 – 45 s of video. For a stills-only programme 12,000 – 16,000 images would be taken over a period of 10 days: not all images or videos involved eagles because several other species would also utilise the carcasses. Typically, an individual eagle would be present at the carcass for 0.5 – 1 h at a time. The cameras were kept operational and the carcasses continued to be replaced after birds had been tagged to allow the recording of any return of birds to the same bait site and to record their behaviour. Periodic observer attendance of bait sites in nearby hides has also allowed additional direct observation of tagged birds' behaviour at these locations.

Other records of birds after they were tagged were made by observers in the field away from the bait sites. Such observations included use of roost sites, watches of birds' behaviour at roost sites and nest sites (at appropriate safe distances on disturbance), and monitoring of birds' breeding status and progress of breeding attempts.

Monitoring of breeding attempts was also conducted on the same territory before a territory-holder was tagged. Of course, it could not be determined definitively (except in one case: see 102 later) that (or for how long) the tagged bird was the territory occupant before it was tagged.

At the time of writing four adult golden eagles had been satellite tagged in Scotland (Cowal) for any post-tagging observations/camera records to be made: 103 (male tagged January 2015), 102 (female tagged November 2015), 104 (male tagged February 2016), and 817 (male tagged early January 2017). All birds were also uniquely colour-ringed and metal ringed. 102 was satellite tagged as a nestling in Kintyre and the tag was subsequently dropped. She was 8 y old when re-trapped on her breeding territory and had probably been present on her territory in Cowal since 2013 at the latest. Her nestling of 2015 was satellite tagged (584) and is still being tracked after dispersal.

7.5.2 Results

7.5.2.1 Territory occupation and survival

All four adult birds continued to occupy their territories after tagging (*cf* Murgatroyd *et al.* 2016) and were still alive at 15 January 2017.

7.5.2.2 Use of nest sites

For three of the four birds where at least one breeding season has followed the tagging date (i.e. 102, 103, and 104: 817 was tagged only recently) there has been no change in the use of nest sites as recorded before tagging from 2013 onwards.

7.5.2.3 Breeding success

Patently, sample sizes are again small but for the three birds where at least one breeding season has followed the tagging date (i.e. 102, 103, and 104) there has been no obvious indication to date that tagging has affected breeding success (Table 7.2). For 2017 the results for breeding outcomes are obviously incomplete as yet.

Table 7.2. Summary breeding outcomes 2013 – 2016 (data as yet incomplete for 2017) for the territories where one member of the pair was satellite tagged. Breeding seasons after tagging are highlighted in grey.

Tagged bird	2013	2014	2015	2016	2017
102	Fail, large chick	Fail, on eggs	Fledged 1	Built nest fell out*	Building nest, mating
103	Fail, around hatch**	Fail, around hatch	Fail, around hatch	Fail, early***	Building nest, mating
104	Fail, small chick	Fledged 1	Nest but no eggs	Fledged 1****	Building nest, mating

* Known to be frequently roosting with fledgling of previous year even in April 2016. Subsequently dispersed fledgling still alive

**Annual early failure since 2006

***Likely, also, disturbance close to nest due to development assessment activities

****Dispersed fledgling still alive

7.5.2.4 Behaviour and reaction to tag harness

After tagging all birds were recorded later at the same bait sites where they were trapped. Through birds' varying use of bait sites after tagging, the time of observation has varied. In all birds, however, there have been no records of excessive preening around or manipulation of the tag's harness (*cf* Stahlecker *et al.* 2015) or any indication of the tag becoming displaced.

817: Tagged 26 January 2017, and was observed back at the trapping bait site on 4 February 2017 for 50 minutes, with no signs of any reaction or attention to the harness when present. The tag was located properly on the bird's back.

102: Recorded at the capture bait site 10 d after trapping in November 2015. Subsequently, she was recorded regularly in the rest of the 2015/16 winter, two to three times a week. In the mild winter of 2016/17, she was recorded only in a period in November 2016. All records revealed no signs of any reaction or attention to the tag harness. 102 was also watched regularly at roost sites, during flight and at the nest site after tagging, with no behavioural signs of reacting to the harness.

103: Again, recorded at the same bait site where he was caught within days of being captured (January 2015), 103 has been seen and recorded by the trail camera during frequent returns in the remaining weeks of the 2015/16 winter, and in the five to six months of 2015/16 and 2016/17 winters. Use of the carcass varied between spells when his visits would be every other day, to when there would be gaps of up to 10 days between his use of the bait site. 103 has also been regularly observed away from the bait site at roost sites, when flying and at nests. In none of the many records were there any signs of discomfort with the harness or the position of the tag.

104: Unlike other birds 104 has not made many returns to the bait site where he was captured, and this was primarily limited to a period of daily visits during five days in the 2016/17 winter. He was watched bringing in food for the nestling and during related time at the nest over five days in 2016. As in other birds he has also been observed at roost sites and during other activities since he was tagged. There have been no records of discomfort with or behavioural attention to the harness or the position of the tag. 104 successfully reared a chick in 2016 which was tagged; this chick dispersed from its natal territory and is still alive at 15 January 2017.

7.5.3 Conclusions

As noted earlier in this section, concerns over possible adverse effects of satellite tagging on golden eagles from the USA is restricted to tagging of adult birds (e.g. Marzluff *et al.* 1997, USFWS 2013, Stahlecker *et al.* 2015). It is important, therefore, to reiterate a fundamental distinction here, as regards the present project's brief and its subjects (eagles tagged as nestlings). No published study or unpublished USA data have raised similar concerns over possible adverse effects on birds tagged as nestlings.

Nevertheless, recent experience described here from tagging adult golden eagles in Scotland, while limited in sample size, is replete with responsible monitoring of any possible adverse effects at several biological levels; from birds' behaviour (Stahlecker *et al.* 2015) to territory occupation and nest site use (Gregory *et al*. 2003) and vital demographic rates (Marzluff *et al*. 1997, Gregory *et al*. 2003, Stahlecker *et al.* 2015).

Current protocols for trapping adult birds in Scotland have also adapted according to the study of Gregory *et al.* (2003) which documented shifts in nest site use and breeding success when adults were trapped at the nest during the height of breeding season. Current practice in Scotland has deliberately and exclusively involved trapping birds well away from nests and during the non-breeding season. To date, there are no incipient signs of the adverse reactions noted by Gregory *et al.* (2003): a ready early indicator, thus far, is that recently tagged adults have not apparently abandoned nest sites (or roost sites).

Protocols and tagging methods may also differ in the USA. For example, Stahlecker *et al.* (2015) note that it took 1 – 2 h to process a bird, which is considerably longer than processing times for the adult Scottish eagles (D. Anderson, *pers. comm.*). Tag harness designs may also differ in at least some circumstances. Given the experience from the USA, nevertheless, we would urge that post-tagging monitoring of tagged adults in Scotland should be essential and attentive to any possible adverse effects, even though these, as yet, have not been apparent.

7.6 Post-tagging monitoring of nestling eagle behaviour in Scotland

7.6.1 Methods

Nest cameras were deployed at seven golden eagle nests, employing the same protocols and programming as described for the cameras at bait sites, but with a high definition camera set-up at two of the seven sites, in 2015 and 2016 (BBC Springwatch 2016). Nest cameras where nestlings were satellite tagged were set up in 2014 (n = 2), 2015 (n = 4) and 2016 (n = 1). Deployment was mostly before birds were tagged but at tagging in some cases, depending on the accessibility of the nest. Some cameras were put in to record prey items from nests containing small young: such nests were chosen where access to and from the nest could be within 10 minutes of deployment. Nests where chicks were tagged were fitted with cameras to gauge reaction of both the chicks and adults to the tags. This was only done at nests where the camera could be deployed quickly and without being obstructive to the nesting birds. Cameras were set to take images every minute and only during daylight where cameras had this capability. 32-GB SD cards were used to maximise the data to be collected. By setting the cameras on a lower resolution and restricting the camera use to daylight hours, cameras could be run for several weeks before the SD cards were full. Cameras would record between 12,000 to 16,000 images per SD card. Records were continued for the weeks after tagging until the bird had left the nest at fledging: all nestlings successfully fledged and subsequently dispersed from their natal territory.

7.6.2 Results

There were no records of tagged nestlings manipulating or excessively preening around the tag's harness; perhaps, surprisingly, even in the hours and days immediately after tagging. Parents also were not recorded as paying undue attention to the nestlings' harnesses. All birds successfully fledged and dispersed.

Several golden eagles, satellite tagged as nestlings, were also recorded feeding at carcasses by the 'bait cameras' (described earlier), after fledging and dispersal. These records involved at least seven individuals feeding where baits were placed within the natal territory to examine tag placement. Three individuals were also observed on baits after dispersal: two birds were in their second year, and one was a yearling. All were photographed feeding at baits with no records of birds attending to the harness. Again, the recordings and observations found no signs that the birds' behaviour was affected by the tag or its harness.

7.6.3 Conclusions

From monitoring of several golden eagles satellite tagged as nestlings through trail cameras, in the early days, weeks and months after tagging, there have been no recorded instances of the tagged birds being affected behaviourally.

7.7 Young golden eagle survival and age of first breeding

7.7.1 Survival

Examination of a possible effect of tagging on survival requires comparing the survival rates of tagged birds with untagged birds, ideally contemporaneously and within the same population (Sergio *et al.* 2015). We could not compare the estimated survival rates of young tagged eagles with untagged eagles in Scotland because there were insufficient birds which have been marked using other methods (see Sergio *et al.* 2015), notably too few birds that had been metal ringed (banded) and later recovered. Some published estimates of survival rates elsewhere have involved tagged birds (Hunt 2002, Whitfield *et al.* 2004a, McIntyre *et al.* 2006, Nygård *et al.* 2016) and so examining any effect of tagging was not possible from these studies.

Recently, however, survival rates have been estimated for the USA by Brian Millsap and colleagues at the U.S. Fish and Wildlife Service using ringing (banding) records (USFW 2016). Aside from the data not being Scottish, further caveats should include that different analysis methods were used to those we have used here (see section 10), and different marking methods may have different methodological biases. While not ideal, obviously, comparison with the Scottish estimates from tagged birds with those from USA ringing (banding) does at least allow a broad brush examination and possible elucidation if tags have had a marked effect on survival.

It is also preferable if compared rates are like-for-like so far as causes of mortality, notably if anthropogenic (human-caused) factors and their rates differ between studies, since these could confound the required examination and isolation of the effect of tagging. In this respect we have attempted to contrast ‘natural’ survival rates (i.e. involving only natural deaths). While both studies (the present study and the USA study) have estimated 95 % confidence limits for estimates we have not made reference to these as it would probably be inappropriate to infer these as statistics which have a bearing, when we were simply (given the several caveats) seeking to make only broad comparisons and not seeking any statistically significant difference. Moreover, as relatively few Scottish birds were recorded as dying naturally but data became increasingly censored by the large number of stopped no malfunction tag fates, then survival estimates became increasingly less certain for older birds in Scotland (see section 10).

The USA survival rate estimates (USFWS 2016: Table 7) included all sources of mortality, but USFWS (2016) estimated that annual survival rates would be approximately 10 % higher without human-caused mortality. This assumed that the reduction in anthropogenic mortality was additive, which may not be wholly the case, especially in younger birds. (This same assumption would also apply to the method for calculating Scottish tagged bird survival rates, so on this basis the estimates are comparable.) On the other hand, USFWS (2016) also noted that human-related mortality was much higher in adult birds than first year birds.

7.7.2 Results

USFWS (2016) considered four age classes: HY (hatch year, < 1 y old), SY (second year), TY (third year), and after-third-year (ATY). Survival estimates for each respective age class (including all sources of mortality) were: 70 %, 77 %, 84 % and 87 %. (Note these classes appear to be based on calendar years rather than the age of the bird, or time since fledging/ringing.)

The USA estimates for only the first three age classes are relevant to the Scottish data, and for these, after assuming a 10 % reduction through human-caused mortality for each age class we arrived at higher ‘natural’ survival estimates as follows: 77 % (HY), 85 % (SY) and 92 % (TY).

Combining these (HY + SY + TY) gave a survival rate estimate of 60 % to the end of the third calendar year of life.

Estimated survival rates of young tagged Scottish eagles, involving only natural deaths (and so, for example, killed birds and birds with stop no malfunction tags were censored) had relatively high estimated survival rates (see section 10). To place these estimates within comparable time periods to the USA data, Scottish records gave approximate estimates of: 95 % (HY), 98 % (SY) and 98 % (TY).

An approximate combined survival estimate until the end of the third year calendar year of life was 91 %.

7.7.3 Discussion and conclusions

The estimates of survival rates were considerably higher for the Scottish satellite tagged birds than for the USA estimates derived from ringed (banded) birds. For example, across the first three calendar years of life, the ringed USA eagles had a ‘natural’ survival rate of 60 % compared to 91 % for the tagged Scottish eagles.

There are further reasons why (other than the tagged vs non-tagged comparison) the USA estimates may be lower, other than methodological differences. Such as, the USA sample will have involved migratory birds (unlike the Scottish birds) and migration may incur additional survival costs (Watson 2010). Perhaps consistent with this, Scottish tagged birds appear to have far higher ‘natural’ survival estimates than migratory birds tagged in northern Norway with the same tag models (Nygård *et al.* 2016).

It could be that the higher ‘natural’ (without persecution) survival rates from Scottish tagged eagles was due to a reduced level of competition for resources through the continued absence of territorial birds in several food-rich areas in parts of Scotland; even though these tend to be places where persecution can still be prevalent (e.g. Whitfield *et al*. 2008a). When this persecution was factored out, as in the present Scottish survival analyses, it probably revealed the potential for high survival, through inherently food-rich areas, that is not available to USA birds where breeding populations are probably not so depleted and when food-rich areas for young birds are not kept free of competition by anthropogenic influences. Even though, as we cover later (section 10), such a Scottish coincidence of a food-rich area coupled with a greater likelihood of dying through anthropogenic influences can create an ‘ecological trap’ (Whitfield *et al*. 2004b).

In addition, it seems highly likely that at least a high proportion of the records of stopped no malfunction tag fate in Scotland was a result of anthropogenic interference, and this fate class is much lower in the USA (section 10). Consequently, the higher level of ‘hidden’ human-caused interference in Scotland via the stopped no malfunction tags may have greater Scottish analytical consequences for the misplacement of the common assumption that anthropogenic mortality is additive (Chevallier *et al*. 2015, USFWS 2016). This seems unlikely to explain the large differences in estimates, however, given the scale of differences and especially when survival rates were also very different when such a feature was weaker temporally in the immediate post-fledging period.

In conclusion, while our approach has been necessarily broad-brush, there was no indication that the tagging of Scottish golden eagles has had an adverse effect on birds’ survival. Indeed estimated survival rates, in the absence of the high number of stop no malfunction tag fates, were higher than in any other study (Harmata 2002, Hunt 2002, Whitfield *et al*. 2004a, McIntyre *et al.* 2006, Nygård *et al.* 2016, USFWS 2016, Daouti 2017).

Rather, the high survival rates illustrate the substantial current potential for the Scottish golden eagle population to expand, in the absence of anthropogenic activities, and serves to highlight further those areas where re-occupation of former breeding territories continues to be absent, after many decades.

7.7.4 Age of first breeding

Age of first breeding can be a key demographic rate (e.g. Balbontín *et al.* 2003, Whitfield *et al*. 2004b) and can be illustrative of potential adverse effects of tagging if breeding is delayed (Sergio *et al.* 2015). Unlike the comprehensive study of Sergio *et al.* (2015) we could not contrast this parameter directly against non-tagged eagles in Scotland. The typical age of first breeding is, nevertheless, known from other studies of golden eagles which have not involved tagged birds (e.g. Watson 2010) and this provides a crude baseline to contrast with results from Scottish tagged eagles. Regardless of any effect of tagging, age of first breeding can be affected by several measures, primarily the opportunities of vacant territories which are greater when, through persecution, for example, territorial birds are removed at a high rate (Balbontín *et al.* 2003, Whitfield *et al.* 2004a, b) or when a population is expanding (Horvath *et al.* 2014), such as during a reintroduction project (Evans *et al.* 1999).

Results for eagles tagged as nestlings in Scotland are therefore somewhat anecdotal (and may be temporally right-censored for older birds because of the increasing likelihood for tags to fail with time). Nevertheless, such data can make an illustrative contribution when a 'harm' hypothesis would predict that tagged birds were somehow 'debilitated' and so would find difficulty in entering the breeding population. Hence, their age of first breeding would be delayed, against expectations from non-tagged birds in other studies.

7.7.5 Results and conclusion

At least nine tagged birds have entered the breeding population, in a wide geographical range of locations. Median age of recruitment was 4th year of life (range 3 – 5; n = 9). There were no birds still tracking beyond these ages and which had not settled on a breeding territory.

This observation is as expected from studies of non-tagged birds in which the age of first breeding is typically in the 4th, 5th or 6th year of life (e.g. Watson 2010) although it can also occur earlier, in the 3rd year of life (e.g. Steenhof *et al.* 1983, Whitfield *et al.* 2004b, Urios *et al*. 2007), as was observed in two of the nine tagged Scottish birds.

This finding suggests no adverse effect of tagging on this demographic parameter.

7.8 Tagging best practice

We noted earlier (section 2) that there were several people involved in the tagging of eagles in Scotland, and that potentially suspicious (stopped no malfunction) fates were not apparently due to particular operators (or, by proxy, teams of taggers); or to particular tag types. So, as we have described earlier also, the most frequently deployed tag in recent years (MTI 70GPS) has resulted in many stopped no malfunction fates, no matter the operator (Table 2.4).

In the absence of a dedicated specific brief, this report is not the forum to discuss or consider the legislative and licencing practices, checks, training and supervisory requirements underpinning the satellite tagging of raptors in Scotland. We are aware, nonetheless, of the many and strict procedures for licencing of harness tagging of raptors and other species (Annex 3).

Our brief, however, was to examine the consequences of satellite tagging so far as a wide-ranging quantitative assessment of possible adverse effects. We have drawn together a number of disparate and previously unpublished data to fulfil this brief, and find no substantive evidence of 'harm'.

We cannot say that there have been no mistakes in tagging Scottish eagles, when mistakes are probably inevitable in any marking scheme (Kenward 2001, Sergio *et al.* 2015). Definitively, however, within the project brief we can state that it is inconceivable that the spatial pattern of the last fixes of the stopped no malfunction tags (described earlier in this report) could be explained by any possible 'harm' to the tagged birds. Any (at worst negligible) harm caused by the tagging of golden eagles cannot possibly explain the 'suspicious' pattern of the numerous tags which suddenly stopped with no malfunction.

This is, in part, because there is no reason why any 'harmed' tagged birds should suddenly stop transmitting in geographical clusters (as observed) and that their bodies (and tags) should disappear (as observed). Moreover there were numerous stopped no malfunction tags, and there is no evidence from this section's review for tagging causing such a level of 'harm' to Scottish golden eagles, anyway.

It is essential to continue to maintain the high legislative and procedural standards for best practice in satellite tagging of all raptors: these standards involve continued feedback for any opportunity to learn and improve. It is always possible that occasionally a mistake is made. In considering such possible mistakes it is important that these are put in a wider context: in our quantified assessment of the available evidence to date any such mistakes are presumably unusual and have not apparently affected the key vital rates of the tagged birds (and so the wider population).

Corrigendum

It has come to our attention that since publication of this report, some aspects of its characterisation regarding the results of the study by Peniche *et al.* (2011) incorrectly attributed the origin of all of the birds involved to a red kite release site in North Yorkshire. In fact, the birds autopsied originated from more than one release area in the North of England, only one having been from Yorkshire. Moreover, the Report's suggestion that just one person was responsible for tagging the birds, which Peniche *et al.* (2011) identified as having lesions or inflammations causing or contributing to lethal effects (in four out of 18 corpses), was not correct. The Report also indicated that the Peniche *et al* (2011) study recorded that harnesses had been improperly fitted. This was not correct. The study referred to harnesses which may have appeared poorly fitted through subsequent changes in the birds' condition, and recorded no findings specifically relating to their original fitting.

This does not affect the Report's statements and conclusions that: a) the problematic (now discontinued) harness attachment method was not used on any Scottish eagles; b) post-mortem examinations of many harness-tagged Scottish raptors found no signs of the problems noted by Peniche *et al.* (2011); and c) a review of the literature and contacts (as noted in the report) concluded that the problems identified by Peniche *et al.* (2011) were highly unusual and apparently restricted to the tagging of some red kites in England.

8. LAND USE: WIND FARMS AND GROUSE MOOR

8.1 Summary

- Previous results have strongly indicated that the source of the sudden no malfunction fate was largely through anthropogenic intervention.
- Two primary candidates were considered for this intervention source in this section: an association with wind farms and an association with grouse moor management.
- We found no evidence that wind farms or activities associated with their operation could have been an interventionist source behind the many tagged eagles whose tags suddenly stopped functioning, and whose bodies were not subsequently found.
- There were several indications that the management of grouse moors was associated with many of the tags which suddenly failed to function, and which subsequently disappeared along with the birds carrying them.
- We emphasise, however, that not all areas managed for driven shooting of grouse could have been involved in the suspicious disappearance of many birds, tags and their transmissions.

8.2 Introduction

Previous results have strongly indicated that the source of the sudden no malfunction fate was largely through anthropogenic intervention. The probable form of this intervention was mostly a swift forceful trauma to the tag (see section 6: Tag Reliability) and, presumably, its carrier i.e. both the transmitter and the tagged bird were killed. Since none of these tags were discovered from searches after the sudden stop in transmissions, it is also highly likely that at least many of the dead birds and their destroyed tags were removed and disposed of.

Given how many of the tags suddenly stopped transmitting, and their distribution (section 2 Tag Metadata and section 4 Cluster Analysis), primary candidates for anthropogenic intervention must be relatively widespread and have the potential for killing several birds (including an impetus for removal of the evidence of killing and tag destruction in at least some cases). Two primary candidates were considered on these bases: an association with wind farms and an association with grouse moor management.

Wind turbines can kill birds through collision with rotating blades (e.g. Madders & Whitfield 2006). Potentially, this could produce at least some of the features of the stopped no malfunction tag fate, for a couple of reasons.

First, the trauma of being struck by a spinning turbine blade, when sufficiently forceful to dismember the victim in some cases, could potentially suddenly fracture the tag's housing too, and cause a sudden stop of transmissions. While this may happen on occasion, there are nevertheless, many examples of tagged but dead birds of prey having been recovered through continued transmissions and reported as casualties of turbine strike at wind farms (e.g. Hunt 2002, May *et a*l. 2011) including many in Scotland either included in published analyses (e.g. Sansom *et al*. 2016, Urquhart & Whitfield 2016) or otherwise reported to Wind Farm Advisory Groups or through other planning conditions, to statutory authorities associated with conditions of operational monitoring. Interestingly, and by contrast, from the many data sources we have received and examined, we are not aware of dead tagged raptors having being reported by managers or employees of game bird shooting estates in Scotland.

There were no records of any turbine-blade stricken golden eagle at a wind farm in Scotland that we were aware of at the time of writing (tagged or not tagged) despite some theoretical possibilities (Hunt 2002, Fielding *et al*. 2006). Although, there have been two deaths of the less abundant white-tailed eagle *Haliaaetus albicilla* in Scotland, including one (still transmitting at the time) VHF-tagged bird, and a few tagged white-tailed eagles in Ireland have been found (all still transmitting when recovered, apparently http://www.goldeneagletrust.info/; A. Mee *pers. comm.*).

An expectation, without any secondary source of intervention (see immediately below), would be that a good proportion, at least, of stopped no malfunction tags in the present study would have been discovered by subsequent searches around the last fix within a wind farm had the tag carriers been killed by turbine strike (as in many other studies and examples).

A second possible explanation of the stopped no malfunction fate as regards wind farms, however, comes from evidence away from the UK (e.g. Vasilakis *et al*. 2017) in that technicians engaged regularly to service the turbines, may incidentally discover a stricken carcass below the turbine and dispose of it (tag-and-all if it was tagged); fearing for the consequences of such an adverse result on their future employment via the continued operation of the wind farm.

In Scotland this possibility seems remote given that: a) on incentive, the continued operation of no wind farm in Scotland is conditional on operational monitoring feedback in planning; b) technicians are not employed directly by the developer and are contracted independently by the turbine manufacturer and according to the projected lifespan of the wind farm; c) independent checks on reporting fatalities can be conducted at several wind farms by other contractors, and at least some developers (P. Robson *pers. comm.*) further blind-check these in staged exercises due to additional baseline legal requirements on environmental liability reporting; and d) many dead birds of prey (including tagged birds) have been routinely recorded incidentally by technical engineers and reported through several channels (e.g. Sansom *et al*. 2016, Urquhart & Whitfield 2016).

In other words there are several checks and balances in Scotland to circumvent the possibility that carcasses of dead birds of prey would not be reported at wind farms and not disposed of once discovered (and even when relatively few birds will have been tagged). Nevertheless, our analyses were grounded to consider such a possibility; however remote.

Turning to the second potential candidate for an anthropogenic influence which may have caused the many stopped no malfunction tag fates: ‘grouse moor managers’. Many previous studies of birds of prey in the UK have pointed to this influence as a cause of the illegal killing of birds of prey including golden eagles (see section 9). We do not re-iterate them in this section.

It is worth noting, however, that there were ample reasons, described elsewhere, why such potential perpetrators should not only kill golden eagles (tagged or untagged) but also then dispose of the evidence of killing. By contrast to the several legislative processes that are required of wind farm managers on reporting any discovered deaths of birds (including birds of prey such as golden eagles) there is no such comparable legislative requirement for managers of other land uses. Perhaps, as noted earlier and arguably appropriately and reasonably, this may be why we could not find any evidence that any report of a dead eagle, or other dead raptor, had been provided by a ‘daily on the ground’ employee on a grouse moor land use. Whereas we found more records of dead birds of prey (but no golden eagles), reported by the more periodic presence of technicians dealing with maintenance of wind turbines.

The objectives of this section were to investigate: 1) the possibility that a number of the stopped no malfunction tags fitted to golden eagles were the result of wind farm incidents; and 2) to investigate any possible association between the occurrence of such a tag fate and the distribution of land managed for driven grouse shooting.

8.3 Methods

An initial problem was the absence of a detailed map of turbines across Scotland. Consequently, a data base had to be developed for use with this project. Once a turbine database was available we could examine the overlap between golden eagle and wind farm locations and, in particular, the locations of stopped no malfunction locations and wind farms.

A further problem was the availability of a contemporary source of information on the distribution of moorland managed for intensive (driven) shooting of grouse. The presence of this land management can be determined from aerial and satellite photography because of the distinctive management of 'strip muirburn' created by periodic burning of vegetation. Whitfield *et al*. (2003) used a database which was produced in 1988 and while this land use may not have changed much since, it was decided to produce a new spatial record based on more contemporary information sources.

8.3.1 Use of Landsat 8 imagery

Landsat 8 imagery was used to document both the distribution of wind farms (via turbine locations) and areas managed for driven grouse moor ('strip muirburn' distribution: see Whitfield *et al*., 2003). Landsat 8 images were downloaded from https://pages.awscloud.com/public-data-sets-landsat.html to provide contemporary land cover information (image acquisition date range 09/05/2014 to 09/10/2016) (Table 8.1). All downloaded images were pre-screened to exclude images with excessive cloud cover over land.

Table 8.1. Locations of relevant MTL files for each Landsat 8 image and their acquisition dates

Catalogue ID	Row	Path	Acquisition	General region
LC82040212015273	204	021	30/09/2015	Edinburgh
LC82040222015113	204	022	23/04/2015	Borders
LC82050212016059	205	021	09/10/2016	North East
LC82050222014309	205	022	09/05/2014	Highlands
LC82060192016130	206	019	09/05/2016	Sutherland and Orkney
LC82060202016130	206	020	09/05/2016	Highlands
LC82060212016130	206	021	09/05/2016	Argyll
LC82060222015111	206	022	21/04/2015	South west
LC82070202016153	207	020	08/06/2016	Skye
LC82070212016153	207	021	08/06/2016	Inner Hebrides
LC82080192015045	208	019	06/06/2015	Lewis and Harris

Under licence conditions, there were no restrictions on the use of data received from the U.S. Geological Survey's Earth Resources Observation and Science (EROS) Center or NASA's Land Processes Distributed Active Archive Center (LP DAAC), unless expressly identified prior to or at the time of receipt.

For image processing, Bands 4, 3 and 2 were rescaled to the Top Of Atmosphere (TOA) reflectance and/or radiance using the using the QGIS (v 2.18) Semi-Automatic Classification Plugin (v 5.1.5) (Congedo Luca 2016). The bands were also pan sharpened to a 15 m resolution using the panchromatic Band 8 and saved as false colour composite images using the 1936 OSGB Coordinate Reference System. An example showing the quality of detail provided by these images is in Figure 8.1.

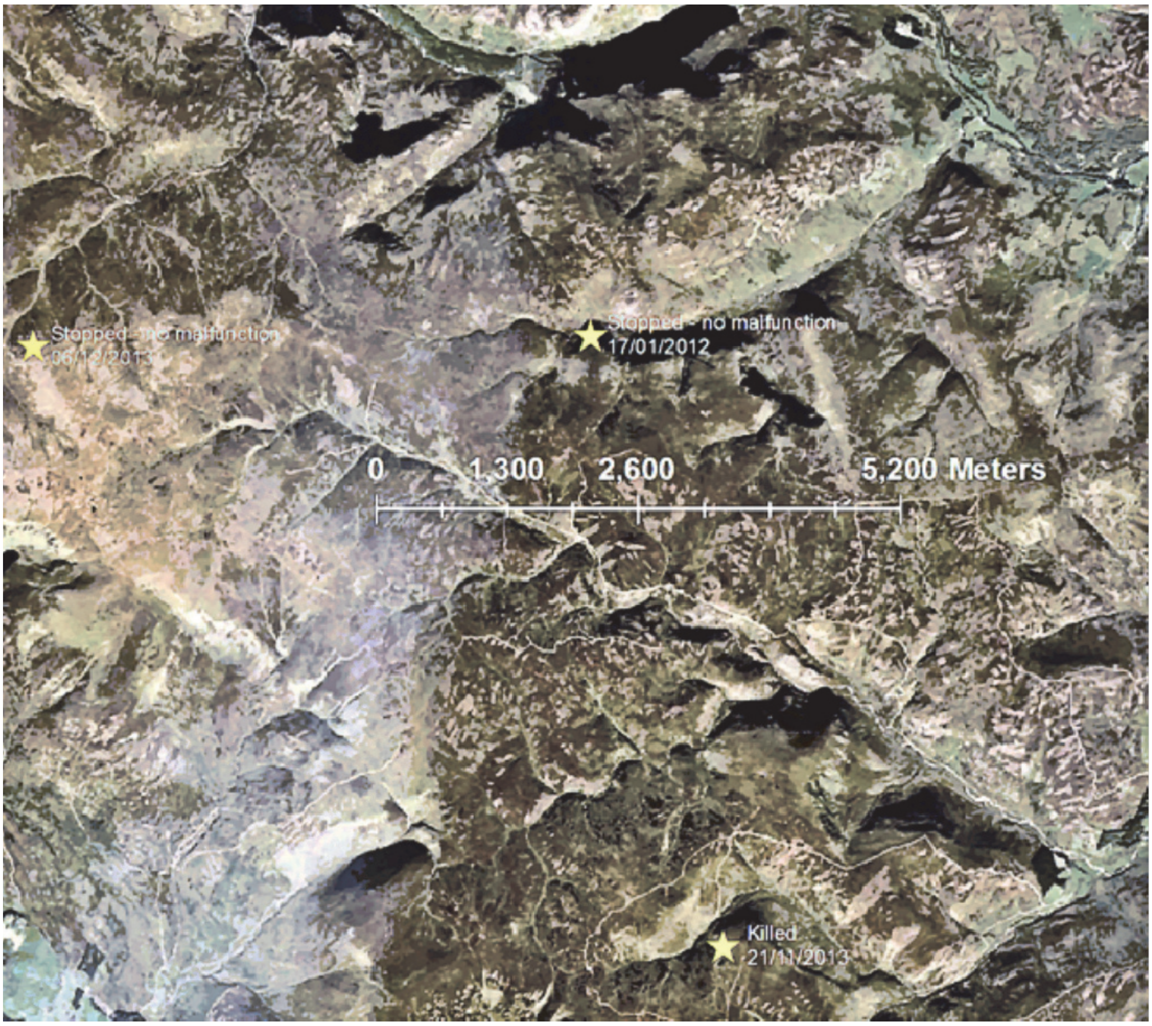

Figure 8.1. Example from a Landsat 8 image (WRS_PATH = 204, WRS_ROW = 21, DATE_ACQUIRED = 11:10 am 30/09/2015) and three last known locations of satellite tracked birds.

Turbine locations and the distribution of strip muirburn (see also Whitfield *et al*. 2003) revealed the locations and distribution of wind farms and driven grouse moor, respectively. The processed Landsat 8 images were thereby used to map turbine locations and the extent of grouse moor management, and were transferred into the GIS. If necessary, according to image quality, before analysis, aerial photographs were consulted and cross-checked with the Landsat imagery using https://www.bing.com/maps to confirm the putative land use. Initial digitised boundaries for grouse moor were also exported as a kml file to check against Google Earth imagery.

8.3.2 Producing a database of wind farms, their locations and operational start dates

Initial sources for the wind farm data were the DECC Oct 2016[7] renewable energy database, the SNH October 2016 wind farm database[8] and information provided by www.renewables.co.uk and developers' websites.

Turbine locations were digitised from 2014 - 2016 Landsat 8 satellite images (section 8.3.1) with clarifications from developers' web sites and Bing and Google Maps aerial photography

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[7] https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract
[8] https://gateway.snh.gov.uk/natural-spaces/index.jsp

where necessary (see Figure 8.2 for an example showing the Landsat 8 imagery used to map turbines). The mapping exercise excluded single turbines plus all of Orkney and Shetland. We used December 2016 as a cut-off and included all operational wind farms plus those that were under construction but were currently non-operational. At least four other wind farms with >10 turbines were due to begin construction by the end of 2016 but these were excluded because turbine locations were uncertain and there were no last fixes from stopped no malfunction tag fates around this time.

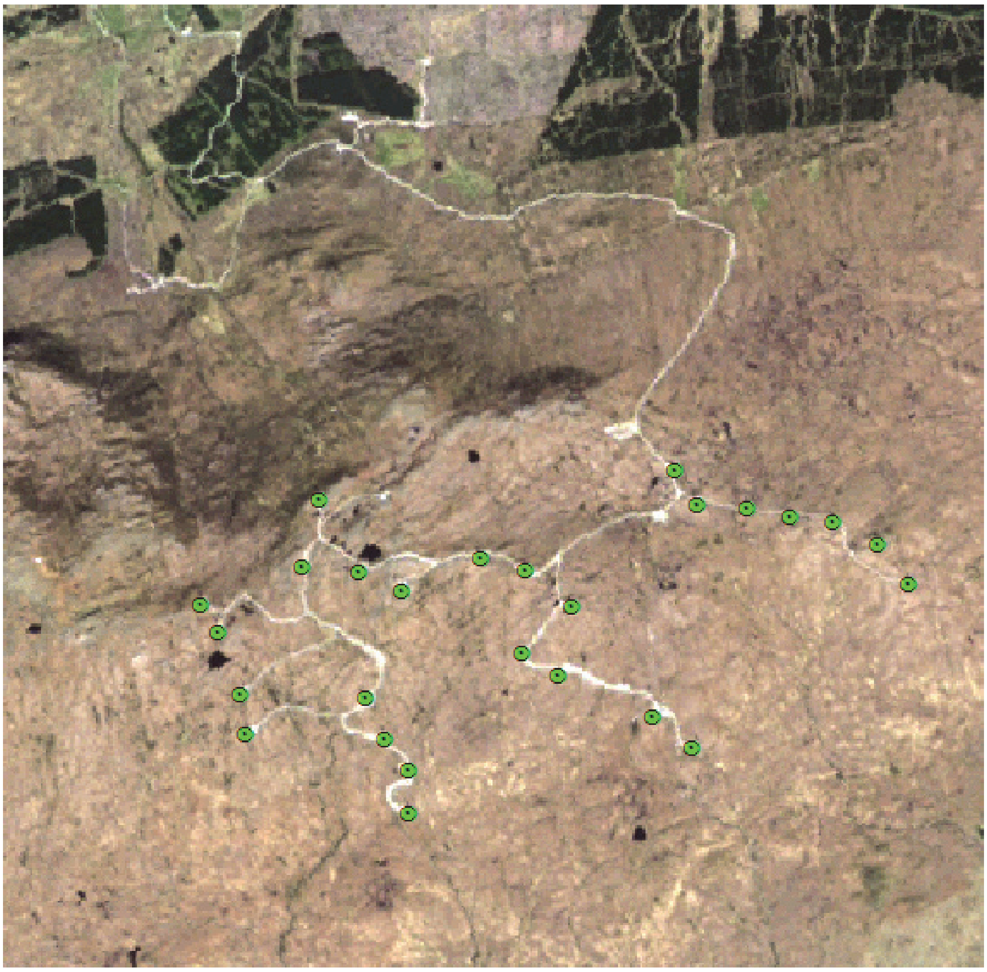

Figure 8.2. Millennium Wind Farm (26 turbines) with a false colour composite images (bands 4, 3 and 2) from a Landsat 8 image acquired on 08/06/2016 (Path 207, Row 020).

8.3.3 Tagging data

Against the digitised backdrop of the distribution of wind turbines and grouse moor in the GIS, the locations of the final fixes of the tagged eagles (including their fate) and all locations transmitted by tagged birds, were also added.

Spatial relationships between the tagging data and the distribution of wind turbines and grouse moor were examined by virtue of overlap and/or distances.

8.4 Results and Discussion

8.4.1 Wind farms

Metadata for the wind farms included in the mapping exercise are provided in Appendix 8.1.

We identified 195 wind farms with a total of 3,274 turbines with an installed capacity of 7,076 MW. The wind farms ranged in size from 2-214 turbines with a mean of 17and a median of 11 turbines (Table 8.2). On October 1st 2016 there were 172 operational wind farms in Scotland with 2,842 operational turbines and an installed capacity of 5,885 MW.

Table 8.2. Summary of the 'size' of Scottish wind farms (by turbine number classes) and the number (n) of wind farms in each size class.

Turbines	n
2-5	69
6-10	25
11-15	35
16-20	19
21-25	18
26-30	5
31-35	7
36-40	3
41-45	0
46-50	3
51-100	9
100+	2

By area of land, 946.9 km^2 of the mapped area of Scotland (i.e. excluding the Orkney and Shetland Isles), was within 500 m of a turbine (wind farm range was 0.8 to 66.0 km^2), 488.7 km^2 was within 250 m of a turbine (3,274 turbines) and 221 km^2 was within 150 m of a turbine.

8.4.2 Golden eagle locations and wind farms

None of the last known fixes, including the stopped no malfunction tags, was within 1 km of a turbine (Figure 8.3). It is difficult to believe that a bird struck by a turbine blade which may have damaged the tag would be able to travel for more than 1 km. The mean distance from a turbine to a last known location was 19.6 km (sd 11.8 km, median 17.2 km). Only three last known locations were between 1 and 2 km from a turbine (tag 107135, 1,220 m (Calliachar); tag 286611, 1,860 m (Hill of Glaschyle); and tag 582, 1,990 m (Braes of Doune[9]) respectively. Tag 107135 had a stopped no malfunction fate near to the Calliachar wind farm. However, there was only a single golden eagle location record within 500 m of a Calliachar turbine and this was from a different tag (93437). Tag 286611 was fitted to a bird known to have been killed before the adjacent wind farm was constructed and tag 582 was still tracking at the end of 2016.

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[9] Where several red kite collision victims have been discovered and reported (Urquhart & Whitfield 2016).

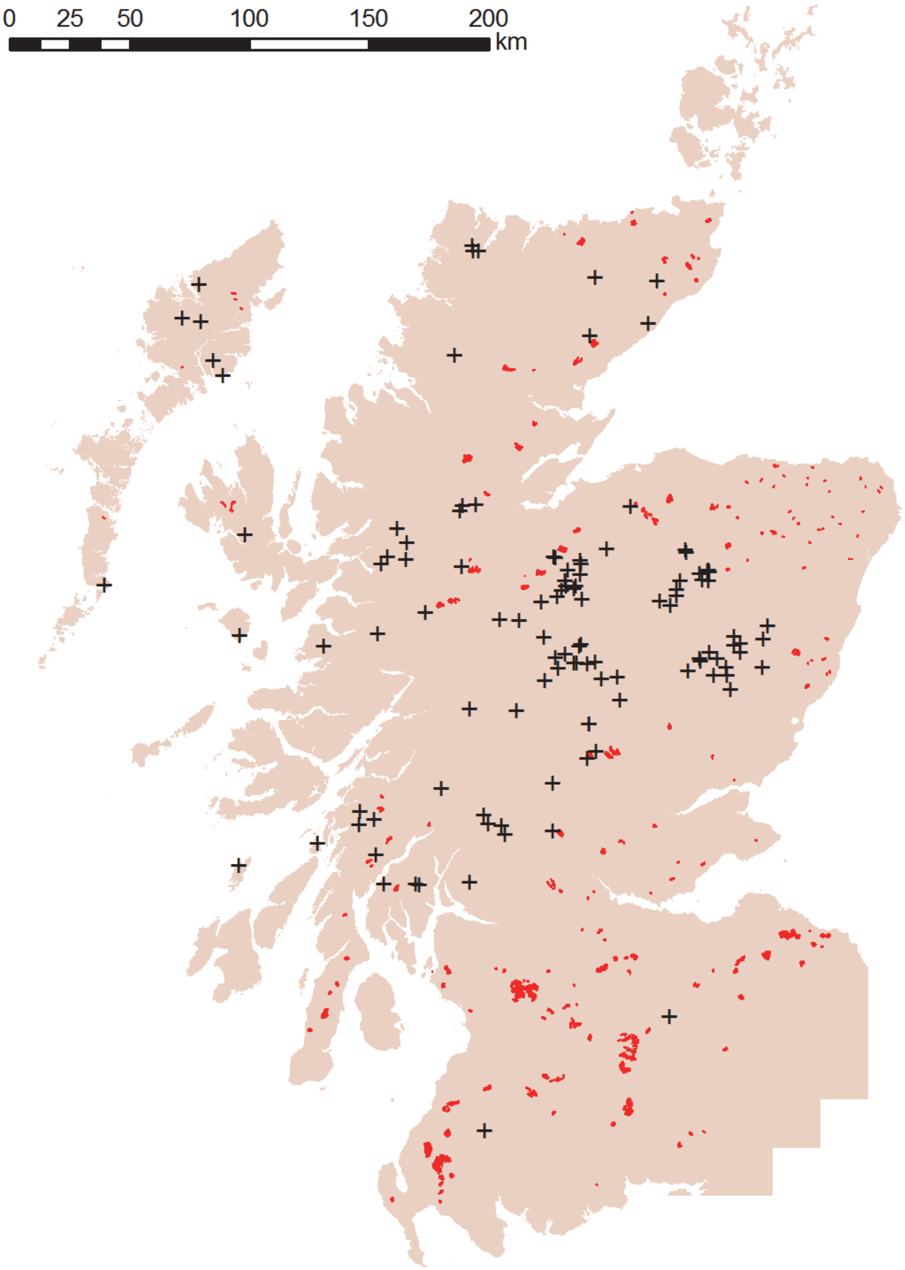

Figure 8.3. Wind farm locations (red polygons showing turbine locations and 500 m buffers) plus last known locations for all tags (black +).

Just 610 (0.14 %) of 439,556 golden eagle satellite tag locations, from 112 tagged birds, were within 500 m of a turbine in 39 operational or under-construction wind farms. 81 and 226 records, respectively, were within 150 m and 250 m of a turbine. 40 % of the records, within 500 m of a turbine, were beside the Dunmaglass (114) and Corriegarth (128) wind farms with a further 60 in An Suidhe, 39 in Bhlaraidh, 30 in Carraig Ghael, 24 in Clyde, 30 in Kildrummy and 26 in Moy (see Appendices 8.2 and 8.3 for details.

It should be emphasised that the Dunmaglass and Corriegarth wind farms were not operational when the tag data were collected and many records from other wind farms were transmitted prior to the wind farm becoming operational. Taking account of tag record dates and wind farm operational dates, only 125 of the 360,711 (0.03 %) records were within 500 m of an operational turbine. Only 17 (0.005 %) and 57 (0.016 %) records were within 150 m and 250 m of operational wind turbines, respectively. Detailed results for tag records by wind farm are in Appendices 8.2 and 8.3.

8.4.3 Golden eagle locations and grouse moor

Tagged birds whose tags had a suspicious fate (i.e. snmlfs: see section 5, Spatial Pattern Analysis) tended to spend more time on grouse moors than other birds (Table 8.3).

Table 8.3. Descriptive statistics for the % of time which birds were located on grouse moor according to whether their fate was not suspicious (non-snmfls) or suspicious (snmfls). Suspicious (snmfls) fates were killed, dropped suspicious or stopped no malfunction fates, and n gives the number of birds

Tag fate	**n**	**mean**	**sd**	**median**	**maximum**
non-snmfls	76	11.3	15.0	4.0	54.6
snmfls	39	21.3	16.0	19.1	57.6

Mean % records on grouse moor was almost double for those birds with a suspicious end, although the difference was much greater when using the medians which are probably more appropriate given the frequency distributions (Table 8.3). The difference in median values was highly significantly different between the non-snmfl birds and the snmfl birds (Kruskall-Wallis chi-squared = 11.895, df = 1, p < 0.001).

This indicated that birds which spent more time on grouse moors were significantly more likely to have a suspicious end. It was also apparent, however, that some birds without a suspicious fate spent substantial parts of their time on grouse moor: the maximum statistics were very similar, for example (Table 8.3).

The frequency distributions of use of grouse moor were very different between the birds with no suspicious fate and those with a suspicious fate (Figure 8.4). Several of the birds with a suspicious fate spent more time on grouse moors, whereas most of the birds (> 40 %) whose fate was not suspicious spent little time on grouse moor. On the other hand, there were some birds with a suspicious fate who rarely used grouse moors, and some birds with a non-suspicious fate spent much time on grouse moor (although recall that most of the non-suspicious birds were still tracking and so their tags had not yet “died” at the time of analysis). An association with grouse moor and suspicious fates would seem to be a localised issue and not ‘systematic’. Some grouse moors seemed to have a lot of activity but no birds meeting a suspicious fate.

A similar ‘mixed’ picture emerged when considering the land use where the final fixes of non-suspicious and suspicious tags occurred (Table 8.4).

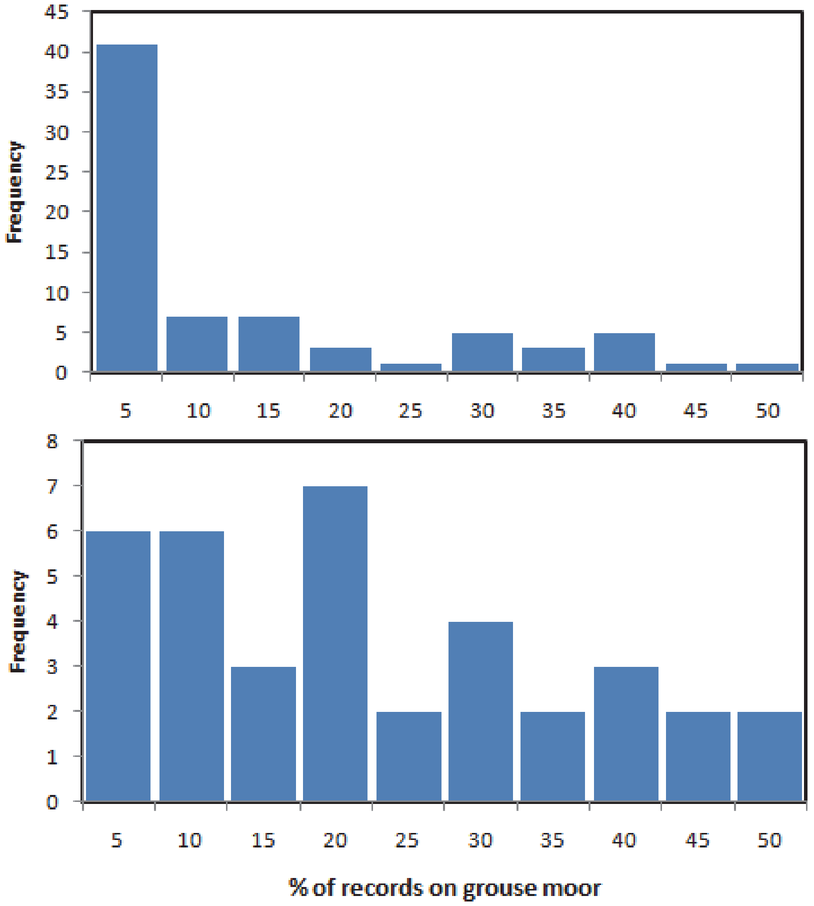

Figure 8.4. Frequency distributions (number of birds/tags on y axis) for the % of locational records on grouse moor (in 5 % bins, up 50 %, on x axis). The upper plot is non-suspicious tags (non-snmfls) and the lower plot is suspicious tags (snmfls).

While there were several suspicious tags whose final fixes were on grouse moors there were also several whose final fixes were not on grouse moors. Similarly, while there were relatively more final fixes of non-suspicious tags away from grouse moors, there were also some which were on grouse moor (Table 8.4). A statistical test of the distribution of final fixes by classed degree of suspicion and land use (grouse moor or not) in Table 8.4 was marginally beyond statistical significance (alpha = 0.05) (chi-squared = 3.7, df = 1, p = 0.055).

Table 8.4. Numbers of birds/tags with non-suspicious or suspicious final locations and whether these locations were on grouse moor or not on grouse moor.

Tag fate	**Final location**	
	Not grouse moor	**Grouse moor**
Non-suspicious	58 (79 %)	15 (21 %)
Suspicious	23 (59 %)	16 (41 %)

Such a simple and rigidly precise spatial delineation of final fixes was too simple, however, because it was apparent in several cases that birds' final fixes were related to roosting locations in woodland adjacent to grouse moor and were not determined, strictly, as grouse moor (and see also section 1.1, Introduction). For example, as illustrated in Figure 8.1 a last fix of a stopped no malfunction tag (on 17/01/2012) was not on grouse moor but was closely surrounded by it. Moreover, it was not a great stretch of possibilities to project that perpetrators were operating within or close to confines of the management boundaries of their employment; and so analysing potentially nefarious activities should be better conducted by looking at such potential proximities (albeit crudely). (As an example, as described earlier, there was one case where a likely-trapped eagle - both legs near-severed - was apparently taken at night many kilometres away from where it had originally been 'downed' on a grouse moor before final 'disposal' beside an A-roadside.)

We accordingly re-cast the distribution of spatial distribution of 'grouse moor' to incorporate increasing surrounding buffers (within 1, 2 and 4 km) so far as spatial coincidence with the final locations of non-suspicious and suspicious tag fates. These results are given in Table 8.5.

Figure 8.5. Numbers of birds/tags with non-suspicious or suspicious final locations and whether these locations were on grouse moor or not on grouse moor, according to an increasing spatial buffer around the strict delineation of grouse moor distribution (within 1, 2 and 4 km buffers). Results of statistical tests of differences between the locations of final fixes of non-suspicious against suspicious tags are shown for each spatial buffer limit.

Tag fate	**Final location**	
	Not grouse moor	**Grouse moor**
Within 1 km		
Non-suspicious	46 (63 %)	27 (37 %)
Suspicious	17 (44 %)	22 (56 %)
	Chi squared = 5.6, df = 1, p = 0.018	
Within 2 km		
Non-suspicious	42 (58 %)	31 (42 %)
Suspicious	12 (31 %)	27 (69 %)
	Chi squared = 8.1, df = 1, p = 0.004	
Within 4 km		
Non-suspicious	37 (51 %)	36 (49 %)
Suspicious	9 (23 %)	30 (77 %)
	Chi squared = 9.8, df = 1, p = 0.002	

The results of this process (Table 8.5) revealed an increasingly significant statistical relationship between the final locations of suspicious tag fates and grouse moor as the potential spatial influence of grouse moor management increased.

8.5 Conclusions

8.5.1 Wind farms

No stopped no malfunction last fixes were within 1 km of an operational wind farm. It is difficult to envisage a situation whereby a trauma sufficient to suddenly destroy a tag would allow a bird to travel afterwards for more than 1 km.

Moreover, records of tagged eagles close to wind farms were rare with only 0.005% of 360,711 fixes being within 150 m of an operational turbine. This indicated that even the risk of collision with a turbine blade was miniscule. Furthermore, it would add no support to a notion that technicians visiting turbines were discovering and then 'covering up' victims of collision, including moving dead birds away from the wind farm before, or then, curtailing the operation of the tag.

Overall, there was no evidence that wind farms were a direct or indirect agent of anthropogenic influence on the sudden tag failures of many young golden eagles. The reverse was more evidentially likely – that young golden eagles appeared to avoid operational wind farms.

Therefore, it was very improbable that the fates of stopped no malfunction tags were related to wind farm issues.

It would be interesting to examine in greater detail if activity changed in the vicinity of wind farms once they were constructed and become operational. There was some evidence from the operational wind farms that the number of records fell once a wind farm became operational; although this topic is for further detailed analyses beyond the scope of the present project.

8.5.2 Grouse moors

For an involvement of grouse moors as a land use and potential source of perpetrators the picture which emerged was not quite so straightforwardly obvious as it was for wind farms. Birds which spent more time near or on grouse moors were significantly more likely to have a suspicious end. While many of the suspicious tags (including the stopped no malfunction tags) were associated with grouse moor, these were in particular areas of grouse moor, notably where there were clusters in the central and eastern Highlands (see section 4: Cluster Analysis). Several suspicious tags were not discovered on grouse moors: for example, there were isolated events including a bird (stopped no malfunction) on Colonsay and a poisoned bird in the Loch Morar area of the northwest Highlands.

There were several areas of grouse moor which were intensively used by young eagles but where there were no suspicious tag fates (see section 3: Location Densities); although there were also vast swathes of ground away from grouse moors where there was a lot of use and, also, no suspicious tag fates.

Nevertheless, the association of suspicious last fixes with grouse moors became much stronger as the geographical buffer around grouse moor distribution increased. Moorland managed for driven shooting of grouse is not a direct threat to golden eagles *per se* but, in the context of an anthropogenic threat to golden eagles, is a proxy for the activities of managers of this habitat. These activities spread beyond the area which could be detected by remote means as being managed for driven grouse shooting (distribution of strip muirburn). Hence, it is reasonable to assume that the wider geographical buffers were a more appropriate measure of those activities, and the anthropogenic threat posed to golden eagles, than a strict adherence to the strip muirburn habitat itself. There was, therefore, statistical evidence for suspicious tag fates to be associated with the likely activities of grouse moor managers; as well as tagged birds which spent more time near or on grouse moors being significantly more likely to have a suspicious end.

The situation would not appear to be simple, however, and while much of the intensive clustering of suspicious fates was associated with grouse moors and their immediate environs there were other suspicious tag fates away from this land use. So far as any responsibility associated with grouse moor management, the results suggested that while many young tagged eagles were probably killed in association with some grouse moors there were also other grouse moors where there was no evidence from the satellite tagging data of killing of young eagles.

Appendix 8.1. Wind farm metadata.

RefID	Wind farm	Site Name	Installed MW	Turbine MW	Turbines	Status	County	Construction	Operational
3,285	Achairn	Achairn	6.2	2.1	3	Operational	Highland	01/04/09	20/05/09
3,205	Achany	Achany Wind Farm	38.0	2.0	19	Operational	Highland	01/04/09	11/10/10
4,331	AChruach	A'Chruach (Phase 1)	43.1	2.1	21	Operational	Strathclyde	04/06/15	29/06/16
4,526	Aikengall	Aikengall	48.0	3.0	16	Operational	Lothian		01/11/08
4,328	Allt Dearg	Srondoire Community Wind Farm	24.0	2.0	12	Operational	Strathclyde	20/06/14	20/12/15
3,298	An Suidhe	An Suidhe	20.7	0.9	23	Operational	Strathclyde	01/06/07	04/08/10
3,855	Ardoch	Ardoch and Over Enoch Wind Farm (Over Enoch)	11.5	2.3	5	Operational	Strathclyde	05/11/13	12/11/14
4,668	Ardrossan	Ardrossan	30.0	2.0	15	Operational	Strathclyde	01/03/08	01/11/08
3,258	Arecleaoch	Arecleoch Windfarm	118.0	2.0	59	Operational	Strathclyde	01/09/09	14/06/11
4,062	Ark Hill	Ark Hill	6.4	0.8	8	Operational	Tayside	17/08/12	29/03/13
3,306	Arnish Moor	Arnish Moor	3.9	1.3	3	Operational	Western Isles	01/12/06	01/12/06
4,518	Artfield Hill	Artfield Fell	19.5	1.3	15	Operational	Dumfries & Galloway		23/06/05
3,806	Auchiderran	Auchinderran Wind Farm	2.4	0.8	3	Operational	Grampian	01/08/14	01/12/14
4,021	Baillie	Baillie Wind Farm	52.5	2.5	21	Operational	Highland	01/07/11	29/03/13
4,445	Balmurrie Fell	Balmurrie Fell Wind Farm	9.1	1.3	7	Operational	Dumfries & Galloway	01/03/12	01/09/12
2,758	Balquihindachy	Hill of Balquhindachy	2.6	0.9	3	Operational	Grampian		09/07/10
4,055	Bankend Rig	Bankend Rig	14.3	1.3	11	Operational	Strathclyde	09/01/12	27/03/13
4,435	Barlockhart Moor	Barlockhart Moor	8.1	2.0	4	Operational	Dumfries & Galloway		27/08/13
4,525	Beinn an Tuirc	Beinn an Tuirc Phase 2	105.8	2.3	46	Operational	Strathclyde	01/04/10	01/09/14
4,525	Beinn an Tuirc2	Beinn an Tuirc Phase 2	43.7	2.3	19	Operational	Strathclyde	01/04/10	01/09/14
3,295	Beinn Ghlas	Beinn Ghlas Wind Farm	7.7	0.6	14	Operational	Strathclyde		25/06/99
4,272	Beinn Ghrideag	Point Wind / Beinn Ghrideag Farm	9.0	3.0	3	Operational	Western Isles	21/07/14	17/07/15
4,669	BeinnTharsuinn	Beinn Tharsuinn Windfarm Project	33.3	1.8	19	Operational	Highland	01/05/05	01/12/05
3,668	Ben Aketil	Ben Aketil Extension	15.6	1.3	12	Operational	Highland	01/04/10	01/01/11
4,261	Berryburn	Berry Burn	69.0	2.3	30	Operational	Grampian	05/12/12	30/05/14
3,380	Betty Hill	Phase 1 Bettyhill Wind Farm	5.0	2.5	2	Operational	Highland		04/06/13

RefID	Wind farm	Site Name	Installed MW	Turbine MW	Turbines	Status	County	Construction	Operational
3,207	Bilbster	Bilbster Wind Farm	3.9	1.3	3	Operational	Highland		01/02/08
3,574	Black Hill	Black Hill (Borders)	28.6	1.3	22	Operational	Borders	01/05/06	14/02/07
4,580	Black Law	Black Law Extension - 1b	162.0	3.0	54	Operational	Strathclyde	18/08/15	18/02/16
3,810	Blantyre Muir	Blantyre Muir Wind Farm	18.0	3.0	6	Operational	Strathclyde		30/12/13
3,370	Bonerbo	Bonerbo Wind Turbines (resubmission)	1.5	0.5	3	Operational	Fife	11/02/14	15/12/14
3,300	Bowbeat	Bowbeat Wind Farm	31.2	1.3	24	Operational	Lothian		05/09/02
2,691	Boynide Airfield	Boyndie Airfield Extension	20.7	2.3	9	Operational	Grampian		04/01/10
3,119	BraesofDoune	Braes O'Doune	72.0	2.0	36	Operational	Central	01/05/06	01/09/06
2,672	Brockholes	Brockholes Wind Cluster	2.4	0.8	3	Operational	Borders	28/02/12	18/02/13
3,126	Buolfruich	Boulfruich	12.8	0.9	15	Operational	Highland		01/08/05
4,122	Burn of Whilk	Burn of Whilk	22.5	2.5	9	Operational	Highland	30/05/14	07/08/15
4,450	Burnfoot Hill	Burnfoot Hill	30.0	2.0	15	Operational	Tayside		09/09/14
4,125	Burnhead	Burnhead	26.0	2.0	13	Operational	Central	10/01/15	29/02/16
2,724	Cairnmore farm	Cairnmore Farm	2.6	0.9	3	Operational	Grampian	01/04/10	10/07/10
3,688	Calder Water	Calder Water Community Wind Farm	26.0	2.0	13	Operational	Strathclyde		01/09/13
4,027	Calliachar	Calliachar	32.2	2.3	14	Operational	Tayside	01/06/12	30/09/13
4,006	Camster	Camster	50.0	2.0	25	Operational	Highland	01/01/12	09/02/13
3,214	Carcant	Carcant Windfarm	6.0	2.0	3	Operational	Borders	01/04/10	02/11/10
4,619	Carraig Ghael	Carraig Gheal	46.0	2.3	20	Operational	Strathclyde	01/03/11	31/08/13
4,501	Carscreugh	Carscreugh Renewable Energy Park	15.3	0.9	18	Operational	Dumfries & Galloway	01/06/13	15/01/14
3,718	Castleof Auchry	Castle of Auchry Farm	2.4	0.8	3	Operational	Grampian	01/09/13	01/11/13
3,108	Causeymire	Causeymire	42.0	2.0	21	Operational	Highland		01/06/04
3,448	ClachanFlats	Clachan Flats Wind Farm	15.0	1.7	9	Operational	Strathclyde	01/05/06	01/12/08
4,623	Clashindaroch	Clashindarroch 2 (Revised)	36.9	2.1	18	Operational	Grampian	01/06/13	26/06/15
3,701	Clochnahill	Hillhead of Auquhirie, Resubmission	16.1	2.3	7	Operational	Grampian	01/09/12	16/01/13
4,011	Clyde	Clyde Wind Farm	473.8	2.3	206	Operational	Strathclyde		01/10/12
3,746	Corrimony	Glenurquhart and Strathglass Wind Farm	10.0	2.0	5	Operational	Highland	01/08/12	19/04/13

RefID	Wind farm	Site Name	Installed MW	Turbine MW	Turbines	Status	County	Construction	Operational
4,524	Craig	Craig Wind Farm	10.0	2.5	4	Operational	Dumfries & Galloway		01/10/07
2,940	Craigengelt	Craigengelt	20.0	2.5	8	Operational	Central	01/05/09	31/03/10
3,585	Cruach Mhor	Cruach Mhor	33.3	1.0	35	Operational	Strathclyde		31/01/04
3,536	Crystal Rig	Crystal Rig Extension II	190.9	2.3	83	Operational	Borders	01/08/08	25/10/10
4,520	Dalswinton	Dalswinton	30.0	2.0	15	Operational	Dumfries & Galloway	01/04/07	15/03/08
3,554	Deucheran Hill	Deucheran Hill	15.8	1.8	9	Operational	Strathclyde		30/11/01
4,023	Drone Hill	Drone Hill	28.6	1.3	22	Operational	Borders	01/04/11	01/09/12
3,398	Droop Hill	Droop Hill Wind Farm x	4.6	2.3	2	Operational	Grampian	08/09/13	01/07/14
4,009	Drumderg	Drumderg	36.8	2.3	16	Operational	Tayside		09/11/08
3,200	Dummuie	Dummuie	12.3	1.8	7	Operational	Grampian	01/06/06	01/01/07
4,362	Dungavel Hill	Dungavel Hill	29.9	2.3	13	Operational	Strathclyde	01/05/14	28/08/15
3,570	DunLaw	Dun Law	40.3	0.7	61	Operational	Borders		21/08/00
3,201	Earlsburn	Earlsburn	60.0	2.5	24	Operational	Stirling	01/07/06	01/02/07
4,363	Earlseat	Earlseat	18.4	2.3	8	Operational	Fife	30/10/13	30/07/14
3,819	Easter Melrose	Easter Melrose Wind Energy Project	1.5	0.5	3	Operational	Grampian	15/05/15	01/12/15
3,818	Easter Tulloch	Tullo Wind Farm North (Shiels Wind Farm)	37.5	2.5	15	Operational	Grampian	30/04/13	01/04/14
4,674	Edinbane	Edinbane Wind Farm	41.4	2.3	18	Operational	Highland	01/08/08	21/06/10
4,072	Edintore	Edintore Wind Farm	18.0	3.0	6	Operational	Grampian	24/09/15	31/10/16
4,015	Ewe Hill	Ewe Hill	13.8	2.3	6	Operational	Dumfries & Galloway	10/09/15	30/05/16
4,675	Fairburn	Fairburn	43.0	2.2	20	Operational	Highland	01/02/09	07/06/10
4,059	FallagoRig	Fallago Rig	144.0	3.0	48	Operational	Borders	01/03/11	31/03/13
4,676	Farr	Farr Wind Farm	92.0	2.3	40	Operational	Highland	01/04/05	01/10/05
2,704	FMC	F M C Land, Pitreavie Business Park	4.5	1.5	3	Operational	Fife		31/10/11
3,309	Forss	Hill of Lybster	3.9	1.3	3	Operational	Highland		08/02/03
3,309	Forss2	Hill of Lybster	3.9	1.3	3	Operational	Highland		08/02/03
4,370	GlaxoSmithKline	GlaxoSmithKline Wind Project	10.0	2.5	4	Operational	Strathclyde	01/01/14	01/06/14
4,638	Glenchambers	Glenchamber Wind Farm	25.3	2.3	11	Operational	Dumfries & Galloway	06/02/15	01/06/16

RefID	Wind farm	Site Name	Installed MW	Turbine MW	Turbines	Status	County	Construction	Operational
3,538	Glenkerie	Glenkerie Wind Farm	22.0	2.0	11	Operational	Borders	01/04/11	01/02/12
3,311	Glens of Foudland	Glens of Foudland	26.0	1.3	20	Operational	Grampian		22/07/05
3,662	Gordonbush	Gordonbush	70.0	2.0	35	Operational	Highland	01/07/10	12/06/12
3,666	Gordonstown	Gordonstown Hill Wind Farm	12.5	2.5	5	Operational	Grampian	23/07/12	31/03/13
3,487	Green Knowe	Green Knowes	27.0	1.5	18	Operational	Tayside	14/06/08	29/09/08
3,236	Greendykeside	Greendykeside	4.0	2.0	2	Operational	Strathclyde		01/11/07
3,698	Greenhill croft	Greenhill Croft	4.6	2.3	2	Operational	Grampian	01/10/11	01/03/12
3,802	Greenside	Land at Overside and Greenwellheads Farms	9.2	2.3	4	Operational	Grampian		01/11/13
4,028	Griffin	Griffin Wind farm	204.0	3.0	68	Operational	Tayside	01/07/10	28/02/12
3,404	Haddo	Haddo	4.6	2.3	2	Operational	Grampian	01/05/10	25/05/11
4,645	Hadyard Hill	Assel Valley Wind Farm	104.0	2.0	52	Operational	Strathclyde	15/05/15	28/10/16
3,301	Hagshaw Hill	Hagshaw Hill Wind Farm	27.6	0.6	46	Operational	Strathclyde		01/11/95
2,711	Hare Hill	Hare Hill (East Ayrshire)	19.8	0.7	30	Operational	Strathclyde		01/11/00
4,119	Harestanes	Harestanes	140.0	2.0	70	Operational	Dumfries & Galloway	18/10/12	01/07/14
3,532	Hill of Easterston	Hill of Easterton	7.5	2.5	3	Operational	Grampian		01/01/05
3,968	Hill of Fiddes	Hill of Fiddes	6.9	2.3	3	Operational	Grampian	01/07/09	20/02/10
3,433	Hill of Stroupster	Stroupster Wind Farm - additional turbine	29.9	2.3	13	Operational	Highland	01/07/14	15/10/15
4,014	Hill of Towie	Hill of Towie (Drummuir)	42.0	2.0	21	Operational	Grampian	01/09/10	01/06/12
2,923	House OHill	House O'Hill	5.0	1.7	3	Operational	Grampian	01/08/09	04/10/10
4,609	Hunterston	Hunterston Test Centre	14.0	7.0	2	Operational	Strathclyde	21/03/13	15/12/15
4,511	Jacksbank	Jacksbank Wind Farm (Glenbervie)	6.8	2.3	3	Operational	Grampian		12/07/14
3,149	Kelburn	Kelburn	26.0	2.0	13	Operational	Strathclyde	01/11/10	02/05/12
4,303	Kellas	KELLAS WIND FARM	9.2	2.3	4	Operational	Grampian	01/03/15	01/08/15
2,673	Kilbraur Community	Kilbraur Windfarm Farlary	47.5	2.5	19	Operational	Highland	01/12/10	01/09/11
3,202	Kilbraur extension	Kilbraur Windfarm	20.0	2.5	8	Operational	Highland	01/09/07	14/06/08
4,114	KIldrummy	Kildrummy Windfarm	18.4	2.3	8	Operational	Grampian		14/02/13
2,796	Lairg Estate	Lairg Wind Farm	7.5	2.5	3	Operational	Highland		01/01/12

RefID	Wind farm	Site Name	Installed MW	Turbine MW	Turbines	Status	County	Construction	Operational
4,620	Langhope Rig	Langhope Rig	17.6	1.6	11	Operational	Borders	30/10/13	26/03/15
3,722	Little Byth	Little Byth	4.5	1.5	3	Operational	Grampian		31/12/12
4,034	Little Raith	Little Raith Farm	25.2	2.8	9	Operational	Fife	01/09/11	27/11/12
3,581	Lochelbank	Lochelbank Wind Farm II	9.6	0.8	12	Operational	Tayside	01/08/10	25/05/11
3,453	Lochhead farm	Lochhead Farm	6.0	2.0	3	Operational	Strathclyde		01/07/09
4,123	LochLuichart	Lochluichart	69.0	3.0	23	Operational	Highland	01/02/12	14/05/14
3,605	Longpark	Longpark	38.0	2.0	19	Operational	Borders	01/06/09	01/09/09
3,980	Mains of Hatton	Mains of Hatton	2.4	0.8	3	Operational	Grampian	01/11/11	20/03/12
3,260	Mark Hill	Mark Hill	64.4	2.3	28	Operational	Strathclyde	01/10/09	01/06/11
4,013	MeallanTuirc	Novar Wind Farm (Extension)	78.2	2.3	34	Operational	Highland	01/08/10	17/09/12
4,109	Meikle Carewe	Meikle Carewe (Re-Submission)	10.2	0.9	12	Operational	Grampian	26/07/12	30/07/13
4,681	Michelin Dundee	Michelin Tyre Co Ltd - Dundee	4.0	2.0	2	Operational	Tayside		20/05/06
3,702	Middleton	Middleton Wind Farm	12.0	2.0	6	Operational	Strathclyde	29/05/12	04/09/13
4,627	MidHill	Mid Hill - Phase II	73.6	2.3	32	Operational	Grampian	25/08/14	02/12/14
3,598	Millenium	Millennium Extension	65.0	2.5	26	Operational	Highland	13/01/08	01/12/08
3,809	MIlton of Fisherie	Milton of Fisherie Wind Cluster	4.6	2.3	2	Operational	Grampian	01/04/15	01/02/16
4,517	Minsca	Minsca	36.8	2.3	16	Operational	Dumfries & Galloway		01/03/08
4,629	Monan	Monan Hill Wind Turbines	1.5	0.5	3	Operational	Highland	01/07/14	19/03/15
3,647	Moy	Moy Wind Farm (2nd Application)	69.3	3.3	21	Operational	Highland	22/04/14	12/05/16
3,594	Muirake	Muirake	4.6	2.3	2	Operational	Grampian		13/12/11
3,873	Muirhall Hill	Muirhall Extension	30.6	3.4	9	Operational	Strathclyde		30/04/14
3,090	Myers Hill	Myres Hill	1.8	0.9	2	Operational	Strathclyde		01/11/01
3,804	Myreton	Myreton Crossroads	1.6	0.8	2	Operational	Grampian	01/03/12	05/07/13
3,090	National windfarm test	Myres Hill	1.8	0.9	2	Operational	Strathclyde		01/11/01
3,857	Neilston	NEILSTON WIND FARM	11.5	2.3	5	Operational	Strathclyde	01/03/12	13/05/13
3,691	Netherton	Netherton of Windyhills	4.6	2.3	2	Operational	Grampian	01/11/13	01/11/14
2,965	North Red Bog	North Red Bog	1.6	0.8	2	Operational	Grampian		23/06/08
4,508	North Rhins	North Rhins	22.0	2.0	11	Operational	Dumfries & Galloway	01/10/09	20/01/10

RefID	Wind farm	Site Name	Installed MW	Turbine MW	Turbines	Status	County	Construction	Operational
4,013	Novar	Novar Wind Farm	34.5	2.3	15	Operational	Highland	01/08/10	17/09/12
3,676	Nutberry	Nutberry Wind Farm	15.0	2.5	6	Operational	Strathclyde	01/12/11	30/09/13
3,232	Pates Hill	Pates Hill	14.0	2.0	7	Operational	Lothian	01/06/09	20/01/10
4,687	PaulsHill	Paul's Hill and Extension	69.0	2.3	30	Operational	Grampian	01/01/04	01/04/06
4,600	Penmanshiel	Penmanshiel Wind Farm	28.0	2.0	14	Operational	Borders	06/05/15	01/07/16
4,063	Pentland Road	Pentland Road Wind Farm	13.8	2.3	6	Operational	Western Isles	01/03/12	28/03/13
4,484	Plascow	Plascow wind cluster (resubmission)	2.4	0.8	3	Operational	Dumfries & Galloway	01/04/15	15/07/15
4,223	Rhodders	Rhodders Wind Farm	12.0	2.0	6	Operational	Central	01/08/15	29/02/16
4,051	Rosehall	Rosehall Hill Forest Windfarm	24.7	1.3	19	Operational	Highland	01/08/11	28/02/13
3,651	Rosehill	Rosehill Wind Turbines	2.4	0.8	3	Operational	Central	15/05/15	15/12/15
4,303	Rothes	KELLAS WIND FARM	87.4	2.3	38	Operational	Grampian	01/03/15	01/08/15
3,784	Shielburn Farm	Shielburn Farm	6.9	2.3	3	Operational	Grampian		30/03/13
3,075	Skelmonae	Skelmonae Wind Farm	3.6	0.9	4	Operational	Grampian		20/12/09
3,670	South Uist	Lochcarnan Community Windfarm	6.9	2.3	3	Operational	Western Isles	21/03/12	18/02/13
4,328	Srondoire	Srondoire Community Wind Farm	6.0	2.0	3	Operational	Strathclyde	20/06/14	20/12/15
2,741	St Fergus Moss	St Fergus Moss Wind Farm	6.0	2.0	3	Operational	Grampian	31/03/12	18/12/12
2,867	St John Hill	St John Hill	7.5	2.5	3	Operational	Grampian		07/03/13
4,031	St JOhns Hill	St. Johns Hill	8.4	2.8	3	Operational	Grampian		01/04/13
2,999	St Johns Well	St John's Well	4.8	0.8	6	Operational	Grampian		15/07/09
2,708	Strath of Brydock	Strath of Brydock	3.9	1.3	3	Operational	Grampian		01/12/09
4,625	Strathy North	Strathy North	67.7	2.1	33	Operational	Highland	31/01/14	01/12/15
4,024	Tangy	Tangy Wind Farm	18.7	0.9	22	Operational	Strathclyde	01/05/06	17/06/11
3,415	Tod Hill	Tod Hill Farm Wind Turbines	12.0	3.0	4	Operational	Central	01/04/14	22/01/15
3,457	Toddleburn	Toddleburn	27.6	2.3	12	Operational	Borders	01/04/10	12/10/10
4,085	Torrance Farm	Torrance Farm Wind Park	15.0	3.0	5	Operational	Strathclyde	18/12/14	18/06/15
3,524	Upper Ardrain	Upper Ardgrain Wind Farm	2.4	0.8	3	Operational	Grampian		01/10/10
4,235	Wardlaw Wood	Millour Hill Community Windfarm	52.5	3.5	15	Operational	Strathclyde	15/01/16	31/03/16
3,757	Wathegar	Wathegar wind farm	10.0	2.0	5	Operational	Highland	01/06/12	31/03/13

RefID	Wind farm	Site Name	Installed MW	Turbine MW	Turbines	Status	County	Construction	Operational
4,427	West Browncastle	West Browncastle	30.0	2.5	12	Operational	Strathclyde	01/02/13	30/06/14
3,681	West Knock	West Knock Wind Cluster	2.4	0.8	3	Operational	Grampian		04/10/11
4,526	Wester Dod	Aikengall	60.0	3.0	20	Operational	Lothian		01/11/08
3,684	Westfield	Westfield	10.0	2.5	4	Operational	Fife	30/07/12	31/03/13
4,519	WetherHill	Wether Hill	18.2	1.3	14	Operational	Dumfries & Galloway	01/08/06	01/05/07
3,981	Whitelees	Whitelee Windfarm	642.0	3.0	214	Operational	Strathclyde	01/12/10	31/10/12
4,527	Windy Knoll	Windy Standard	39.0	0.6	65	Operational	Dumfries & Galloway		01/10/96
6,173	Woodlands	Woodlands Wind Farm	2.6	0.9	3	Operational	South Lanarkshire	01/03/16	28/07/16
3,405	Yonderton	Gairnieston Farm	6.9	2.3	3	Operational	Grampian	01/05/10	01/11/10
4,110	Andershaw	Andershaw	35.0	2.5	14	Construction	Strathclyde	28/10/15	
4,462	Aries_Farm	Airies Farm	40.6	2.9	14	Construction	Dumfries & Galloway	08/02/16	
4,337	Auchrobert	Auchrobert Wind Farm	30.0	2.5	12	Construction	Strathclyde	01/04/15	
3,619	Beinneun	Beinneun Windfarm Extension	78.2	3.4	23	Construction	Highland	15/07/15	
4,640	Bhlaraidh	Bhlaraidh (previously Balmacaan)	105.6	3.3	32	Construction	Highland	01/03/16	
4,350	Cairnborrow	Cairnborrow - resubmission	12.5	2.5	5	Construction	Grampian	12/08/15	
4,664	Corriegarth	Corriegarth	69.0	3.0	23	Construction	Highland	08/05/15	
4,120	Corriemoille	Corriemoille - resubmission	45.6	2.85	16	Construction	Highland	15/10/15	
3,772	Cour	Cour Wind Farm	25.0	2.5	10	Construction	Strathclyde	19/11/15	
4,269	Dersalloch	Dersalloch	66.0	3.0	22	Construction	Strathclyde	24/09/15	
4,118	Dunmaglass	Dunmaglass Wind Farm	99.0	3.0	33	Construction	Highland	01/06/14	
3,886	Fraesdail	Freasdail Wind Farm	22.0	2.0	11	Construction	Strathclyde	20/02/16	
4,368	Galawhistle	Galawhistle	66.0	3.0	22	Construction	Strathclyde	18/06/15	
4,211	Harburnhead	Pearie Law Wind Farm	70.4	3.2	22	Construction	Lothian	15/09/15	
4,381	Hill of Glaschyle	Hill of Glaschyle Wind Farm	27.6	2.3	12	Construction	Grampian	01/06/16	
3,911	Hill of Tillymorgan	Hill of Tillymorgan (Kirkton Farm) Wind turbines (resubmission)	6.9	2.3	3	Construction	Grampian	01/07/15	
4,386	KIlgalioch	Kilgallioch wind farm	247.5	2.5	99	Construction	Dumfries & Galloway	28/07/15	
4,601	Kinegar Quarry	Kinegar Quarry (resubmission)	5.0	2.5	2	Construction	Borders	15/07/14	
4,664	Aberchalder	Aberchalder	3	3.0	1	Construction	Highland	08/05/15	

RefID	Wind farm	Site Name	Installed MW	Turbine MW	Turbines	Status	County	Construction	Operational
4,211	Pearie Law	Pearie Law Wind Farm	19.2	3.2	6	Construction	Lothian	15/09/15	
4,179	Quixwood	Quixwood Moor	29.9	2.3	13	Construction	Borders	06/01/16	
4,441	Sanquhar	Sanquhar Community Windfarm	54.4	3.4	16	Construction	Dumfries & Galloway	15/05/15	
4,263	Tormywheel	Tormywheel	39.0	2.6	15	Construction	Lothian	07/12/15	

Appendix 8.2. Cross tabulation of tag records against wind farm. The main part of the table refers to land within 500 m of a turbine. All wind farms (includes those under-construction) and all records. Note the table is split into two sections.

TAG	Aberchalder	Achany	AChruach	Allt Dearg	An Suidhe	Ark Hill	Arnish Moor	Beinn Ghlas	Beinn Ghrideag	Beinneun	Ben Aketil	Berryburn	Bhlaraidh	BraesofDoune	Calliachar	Carraig Ghael	ClachanFlats	Clashindaroch	Clyde	Corriegarth	Corriemollie	Cruach Mhor	Crystal Rig	Dunmaglass	Edinbane	Fairburn	Glenkerie	Griffin	Harestanes	Hill of Towie
100					54			5								21	3					7								
101														1	1													6		
583																	8													
584			2	4	5											6						2								
809	1																			7										
21197	2											13								2				5						
32857	1											2									1			1						
57106										1			15							16				1						
57107	7												15							27				8						
57109																				3										
57111																				6				2						
57115												2						2												
57124																				3										
75382																														
82167																														
82169																3														
84133																				22				10						
84134																					6									
84135																			24				1				1		6	
89251																				9				11						
89254																				2				1						
89286												2								17				9						
93437															1															
95065																														
107133														2						1										
107135						1																								
107140													1							1				2						
107143																								22						

TAG	**Aberchalder**	**Achany**	**AChruach**	**Allt Dearg**	**An Suidhe**	**Ark Hill**	**Arnish Moor**	**Beinn Ghlas**	**Beinn Ghrideag**	**Beinneun**	**Ben Aketil**	**Berryburn**	**Bhlaraidh**	**BraesofDoune**	**Calliachar**	**Carraig Ghael**	**ClachanFlats**	**Clashindaroch**	**Clyde**	**Corriegarth**	**Corriemollie**	**Cruach Mhor**	**Crystal Rig**	**Dunmaglass**	**Edinbane**	**Fairburn**	**Glenkerie**	**Griffin**	**Harestanes**	**Hill of Towie**
107144										3			2											8						
119986																				1	2									
119987			1	1	1			2																						
119988		3								1			4							10				1						
120196														2																
129001											1														2					
129006							3		1																					
129007																								2						
129008																									1					
129010	2																			1				7						
129012										1																				
148632																														
148634													1											3		3				
148635																								1						
148640												1												1						
148641																								1						
286611												1												18						1
719304			1																											
821661				4																										
841261																														
892821													1								1									
1199852									1																					
ALL	**13**	**3**	**4**	**9**	**60**	**1**	**3**	**7**	**2**	**6**	**1**	**21**	**39**	**5**	**2**	**30**	**11**	**2**	**24**	**128**	**10**	**9**	**1**	**114**	**3**	**3**	**1**	**6**	**6**	**1**
%	2	0	1	1	10	0	0	1	0	1	0	3	6	1	0	5	2	0	4	21	2	1	0	19	0	0	0	1	1	0

TAG	Klldrummy	LochLuichart	MidHill	Moy	Neilston	PaulsHill	Pentland Road	Strathy North	Whitelees	All	Within 150m	Within 250m
100										90	10	20
101										8	3	3
583				1	1				3	13		1
584	11									30	3	9
809										8	3	5
21197	5			4						31	8	20
32857				1		1				7		1
57106										33	2	12
57107								3		60	5	23
57109										3		2
57111										8	2	2
57115	11		1							16	2	4
57124										3	1	1
75382			1							1		
82167	1			1						2		2
82169										3	1	1
84133		1								33	2	9
84134										6		3
84135										32	4	14
89251				19						39	5	20
89254										3	1	1
89286										28	11	17
93437										1		1
95065	2									2		
107133										3	1	2
107135										1		1
107140										4		
107143										22	3	9
107144										13	4	6
119986										3		
119987										5	2	2
119988										19		6
120196										2		
129001										3		
129006							12			16		2
129007										2		
129008										1		1
129010										10		3
129012										1		1
148632						1				1		
148634										7	1	2
148635										1		
148640										2		1
148641										1		
286611										20	5	15
719304										1		1
821661										4	1	2
841261			2							2		
892821										2	1	1
1199852							3			4		
ALL	**30**	**1**	**4**	**26**	**1**	**2**	**15**	**3**	**3**	**610**	**81**	**226**
%	5	0	1	4	0	0	2	0	0			

Appendix 8.3. Cross tabulation of tag records against wind farm. Records were excluded if the record date was earlier than the wind farm's operational date.

	Within 150m									Within 250m												
Tag ID	AChruach	Allt Dearg	Berryburn	Carraig Ghael	Clyde	Harestanes	KIldrummy	Moy	Total	Aberchalder	AChruach	Allt Dearg	Beinn Ghrideag	Berryburn	Calliachar	Carraig Ghael	Clyde	Harestanes	KIldrummy	Moy	Strathy North	Total
21197			2				1	2	5	1				10					1	4		16
32857			0					0	0	0				1						0		1
57107									0	1											2	3
57115			2				0		2					2					2			4
75382									0													0
82167							0	0	0										1	1		2
82169				1					1							1						1
84133									0													0
84135					1	2			3								9	3				12
89251								3	3											11		11
89286			0						0					1								1
93437									0						1							1
95065							0		0										0			0
119987	1								1		1											1
129006									0				0									0
286611			1						1					1								1
719304	0								0		1											1
821661		1							1			2										2
841261									0													0
All	1	1	5	1	1	2	1	5	17	2	2	2	0	15	1	1	9	3	4	16	2	57

	Within 500m															
Tag ID	**Aberchalder**	**AChruach**	**Allt Dearg**	**Beinn Ghrideag**	**Berryburn**	**Calliachar**	**Carraig Ghael**	**Clashindaroch**	**Clyde**	**Harestanes**	**Hill of Towie**	**KIldrummy**	**LochLuichart**	**MidHill**	**Moy**	**Strathy North**	**Total**
21197	2				13							5			4		24
32857	1				2										1		4
57107	7															3	10
57115					2			2				11		1			16
75382														1			1
82167												1			1		2
82169							3										3
84133													1				1
84135									23	6							29
89251															19		19
89286					2												2
93437						1											1
95065												2					2
119987		1															1
129006				1													1
286611					1						1						2
719304		1															1
821661			4														4
841261														2			2
All	10	2	4	1	20	1	3	2	23	6	1	19	1	4	25	3	125

9. LAST FIXES OF TAGS AND PERSECUTION RECORDS

9.1 Summary

- Persecution can cause substantial reductions in many bird of prey populations, especially in areas of game bird management, as revealed by numerous published UK studies.
- Previous research has indicated that persecution, largely through the killing of birds, was a major constraint on the Scottish golden eagle population in those several regions of Scotland where driven grouse moor predominated as the major land use.
- Elsewhere in this report we found several lines of evidence that the primary cause of the stopped no malfunction tag fate was due to human intervention. A reasonable working hypothesis was that this intervention was due to persecution. This hypothesis predicted that the final fixes of the stopped no malfunction tags should be closer to known contemporaneous locations of persecution events than other tags' final fixes where no suspicion was apparent.
- The objective of this report section was to investigate this prediction.
- Overall, the final fixes of tags which stopped working suddenly with no malfunction were significantly more likely to be closer to contemporary records of persecution events than were the final fixes of other tags which were not suspicious (which excluded tags classed as the bird having been killed). The final fixes of two 'non-suspicious' tag classes did not differ from each other but both were significantly further away from persecution records than were the stopped no malfunction tags' final fixes.
- These results added to other conclusions that the stopped no malfunction tag fates were 'suspicious', and that the locations where these tags last transmitted were significantly closer to contemporary records of persecution than expected from non-suspicious tag final fixes.
- We conclude that the final fixes of the many stopped no malfunction tags were significantly associated with known persecution and that their sudden demise (and the birds carrying them) was due in large part to people killing the tagged bird (and these people disposing of the bird and its tag subsequently).
- Reference to other findings of the present report would suggest largely that the perpetrators of such persecution probably undertook the illegal killing of tagged eagles on <u>some</u> grouse moors, especially in the central and eastern Highlands of Scotland.

9.2 Introduction

Several previous studies have repeatedly shown that persecution in modern times can seriously reduce bird of prey populations in the UK, and most studies point to game bird management (notably driven grouse shooting) as the primary source of such persecution (Marquiss & Newton 1982, Etheridge *et al*. 1997, Green & Etheridge 1999, Hardey *et al*. 2003, Marquiss et al. 2003, Whitfield *et al*. 2008b, Whitfield & Fielding 2009, Smart *et al*. 2010, Fielding *et al*. 2011, Amar *et al*. 2012, Watson 2013, North East Raptor Study Group 2015, Rebecca *et al*. 2016, Sansom *et al*. 2016). The large majority (86 %, n = 49; 1994 - 2014) of convictions for offences linked to bird of prey persecution have involved gamekeepers as an occupation (RSPB 2015). In the uplands of Scotland illegal use of poisons was significantly more likely to occur on land managed for driven grouse shooting than on land used for other purposes (Whitfield *et al*. 2003).

Considerable additional research on Scottish golden eagles has indicated that persecution (predominantly killing of birds), mostly on moors managed for driven grouse shooting, had an adverse effect on this species' demography and was a severe constraint on its conservation status in those regions of Scotland where this land management (with associated persecution) was predominant (Whitfield *et al*. 2004a, b, 2006, 2007, 2008). A failure to meet favourable conservation status in several regions of central and eastern

Scotland was largely attributed to birds being killed where grouse moor management occurred (Whitfield *et al*. 2006, 2008a).

Elsewhere in this report we have found several lines of evidence which pointed to the primary cause of the stopped no malfunction tag fate to be due to human intervention. Given the wealth of previous research (notably for golden eagle: Whitfield *et al*. 2004a, b, 2006, 2007, 2008), and the absence of any indication that this intervention was associated with wind farms (section 8), it was a reasonable working hypothesis that this human intervention was due to persecution. This hypothesis would predict that the final fixes of the stopped no malfunction tags should be closer to contemporaneous locations of persecution events than other tags' final fixes where no suspicion was apparent.

The objective of this section was to investigate if there was a greater spatial coincidence between the final fixes of stopped no malfunction tags and contemporaneous locations of persecution events (poisoning and non-poisoning) than for the final fixes of other tags whose last fixes were explicable and not suspicious.

9.3 Methods

9.3.1 Tag data

We used all data on the final fix locations for young satellite tagged golden eagles (see section 2). Tags were re-cast into three classes:

1. Stop No Malfunction – as described earlier these were tags which had suddenly stopped transmitting, with no prior warning of failure, and where the bird and/or its tag had not been discovered when the final fix location and its environs had been searched later.
2. Stop Other – tags where it was discovered that the bird had died naturally, or which had stopped transmitting because the tag had malfunctioned, or had become unattached from the bird. Tags from birds which had been killed were excluded.
3. Still Track – final locations of birds which were still transmitting at the cut-off time (15 January 2017) for incoming data to be used in analyses.

Hence, for the Stop Other and Still Track tags their final locations were not potentially 'suspicious' and were readily explicable, and none of these tagged birds were considered to have been killed. We used last fix locations because the analysis (see later) which contrasted the tag data was underpinned by particular locations (persecution events).

9.3.2 Persecution data

Data on locations of persecution records were requested and received for a period coincidental with golden eagle satellite tagging efforts (i.e. 2004 – 2016). Data were divided between 'poisoning' persecution records and 'non-poisoning' persecution records.

Poisoning data included only records of "Abuse" as defined by a SASA[10] post-mortem where testing through chemical residue analysis had confirmed the illegal use of a poison in a victim and/or bait. Only records with a SASA reference number were used and no records of "Misuse" were used. We included all records where there was a victim, regardless of species, since the presence of a victim indicated the possibility that a bird of prey could have been vulnerable too. Similarly, we also included records of poisoned baits since these too

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[10] Science & Advice for Scottish Agriculture: a Division of the Scottish Government Agriculture, Food and Rural Communities Directorate. https://www.sasa.gov.uk/wildlife-environment/wildlife-crime

had the potential to kill a bird of prey[11]. We screened the data before analysis for any duplication of records at the same time and place to exclude multiple victims and/or baits. For example, if several poisoned victims and poisoned bait were found at the same location on the same date we classed this as only a single record. We also excluded any records where the spatial resolution was only a two-fig grid reference on the basis that such a resolution was too coarse.

Non-poisoning data involved records of other types of crimes against birds of prey, including a bird being shot, a bird caught by an illegal trap, presence of an illegal trap, nest destruction and illegal disturbance. All data were vetted by Police Scotland's National Wildlife Crime Unit (NWCU), typically involved a confirmed offence and/or a resultant prosecution, and for recent years were the basis for persecution maps produced by PAWS (Partnership for Action against Wildlife crime Scotland http://www.gov.scot/Topics/Environment/Wildlife-Habitats/paw-scotland/types-of-crime/crimes-against-birds/Poisoninghotspotmaps. As for the poisoning data, any records which involved several victims or traps at the same time and location were treated as a single record.

Only a fraction of actual persecution events are likely to have been found and reported, given that criminality was involved and the areas are often remote and seldom visited. For example, even staged experimental trials for searcher efficiency in discovering carcasses within plots of tens of metres-squared show that dedicated searchers do not find them all (e.g. Ponce *et al*. 2010, Stevens *et al*. 2011). Comparable 'search areas' for 'detecting' persecution-related carcasses involve many hundreds of metres-squared, without dedicated searchers, against a background of active concealment or removal of carcasses or associated evidence.

9.3.3 Spatial relationships

All grid references of persecution data were entered into a GIS along with the grid references of the three classes of tag final fixes. For each of the three classes of tag fate we extracted the distance value between a tag's final fix and the first, second and third nearest neighbouring persecution record (poisoning only, non-poisoning only, or any persecution record). We used three different nearest neighbour distances (1st, 2nd and 3rd nearest neighbour distances: NNDs) because these represented three (increasing) spatial scales and avoided any possible small-scale anomalies which may result from using only 1st NND.

Kruskall-Wallis tests were used to test the differences between the 1st, 2nd and 3rd NNDs for the last fix locations of all three tag fates (Stop No Malfunction, Stop Other and Still Tracking) and non-poisoning persecution record, poisoning record, and any persecution record (non-poisoning and poisoning combined).

9.4 Results

Median nearest neighbour distances (NNDs) of last fixes for the Stop No Malfunction tags were invariably and often substantially closer to a persecution record than were the other two tag fate classes (Table 9.1). For example, on average the last fix of a Stop No Malfunction tag was about 6 km from the nearest persecution event. In all Kruskall-Wallis tests there were significant differences between the three tag fate classes and their distances to the closest, second closest and third closest nearest non-poisoning persecution record, poisoning record, and any persecution record (non-poisoning and poisoning combined) (Table 9.1).

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[11] See also the same practice used by PAW Scotland: http://www.gov.scot/Topics/Environment/Wildlife-Habitats/paw-scotland/types-of-crime/crimes-against-birds/Poisoninghotspotmaps

Table 9.1. Median values (km) for 1st, 2nd and 3rd nearest neighbour distance (NND) from last fix locations for three tag fate classes (Stop No Malfunction = Stop NM; Stop Other; and Still Track) to a non-poisoning persecution location, a poisoning location, and any persecution location (= Any: non-poisoning and poisoning locations combined). Also shown are statistics from Kruskall-Wallis tests (Chi squared, df, and p values).

NND	**Stop NM**	**Stop Other**	**Still Track**	**Chi squared**	**df**	**p**
Non-poisoning						
1st	8.3	13.4	13.4	10.937	2	0.004
2nd	10.3	21.5	18.6	13.628	2	0.001
3rd	13.5	39.4	24.4	18.298	2	0.0001
Poisoning						
1st	7.0	19.7	14.2	13.252	2	0.001
2nd	9.7	27.1	17.7	17.878	2	0.0001
3rd	11.4	29.6	23.1	14.364	2	0.0008
Any						
1st	5.7	10.1	8.7	10.201	2	0.006
2nd	8.3	19.7	13.6	14.682	2	0.0007
3rd	11.4	28.0	20.4	14.053	2	0.0009

The consistent highly significant differences for final fixes across the three tag fate classes, so far as their spatial association with records of several forms of persecution, justified further examinations of the data. To look further into this result, pairwise multiple comparisons were conducted by Tukey and Kramer (Nemenyi) tests with Tukey-Dist approximation for independent samples using the R package PMCMR (Version 4.1) (Pohlert 2014) (Table 9.2).

Table 9.2. Tabulated summary of p values for pairwise multiple comparisons between final fixes of the three tag fate classes (Stop No Malfunction = Stop NM; Stop Other; and Still Track) and their three NNDs to persecution event locations (from Tukey and Kramer (Nemenyi) tests with Tukey-Dist approximation for independent samples).

	Stop NM vs Stop Other			**Stop NM vs Still Track**			**Stop Other vs Still Track**		
	NND 1	NND 2	NND 3	NND 1	NND 2	NND 3	NND 1	NND 2	NND 3
Poisoning	0.001	0.0001	0.001	0.026	0.005	0.007	> 0.4	> 0.4	> 0.4
Non-poisoning	0.009	0.002	0.0002	0.015	0.007	0.003	> 0.4	> 0.4	> 0.4
Any	0.006	0.001	0.001	0.064	0.010	0.013	> 0.4	> 0.4	> 0.4

Essentially, in the pairwise comparisons, there were no significant differences between the Stop Other and Still Track final fix locations in terms of their closeness (at three spatial scales) to any recorded location of any form of persecution (poisoning or non-poisoning, or both) (Table 9.1).

By contrast, the final fix locations of the Stop No Malfunction tags were highly significantly closer to a persecution record than those locations for the Stop Other tags in all nine tests: three spatial scales (1st, 2nd and 3rd NND) x three types of persecution records (poisoning, non-poisoning, and both) (Table 9.1). The final fix locations of the Stop No Malfunction tags were also significantly closer to a persecution record than those locations for the Still Track tags in eight of the nine tests for these paired comparisons: the exception being one marginally non-significant result (p = 0.064) for 1st NND to any persecution record (poisoning and non-poisoning combined (Table 9.2).

9.5 Discussion and Conclusions

The final fixes of tags which stopped working suddenly with no malfunction (Stop No Malfunction, 'snm tags') were more likely to be closer to contemporary records of persecution events than were the final fixes of other tags (which excluded tags classed as the bird having been killed).

The final fixes of Stop No Malfunction (snm) tags were those which the project brief had considered to be potentially 'suspicious'. The cessation of transmissions from the other (non-snm) two classes of tag fates were inherently explicable by way of (Stop Other tags) being known to be due to either a natural death of the tagged bird, a dropped (and recovered) tag, or an obvious prior malfunction of the tag; or (Still Track tags) that at the time of temporal censoring of data receipt for this project these birds were still alive and their tags were still transmitting data. The lack of any difference between the final fixes of these two non-suspicious classes of tags and persecution incidents serves to highlight further how the greater proximity of the final fixes of Stop No Malfunction (snm) tags to persecution events was unusual.

The greater and significant spatial coincidence between the snm final fixes and persecution records, as opposed to the final fixes of other tags, contributes to a wider conclusion that the sudden cessation of transmission from many tags on young golden eagles was substantially 'suspicious' and primarily due to human intervention. The significantly different relationship between the snm final fixes and persecution records is consistent with a hypothesis that the form of human intervention causing sudden failure of the tags was persecution i.e. people killing the tagged birds and subsequent disposal of the bird and its tag.

Sadly, these results from satellite tagged young golden eagles point to the continued and frequent killing of eagles in some parts of Scotland, with the implication, given that many likely-killed birds and their snm tags were disposed of (as well as transmissions which rapidly 'disappeared' too under the snm tag fate). This apparent disposal does not require too much stretching of the imagination to infer that the human perpetrators were well-aware of the illegality of their actions.

We have not repeated earlier analyses which showed direct associations between persecution and the management of moorland for driven grouse moors (Whitfield *et al*. 2003, 2006, 2007, 2008a). This repetition did not seem necessary, however, given the same coincidence of results that are still apparent; albeit this time, through the present report, revealed through the comparatively novel research avenue of satellite tagging. Young tagged eagles appeared more likely to be killed and disappear in areas associated with management for driven grouse moors and where there was contemporaneous evidence of persecution. Hence, since the earlier studies, another line of research on golden eagles in Scotland, which is relatively novel, continues to confirm the connection between illegal killing of eagles, illegal persecution and the management of grouse moors.

What may differ from previous research is that the problem appears to be the continued killing of golden eagles on some driven grouse moors (section 8) rather than the more widespread problems identified by earlier research (*cf* Whitfield *et al*. 2003, 2008a). We cover this in a later section (11).

10. SURVIVAL OF TAGGED BIRDS

10.1 Summary

- For large raptors, such as the golden eagle, post-fledging survival rates are particularly influential in affecting their population dynamics and conservation status.
- In this section we estimated post-fledging survival rates of tagged nestlings due to natural losses and to other causes. One ‘other cause’ was the stopped no malfunction tag fate since several lines of evidence pointed to this fate being substantially due to human intervention (humans killing the tagged bird and destroying the tag), with persecution being the most likely agent of this intervention.
- For the 131 birds entered into analyses there were 10 natural deaths, five birds killed and 41 birds with a stopped no malfunction fate.
- Estimated natural survival rates (excluding other causes) were high, with approximately 88 % of birds surviving to three years after tag deployment.
- The effect of birds being definitively killed was not statistically significant, but after about three years of tag deployment accounted for about a 9 % difference in survival rate from the natural estimate.
- As a likely cause of human-caused mortality the stopped no malfunction fate had a dramatic effect on estimated survival rates with statistically significant differences from natural estimates (and natural + killed estimates). These differences first became statistically significant at a time after tagging which equated approximately to when young tagged eagles dispersed from their parent’s territory.
- By about three years after tagging the survival rate estimate for all causes (including definitive and putative persecution) had amounted to a halving of the estimated natural survival rate (88 % natural v 44 % natural + other causes). The effect of ‘other causes’ of mortality on survival would be considerable biologically.
- Additionally, we generously assumed that 25 % of birds which had a stopped no malfunction tag fate did not die from human intervention but their tags had malfunctioned. There were still large and statistically significant effects on survival from an early age due to this residual putative interventionist cause of death.
- Our analyses were necessarily restricted by the nature of the data so far as definitive ‘fates’, including a slight degree of uncertainty on the fate of birds with no stopped malfunction tags; and by an assumption that any non-natural mortality was additive to natural (i.e. that a bird killed by a non-natural cause would not have died naturally later had it not been killed).
- It was obvious nevertheless, that human intervention had a statistically significant effect on tagged birds’ survival and, more importantly, will likely have a substantial biological effect in some areas, at least.

10.2 Introduction

For large raptors, such as the golden eagle, post-fledging survival rates before entering the breeding population are influential in affecting their population dynamics and conservation status; more so than reproductive output but less than adult survival (e.g. Whitfield *et al.* 2004a, b, 2008). Consequently, an objective of the project was to estimate through the satellite tag database ‘natural’ losses (deaths) and losses to other causes. Such comparative estimations may reveal the extent that ‘non-natural’ deaths may be having on vital survival rates (Whitfield *et al.* 2004a, b, 2008).

Many previous studies have shown that persecution of post-fledged large raptors can have adverse effects on their survival; notably, in the context of the present study, for golden eagles in Scotland (Whitfield *et al.* 2004a, b, 2007, 2008). Several lines of evidence described elsewhere in this report point to the strong likelihood that many or most of the stopped no malfunction tag fates were the result of human intervention and that persecution was most likely the agent of this intervention. The stopped no malfunction tag fate therefore gave an obvious indirect surrogate for a ‘non-natural’ cause of death likely due in large part to persecution.

The emphasis of the project through its supporting database was on eagles tagged as nestlings which then fledge and later disperse from their natal territory (Weston *et al.* 2013). Therefore, and given potential tag longevity (section 6) our examination of survival rates involved the period before birds potentially could or did settle on a breeding territory (i.e. typically at best, up to the fifth year of life: section 7), and so mostly during the years of juvenile dispersal (e.g. Weston *et al.* 2013).

The aim of this section was to estimate and contrast estimated survival rates of young tagged eagles by considering three sources of loss: natural, definitive persecution (birds killed), and probable persecution (birds with stopped no malfunction tags).

10.3 Methods

Analyses used data from all 131 tags (70GPS/GSM, 80NS, 96BTOGSM and 105GPS) fitted to golden eagles, excluding the small number of tagged adults. Each record had a ‘Days’ field which was the number of days between a bird’s first and last transmissions, with the first transmission typically being at or shortly after the nestling was tagged (birds were tagged at an age of 45 – 70 days old after hatch: e.g. Weston et al. 2013). An assigned fate of the tagged bird involved the classification described earlier (section 2). According to this classification, several tags were still transmitting (alive) at the time of data receipt for analysis (early 2017).

Three analyses were undertaken in R (R version 3.3.2) using the survminer package (Kassambara & Kosinski (2016), version 0.2.4), based on Kaplan-Meier estimates (see also Nygård *et al.* 2016) with different definitions of censored observations. Censorship definitions by analysis were as follows:

1. All tags except those associated with ‘natural deaths’ were censored. This provided ‘natural’ survival estimates.
2. As for (1) except that tags fitted to birds known to have been killed were no longer censored. Conservatively in these analyses, we did not include a ‘dropped suspicious’ tag fate as evidence of a killed bird, even though this record involved the discovery of an abandoned ‘dropped’ tag whose housing had been stabbed by a sharp instrument and whose harness had been cut cleanly by a sharp instrument. (Other studies, reasonably, have treated such findings as evidence of persecution e.g. Nygård *et al*. 2016). The difference between (1) and (2) gave a minimal definitive ‘persecution’ effect on survival.
3. As with (1) and (2) except that all ‘stopped no malfunction’ records were no longer censored. The difference between (1) and (3) gave a maximum potential ‘persecution’ effect on survival under a worst case assumption that all such stopped no malfunction tags stopped transmitting because of anthropogenic interventions due to persecution. As described elsewhere in this report, the large weight of evidence has pointed to the stopped no malfunction tag fate being largely due to an anthropogenic intervention, with persecution substantially the primary candidate for such intervention.

Given the possibility that some stopped no malfunction tags may actually have malfunctioned (although see section 6: ‘Tag Reliability’), in an additional analysis the status of ten of the 41 stopped no malfunction (snm) tags was randomly converted to a stop malfunction (sm) status to investigate how possible misidentification of 25 % of the snm cases influenced the survival estimates. We chose the value of 25 % as being a generous (if unlikely) upper limit for such misclassification based on data from other researchers' experience (section 6: 'Tag Reliability').

This change from a snm to sm status meant that a tag was censored for the survival analysis. This additional analysis was therefore an extension to Analysis 3 in that the natural deaths and killed birds were included but not subject to a possible conversion to sm status. The conversion scenario was repeated 1,000 times using a random sampling of the relevant tag IDs. A survival model was estimated for each sample and the survival probabilities for each Tagged Day retained. After 1,000 random samples the median survival probabilities and upper and lower 95% CL were calculated for each day.

10.4 Results

There were 10 natural deaths, five birds killed and 41 birds with a stopped no malfunction fate.

Detailed tabulated and graphical outputs from Analysis 1, 2 and 3 are provided at the end of this section for readers interested in all output values (Appendix 10A).

Estimated survival rates and associated statistics from Analysis 1, 2 and 3 after approximately the first and third years (three years accumulated not per annum) following tag deployment are presented in Table 10.1. The full results across time since tagging are illustrated in Figure 10.1.

Table 10.1. Survival probabilities (and upper and lower 95 % CLs) under the three Analyses up to one year after tagging after approximately three years (1064 days) after tagging.

Analysis	**Survival to 1 year after tagging**			**Survival to 3 year after tagging**		
	Probability	**LCL**	**UCL**	**Probability**	**LCL**	**UCL**
1 Natural	0.95	0.908	0.991	0.88	0.785	0.985
2 Natural + killed	0.93	0.879	0.978	0.79	0.684	0.915
3 Natural + killed +snm	0.77	0.700	0.853	0.44	0.344	0.565

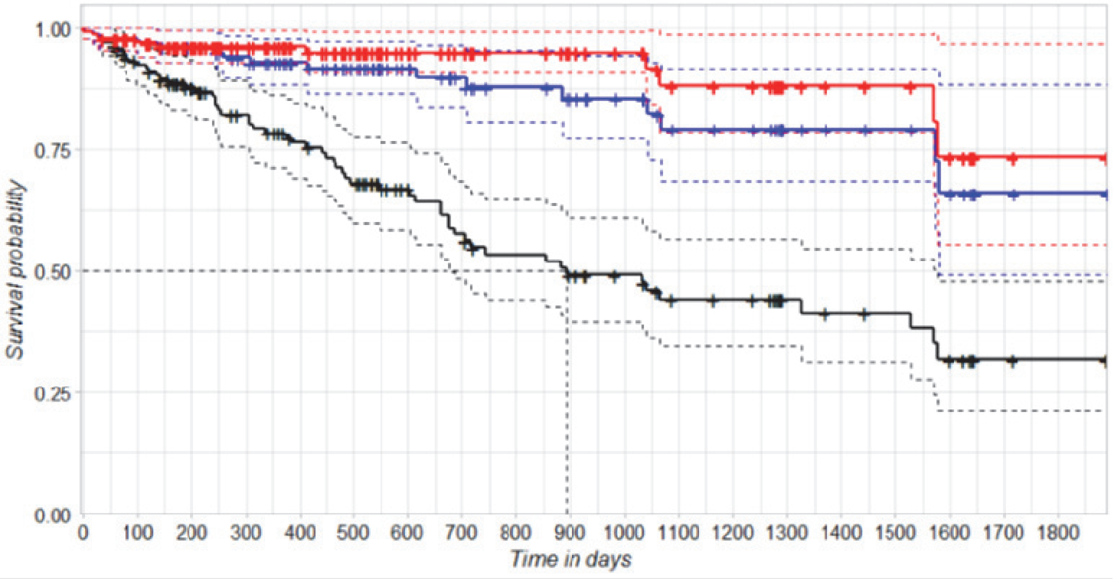


Figure 10.1. A comparison of the survival probability curves (with dotted 95 % CLs) for Analysis 1 (natural deaths only: ***red****), Analysis 2 (natural + killed:* ***blue****) and Analysis 3 (natural + killed + snm:* ***black****) produced using the survminer package (Kassambara & Kosinski 2016). Plus (+) symbols indicate censored events (birds that were still alive on that day). As in all such Kaplan-Meier plots in this report, the plot shows cumulative survival probability (y) with age (x) such that, for example, under Analysis 3 (****black****) by around 900 days after tag deployment 50 % of birds had 'died'. In this example the median value (at 50 %: 0.50 on y axis) for overall survival probability could be calculated under Analysis 3, but could not for Analysis 1 (****red****) or Analysis 2 (****blue****) because the survival probability at 0.50 (y axis) extended beyond the limits of available temporal data (x axis).*

There were no significant differences between Analysis 1 (natural only) and Analysis 2 (natural & killed), which is not too surprising given the number of killed birds which were discovered. By three years after tagging, however, the effect of some birds being killed had produced a discernible biological effect on survival probability (88 % survival v 79 % survival).

The stopped no malfunction fate had a dramatic effect on estimated survival rates with statistically significant differences from natural estimates (and natural + killed estimates) (Table 10.1 and Figure 10.1). The effect of assuming snm tags represented birds which had died through intervention was marked, with a survival rate (including definitive persecution), after about three years from deployment which was half that of the natural only estimate (88 % natural v 44 % natural & other causes). The statistically significant influence of the putative interventionist mortality cause, represented by the snm tag fates, became apparent relatively early after tags were deployed (around 8 months: see Figure 10.1 and tabulated results in Appendix 10A).

As expected, censoring ten of the snm tags to be malfunctioned tags increased the survival estimates. However, even if 25% of the snm tags were misclassified there remained a statistically significant difference in survival compared to that estimated for natural deaths and known killed birds (Figure 10.2).

10.5 Discussion

Known and putative effects of persecution patently had a major statistical and biological effect on tagged eagles' survival, even after we had generously assumed that a quarter of the birds with a snm tag fate were still alive and their tag had actually malfunctioned.

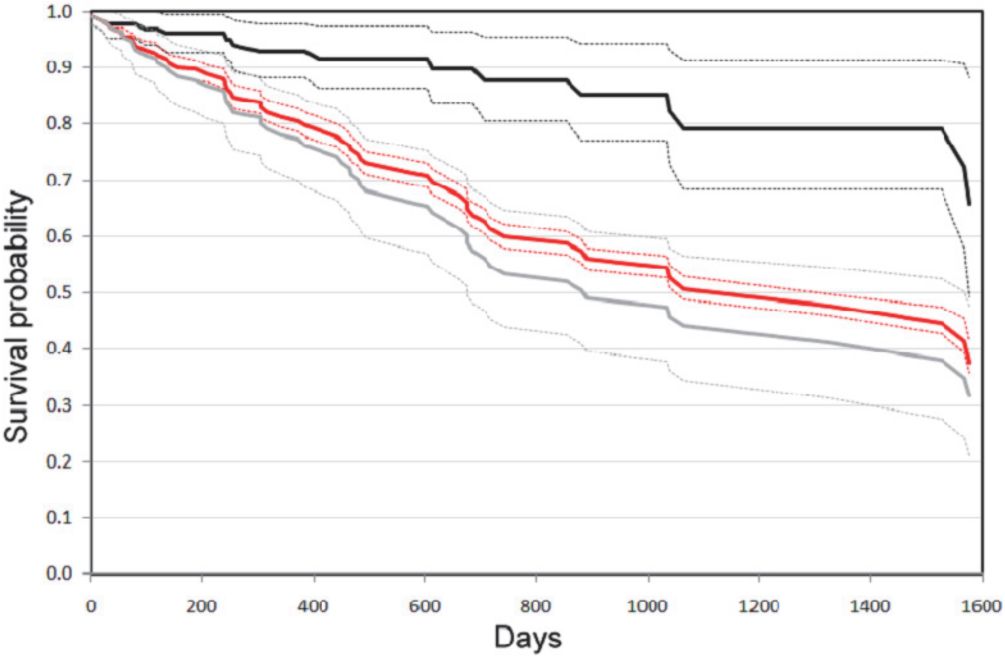


Figure 10.2. Survival probabilities (solid lines) with 95% CL (faded lines) for three analytical scenarios. The black line is the data from Analysis 2 (natural deaths and killed birds). The grey line is the data from Analysis 3 in which all 'stopped no malfunction' records were not censored. The red line is as Analysis 3 except that 10 snm tags were randomly censored in each of 1,000 simulations

It was interesting that when the known and putative influences of persecution first came into play on statistically significant effects these differences first became apparent at a time after tagging which equated approximately to the time around when many young tagged eagles had dispersed from the security of their parent's territory (Weston *et al.* 2013).

Our analyses were necessarily restricted by the nature of the data so far as definitive 'fates', including a slight degree of uncertainty on the fate of birds with no stopped malfunction tags, and by an assumption (see Chevallier *et al.* 2015) that any non-natural mortality was additive to natural (i.e. that a bird killed by a non-natural cause would not have died naturally later had it not been killed). This assumption, of the various causes being additive, was most likely to have been disrupted, so far as true natural survival rates, by the substantial numbers of birds which were taken out of otherwise natural survival estimates by direct or putative human intervention.

The 'natural' survival rates we estimated, therefore, may well be slightly lower in reality because we assumed that they were additive to other causes, and the stopped no malfunction tag fate (probably mostly due to birds being killed) was so frequent it was likely that if some of these birds had not been killed then they would have died later from other natural causes. Nevertheless, much natural mortality of young eagles (as in many other raptors and other birds) occurs in the months after fledging and dispersing (e.g. Newton 1979, USFWS 2016, Newton *et al*. 2016). This much was confirmed by the timing of recorded natural deaths in the tagged Scottish sample. The trait of several young eagles in Scotland to stay on their parents' (natal) territory for many months before dispersing (Weston

2014, Weston *et al*. 2013) may have indirectly saved several from a fate of illegal killing and during a period when mortality would be greatest. So, having overcome an early greatest chance of natural death these birds may well have survived after passing through the temporal phase when illegal killing mostly occurred.

While sample sizes of natural deaths were small in our sample there was a hint that natural mortality may have had a further smaller ‘spike’ at the time when young eagles were of an age in attempting to establish or takeover a breeding territory, when physical conflicts may have occurred (see also Haller 1982, 1994). Anecdotally, one dead tagged eagle was discovered with signs of such conflict at the appropriate age. Such natural deaths were therefore less likely to be recorded because many birds were apparently illegally killed before they could occur. It is also worth noting, on the other hand, that despite the potential compensatory form of illegal killing on natural survival rates, and intrinsic manufactured tag longevity being at its predicted limit for such birds reaching breeding age (section 6, Tag Reliability) several tagged birds were recorded as entering the breeding population (section 6, Tag Reliability).

Hence, even allowing for the possibility of non-additive (compensatory) mortality caused by illegal killing, we venture that such a possibility did not have too much influence on the estimated ‘natural’ survival rates. And as described elsewhere (section 6, Tag Reliability) these rates were higher than estimated by several other studies, whether by tagging or non-tagging research methods. They were higher than assumed by Whitfield *et al*. (2006, 2008a), notably.

Consequently, it was obvious that human intervention had a statistically significant effect on tagged birds’ survival and, more importantly, will have had a substantial biological effect (e.g. Whitfield *et al.* 2008a) given the apparent high level of intervention (survival to around 3 years after tag deployment: 88 % natural v 44 % natural & other causes). This dramatic effect which the ‘non-natural’ anthropogenic sources of mortality will have had on young tagged birds’ survival will not have been spread evenly across Scotland, because its influence was concentrated on some grouse moors and where there was contemporaneous other evidence of persecution. Not all tagged eagles, or all young Scottish eagles, will have been equally exposed to this illegal persecution. We explore the population consequences of this, in the following section.

Appendix 10.1. Tables and graphical outputs from Analysis 1, 2 and 3

Analysis 1: There were 10 natural deaths (0, 19, 28, 98, 136, 410, 1040, 1064, 1569 and 1578 days after tag deployment). A median survival period could not be calculated because there were few deaths.

Analysis 2: There were 10 natural deaths (as in Analysis 1) plus five killed (244, 305, 613, 707 and 882 days after tag deployment). A median survival period could not be calculated because there were insufficient deaths.

Analysis 3: There were 10 natural deaths plus five killed (as in Analysis 1 and 2). There were a further 41 stopped no malfunction records (35, 57, 59, 74, 78, 81, 119, 120, 142, 157, 188, 209, 240, 244, 250, 306, 316, 338, 374, 384, 442, 450, 465, 466, 480, 485, 495, 548, 603, 660, 660, 677, 678, 686, 717, 743, 856, 891, 1034, 1326 and 1528 days after tag deployment). The median survival period was 882 days (95 % LCL 707, UCL could not be calculated).

Table 10A.1. Survival probabilities and associated descriptive statistics from a Kaplan-Meier analysis according to Analysis 1. Days is the progression of time since tagging. N.risk is the number of birds alive at the start of day N, Events is the number of deaths on day N, Survival prob. is estimated survival probability to day N plus its standard error (se) and 95% lower and upper confidence limits.

Days	N.risk	Events	Survival prob.	se	95 % LCL	95 % UCL
0	131	1	0.992	0.0076	0.978	1.000
19	130	1	0.985	0.0107	0.964	1.000
28	129	1	0.977	0.0131	0.952	1.000
98	117	1	0.969	0.0154	0.939	0.999
136	113	1	0.960	0.0175	0.927	0.995
410	73	1	0.947	0.0216	0.906	0.990
1040	28	1	0.913	0.0392	0.839	0.993
1064	26	1	0.878	0.0511	0.783	0.984
1569	12	1	0.805	0.0843	0.656	0.988
1578	11	1	0.732	0.1036	0.554	0.966

Table 10A.2. Survival probabilities and associated descriptive statistics from a Kaplan-Meier analysis according to Analysis 2. Days is the progression of time since tagging. N.risk is the number of birds alive at the start of day N, Events is the number of deaths on day N, Survival prob. is estimated survival probability to day N plus its standard error (se) and 95% lower and upper confidence limits.

Days	N.risk	Events	Survival prob.	se	95 % LCL	95 % UCL
0	131	1	0.992	0.0076	0.978	1.000
19	130	1	0.985	0.0107	0.964	1.000
28	129	1	0.977	0.0131	0.952	1.000
98	117	1	0.969	0.0154	0.939	0.999
136	113	1	0.960	0.0175	0.927	0.995
244	89	1	0.949	0.0203	0.910	0.990
254	86	1	0.938	0.0229	0.895	0.984
305	84	1	0.927	0.0252	0.879	0.978
410	73	1	0.914	0.0279	0.861	0.971
613	48	1	0.895	0.0332	0.833	0.963
707	42	1	0.874	0.0386	0.802	0.953
882	37	1	0.850	0.0442	0.768	0.942
1040	28	1	0.820	0.0520	0.724	0.929
1064	26	1	0.789	0.0588	0.681	0.913
1569	12	1	0.723	0.0829	0.577	0.905
1578	11	1	0.657	0.0980	0.491	0.880

Table 10A.3. Survival probabilities and associated descriptive statistics from a Kaplan-Meier analysis according to Analysis 3. Days is the progression of time since tagging. N.risk is the number of birds alive at the start of day N, Events is the number of deaths on day N, Survival prob. is estimated survival probability to day N plus its standard error (se) and 95% lower and upper confidence limits.

Days	N.risk	Events	Survival prob.	se	95 % LCL	95 % UCL
0	131	1	0.992	0.0076	0.978	1.000
19	130	1	0.985	0.0107	0.964	1.000
28	129	1	0.977	0.0131	0.952	1.000
35	128	1	0.969	0.0150	0.940	0.999
57	127	1	0.962	0.0167	0.930	0.995
59	125	1	0.954	0.0183	0.919	0.991
74	123	1	0.946	0.0197	0.909	0.986
78	121	1	0.939	0.0210	0.898	0.981
81	119	1	0.931	0.0223	0.888	0.975
98	117	1	0.923	0.0235	0.878	0.970
119	116	1	0.915	0.0246	0.868	0.964
120	115	1	0.907	0.0256	0.858	0.958
136	113	1	0.899	0.0266	0.848	0.953
142	112	1	0.891	0.0276	0.838	0.946
157	108	1	0.883	0.0285	0.828	0.940
188	101	1	0.874	0.0296	0.818	0.934
209	97	1	0.865	0.0306	0.807	0.927
240	90	1	0.855	0.0317	0.795	0.920
244	89	2	0.836	0.0338	0.772	0.905
250	87	1	0.826	0.0347	0.761	0.897
254	86	1	0.817	0.0356	0.750	0.890
305	84	1	0.807	0.0365	0.738	0.882
306	83	1	0.797	0.0374	0.727	0.874
316	82	1	0.788	0.0381	0.716	0.866
338	81	1	0.778	0.0389	0.705	0.858
374	76	1	0.768	0.0397	0.694	0.850
384	74	1	0.757	0.0405	0.682	0.841
410	73	1	0.747	0.0413	0.670	0.832
442	72	1	0.736	0.0420	0.659	0.823
450	71	1	0.726	0.0426	0.647	0.815
465	70	1	0.716	0.0433	0.636	0.806
466	69	1	0.705	0.0439	0.624	0.797
480	68	1	0.695	0.0444	0.613	0.788
485	67	1	0.685	0.0450	0.602	0.779
495	66	1	0.674	0.0455	0.591	0.770
548	55	1	0.662	0.0463	0.577	0.759
603	49	1	0.648	0.0472	0.562	0.748
613	48	1	0.635	0.0482	0.547	0.737
660	47	2	0.608	0.0498	0.518	0.714
677	45	1	0.594	0.0504	0.503	0.702
678	44	1	0.581	0.0511	0.489	0.690
686	43	1	0.567	0.0516	0.475	0.678
707	42	1	0.554	0.0522	0.461	0.666
717	40	1	0.540	0.0527	0.446	0.654
743	39	1	0.526	0.0531	0.432	0.641
856	38	1	0.512	0.0535	0.418	0.629
882	37	1	0.499	0.0538	0.403	0.616
891	36	1	0.485	0.0541	0.390	0.603
1034	30	1	0.469	0.0546	0.373	0.589
1040	28	1	0.452	0.0552	0.356	0.574
1064	26	1	0.434	0.0557	0.338	0.559
1326	16	1	0.407	0.0585	0.307	0.540
1528	13	1	0.376	0.0618	0.272	0.519
1569	12	1	0.345	0.0641	0.239	0.496
1578	11	1	0.313	0.0655	0.208	0.472

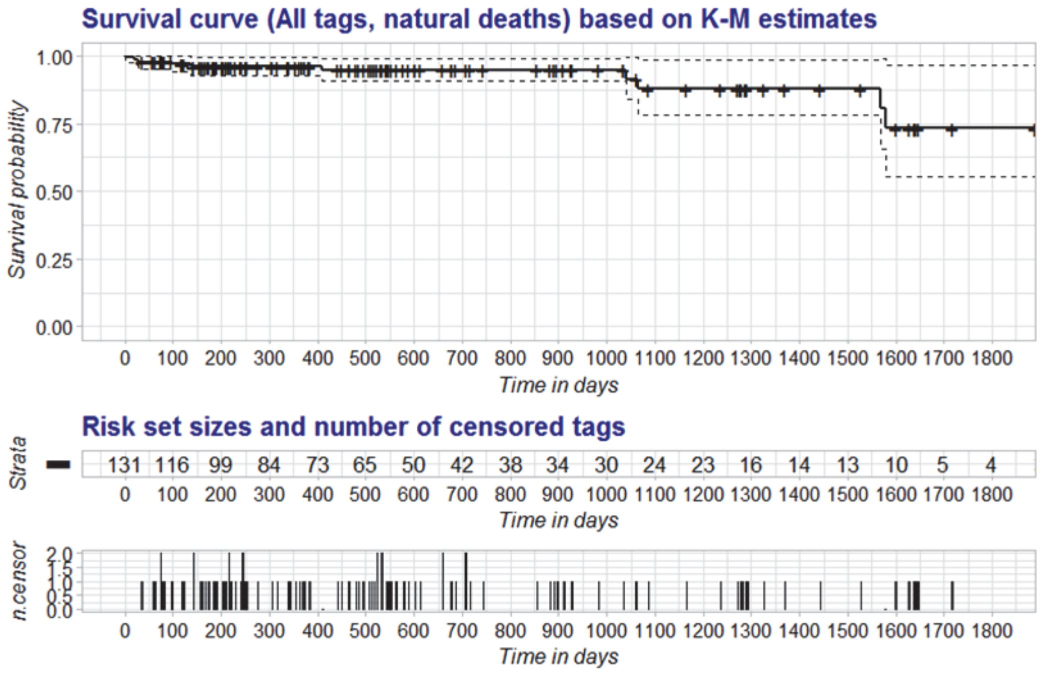


Figure 10A.1. Survival plots produced using the survminer package (Kassambara & Kosinski 2016) for Analysis 1. Upper plot is survival probability against day with dotted 95 % CLs. Plus (+) symbols indicate censored events (birds that were still alive on that day). The lower plot shows the number of birds per 100 day time block and the number of censored events per day.

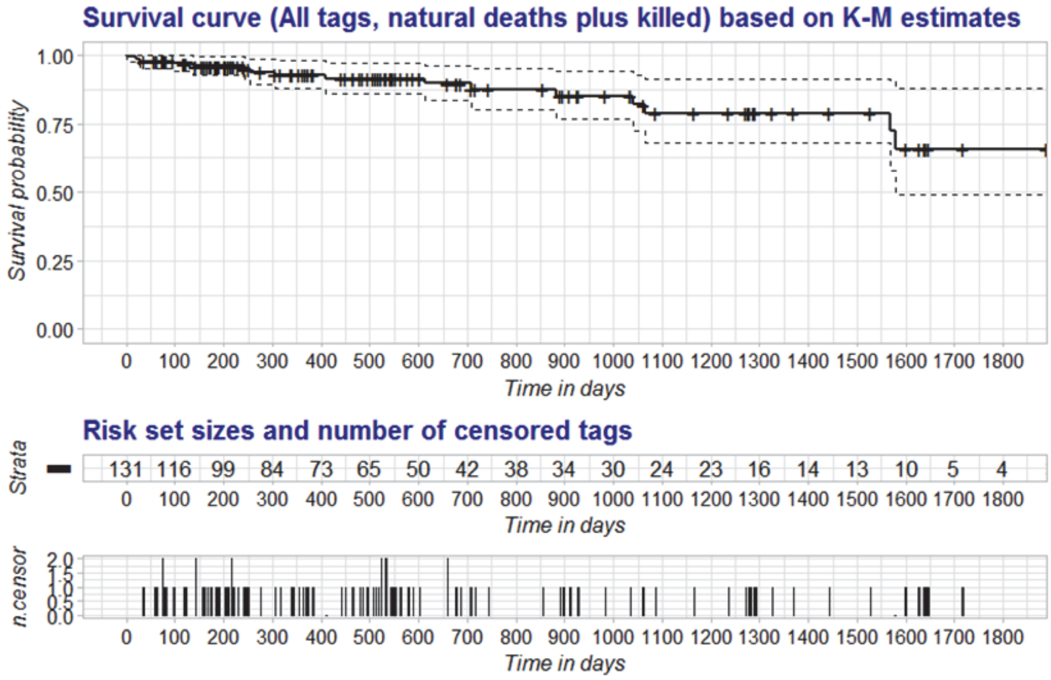


Figure 10A.2. Survival plots produced using the survminer package (Kassambara & Kosinski 2016) for Analysis 2. Upper plot is survival probability against day with dotted 95 % CLs. Plus (+) symbols indicate censored events (birds that were still alive on that day). The lower plot shows the number of birds per 100 day time block and the number of censored events per day.

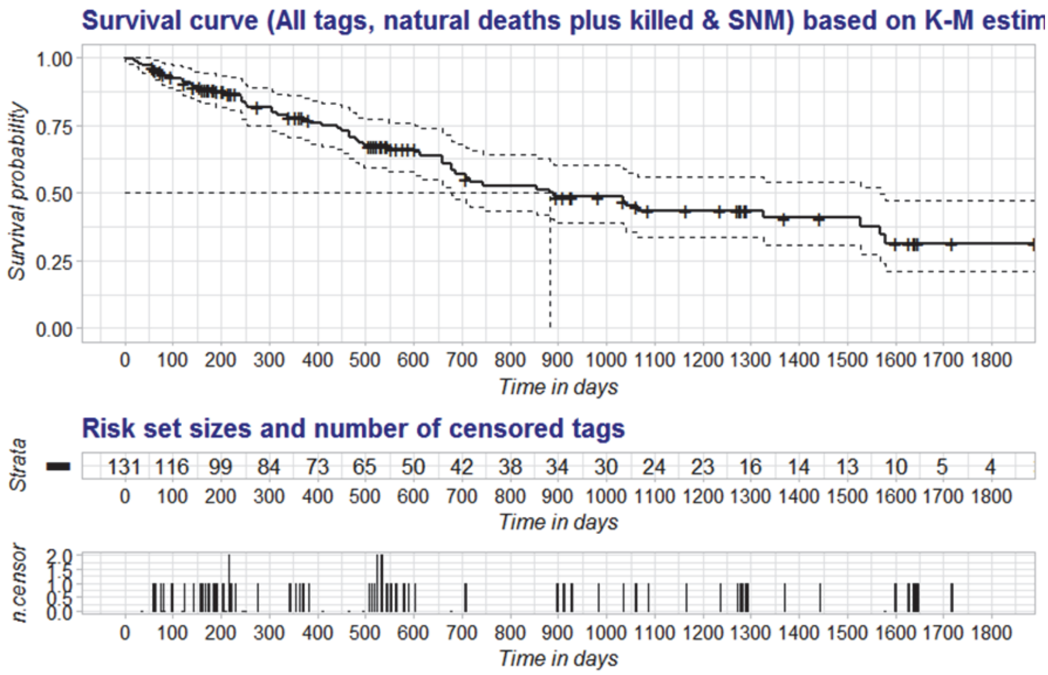


Figure 10A.3. Survival plots produced using the survminer package (Kassambara & Kosinski 2016) for Analysis 2. Upper plot is survival probability against day with dotted 95 % CLs. Plus (+) symbols indicate censored events (birds that were still alive on that day). Horizontal and vertical dotted lines give the median. The lower plot shows the number of birds per 100 day time block and the number of censored events per day.

11. POPULATION MODELLING

11.1 Summary

- It was apparent from previous sections that satellite tagging of young golden eagles has revealed that many young birds have probably been illegally killed in some parts of Scotland between 2004 and 2016: largely in the central and eastern Highlands.
- Such illegal killing will potentially have had consequences for the future golden eagle population trajectory within mainland Scotland; especially in those regions of Scotland where such killing continues to occur; many decades after such acts became illegal.
- Our analyses were preliminary but illustrative, given that much further information will be available in the near future, and concentrated on the population consequences revealed by the project's novel estimations of 'natural' survival rates on young (≤ 4 y old) eagles, and the influence on these rates through young eagles being killed (known and suspected).
- The modelling showed that with the estimated 'natural' survival rates of young (up to 4 y old) even with relatively low productivity and relatively low adult (4 +) survival rates, a Scottish golden eagle population was expected to grow and that there was a high probability of this outcome.
- By contrast, the survival rates of young eagles, even after accounting for varying assumptions around the extent of the illegal killing involved in the stopped no malfunction tags showed that any prospect for a stable or increasing population became increasingly reliant on relatively high reproductive output and high adult (4+) survival; and greater uncertainty in the probability of such an outcome, as reliance on such high values of other demographically vital rates increased.
- We expect that since the 2003 National Survey of golden eagles many regions of Scotland away from the continued depressive effect of illegal killing of dispersing young birds will have seen further evidence of population expansion, or continued stability.
- We also expect that there may have been some recovery in some parts of the central and eastern Highland regions where the species' conservation status was previously unfavourable due largely to illegal persecution. These regions, however, still yield evidence of continued illegal persecution in parts, and so we would not expect recovery to the full capability of breeding birds being evident.
- Overall, our analyses would indicate that the persecution of young eagles is continuing to suppress the golden eagle population in the central and eastern Highlands, and is still hampering overall recovery from historic, widespread persecution.

11.2 Introduction

Satellite tagging of young golden eagles has revealed that many young birds have been illegally killed in some parts of Scotland between 2004 and 2016. As alluded to earlier (e.g. section 10, Bird Survival), such illegal killing will have had consequences for the potential future golden eagle population trajectory within mainland Scotland; especially in those regions of Scotland where such killing continues to occur, many decades after such acts became illegal (Whitfield *et al*. 2004a, b, 2008a). The revelatory information from the present project was the relatively large effect that such killing had on tagged eagle survival rates, and so it is this information on a key demographic rate which this section concentrates on so far as population consequences.

We have previously shown that there was no substantial evidence that the tagging of young eagles caused the birds any harm (section 7, Potential Tag Harm). It is therefore safe to assume that the information from tagged birds is representative of a wider (untagged) population – at least broadly for those birds which had similar patterns of dispersal behaviour after leaving their natal territories in those areas where birds were tagged.

One overarching caveat may apply however, because illegal killing is not an 'unthinking' process of natural selection which could be assumed for other 'natural' ecological influences. Illegal killing involves people and human culture. This caveat would apply if a perpetrator was aware of a bird being tagged before it was killed and was also aware of the greater difficulties involved in concealing and disposing of evidence through the act of killing a tagged bird. This awareness does seems likely in at least some cases, given that perpetrators presumably knew that their actions were illegal (and when no 'stopped no malfunction' tags were retrieved after searches). As we have also noted earlier (section 8, Land Use: Wind Farms and Grouse Moors), we had no evidence of any associate of grouse moor management having reported a 'downed' tagged eagle; even though grouse moor management was implicated in several stopped no malfunction tags. It is possible therefore, that on grouse moors tagging conferred a survival advantage for a tagged bird over an untagged bird.

Consequently, untagged birds using the areas where killing was prevalent may have had even lower survival rates than tagged birds as a result of direct human behaviour. For untagged birds which did not use the areas where tagged birds were killed, we would not expect such a caveat to be relevant.

The tagging of young eagles has also revealed many other features of eagle biology and their population dynamics which was beyond the scope of the present project to document thoroughly and incorporate into population analyses. Indeed, the purpose of the tagging in the first place was to reveal such features of 'natural' eagle biology which are impossible from other research techniques. In this respect, the high level of human intervention created an obstacle to the furtherance of such research (admittedly this paled into insignificance compared to the effects on the birds themselves), as well as prematurely destroying a large number of expensive transmitters.

Tagging has revealed an estimate of age of first breeding and measures of natal dispersal distance (section 6, Tag Reliability) and the extent of connective movements between different regions of Scotland during the juvenile dispersal period (Weston 2014, section 2 Tag Metadata). This is important novel information. At the time of writing, we are also on the cusp of additional data sources becoming available and reviewed, notably data from the 2015 National Survey of golden eagles and DNA-based estimates of survival and turnover in territorial golden eagles (Natural Research unpublished data; after methods in Rudnick *et al*. 2005, 2009). Once these data are available, along with the additional data being generated by satellite tagging of young eagles, more sophisticated analyses will be possible in the near future.

In the meantime, the modelling we have undertaken in this section is illustrative only on potential effects, and directed primarily at examining the potential demographic influence revealed by human interference on the survival of young (pre-breeding) golden eagles in some areas of Scotland (section 10). The effects were investigated by examining the predicted population growth rate in relation to a combination of survival and productivity rates. The modelled values of survival and productivity were derived empirically from the bird survival analyses (section 10, Bird Survival) and additional sources e.g. Whitfield *et al*. (2008a, and references therein: see also sections 6 and 10 for additional referenced sources).

11.3 Methods

In population modelling we assumed that the sex ratio at fledging was equal and survival rates were the same for both sexes. No density dependent effects on survival or productivity were assumed.

Following from previous studies and the revelations from the Scottish tagged birds a key population metric for fledged young eagles was their survival between fledging and entry to the breeding population, at whatever age this occurred (e.g. Whitfield *et al*. 2004a, 2008a). These previous studies have taken this age as the 4th year of life, a figure confirmed by the tagged birds (section 7). The next major demographic phase is in the 4 + years period, when birds were assumed to be settled on a territory and capable of producing fledglings; and when survival rates are usually higher than earlier in life (e.g. Whitfield *et al*. 2004a, 2008a, USFWS 2016).

We derived several estimates of survival to age four (S1) from the satellite tagging data (see sections 7 and 10). We modelled 12 S1 survival rates, 10 of which were derived from the tagging data. An additional two were added to provide comparability with previous models (e.g. Whitfield *et al*. 2004a, 2008a).

The survival rate for this period (S1) varied, depending on how it was calculated according to several known or potential external effects on the tagged sample (section 10). Survival to age 4, which assumed only natural mortality (section 10), gave an estimate of 0.806 (CL 0.657-0.989). When birds known to have been killed were included, the survival rate dropped to 0.725 (95 % CL 0.580 to 0.907) (see also section 10). These estimates were based on a tag age of 1,569 days after deployment.

If all stopped no malfunction tag fates were undocumented bird deaths and additional to the known killed birds (section 10) the S1 survival rate dropped to 0.381 (95 % CL 0.277 to 0.525) after 1,528 days since deployment.

We also modelled survival rates to account for the possibility that five or more stopped no malfunction events were actually (undetected) tag malfunction events which meant that they became censored observations in the survival analysis. The mean survival rates to age 4 varied with the number of such fate-conversions (5 to 35 in increments of 5): 0.381, 0.429, 0.459, 0.491, 0.519, 0.546, 0.569, 0.584, 0.725 and 0.806. We added 0.350 and 0.400 to this list for compatibility with previous golden eagle population models (e.g. Whitfield *et al*. 2004a, 2008b).

We modelled 15 adult annual survival rates (S2) that were equivalent to 10 to 24 years of territory occupancy i.e. 0.9000 (90.00 %) to 0.9583 (95.83 %). We modelled nine productivity rates (F: females fledged per occupied territory) ranging from 0.15 to 0.50 in steps of 0.025.

In total we modelled 2,700 combinations of S1, S2 and F. For each combination of S1, S2 and F we ran 1,000 simulations with values of S1 and S2 sampled from beta distributions (see Appendix 11.1). At the end of each 1,000 simulations we calculated the mean and sd of the predicted growth rate, k, and counted how many of the values of k were greater than 1 (= population expansion).

All population modelling was undertaken in R using popbio (Stubben & Milligan. 2007, version 2.4.3).

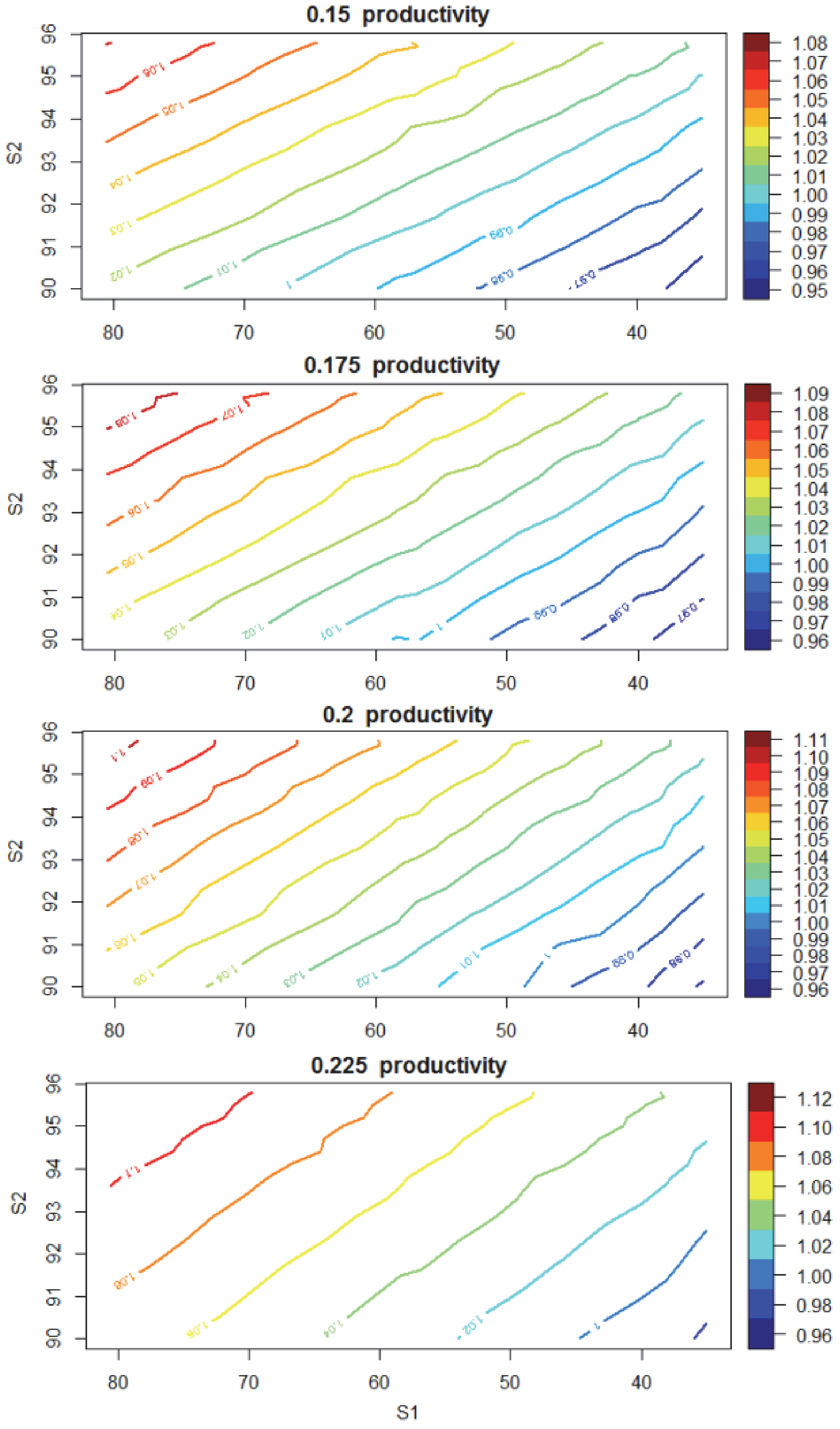
11.4 Results

The results are summarised in a series of contour plots. The population growth rate contours versus annual survival rates for seven productivity levels are shown in Figure 11.1. Plots are not shown for a productivity > 0.3 females per occupied territory because the mean growth rate was above 1 for all tested combinations of S1 and S2.

Whitfield *et al*. (2006, 2008a) suggested that productivity had to be above 0.3 (0.15 females) at the lower limits of survival to be compatible with favourable conservation status. The results presented in Figure 11.1 were consistent with that conclusion, assuming the minimum acceptable annual survival rates described by those studies.

Recalling the ‘natural’ SI rates and the varying levels of assumed ‘unnatural’ mortality affecting S1 with 0.381, or 38.1 %, as the S1 rate if all stopped no malfunction birds were killed (Methods) it was apparent that the effect of ‘unnatural mortality’ was marked with a greater necessity for a higher productivity and/or higher adult (S2) survival for the population to be stable or grow, and not decline. For the ‘natural’ S1 survival rate the capacity for the population to grow was not reliant on high productivity and even at relatively low adult (S2) survival rates the population was expected to grow.

All of the tested levels of productivity within the contours for k = 1 (population stability) are summarised in Figure 11.2. Areas to the left of the contours have values of k >1 meaning that, at the modelled productivity, any combination of S1 and S2 would allow population expansion. Conversely, in Figure 11.2 areas to the right show that at the modelled productivity the population would decline. For a productivity of 0.15 females, combinations of S1 and S2 which result in k > 1 are illustrated as a green shaded area of the plot (Figure 11.2).



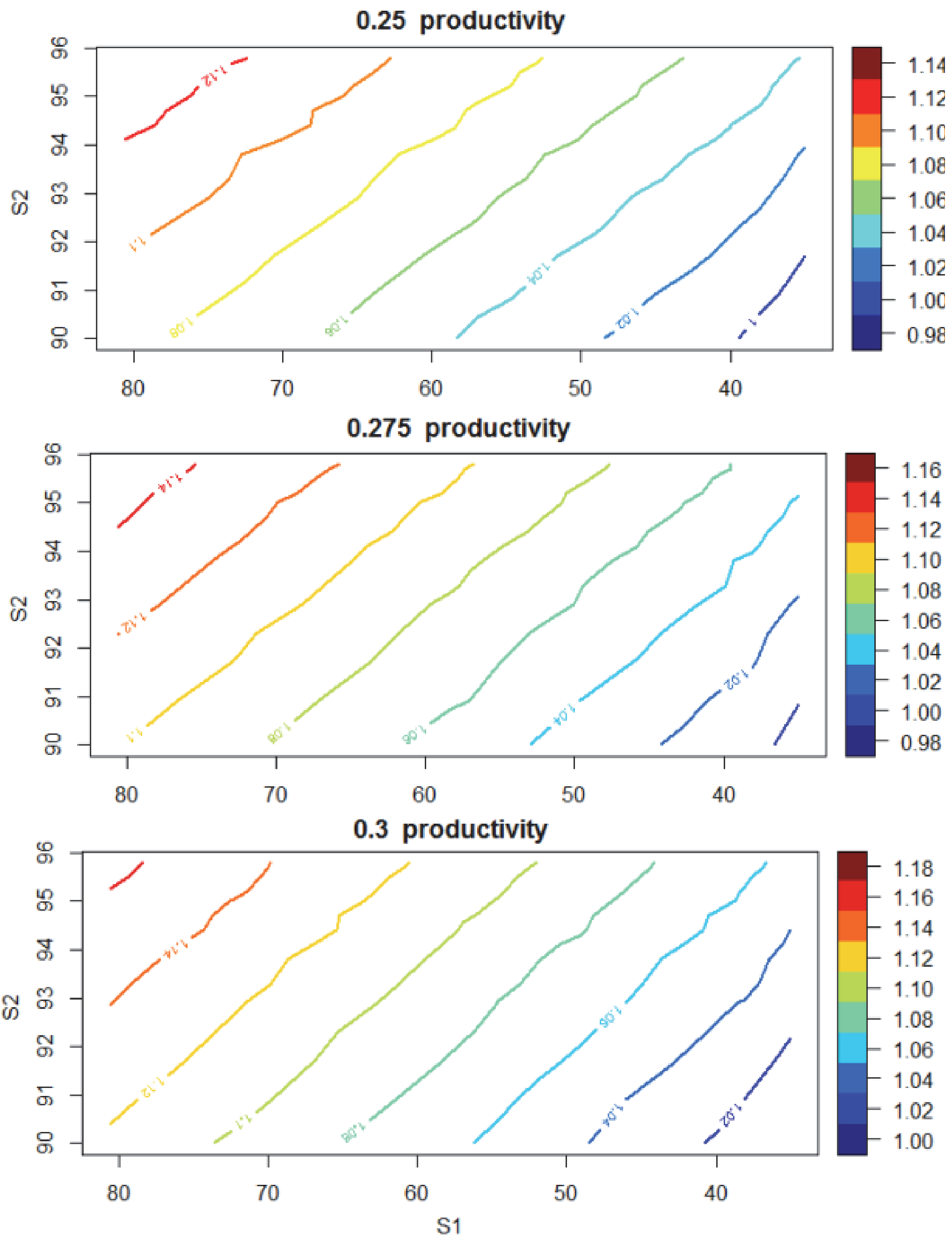


Figure 11.1. Population growth rate contours versus survival rates for seven productivity levels (female only) shown as a header above each plot. S2 (adult territorial bird survival at age 4 +) is annual, whereas S1 (pre-breeding survival after tagging) is for approximately the first four years, and values are given as percentages (e.g. S1 40 = 40 %). The colour-coded strapline on the right gives values of k (the population growth rate) with k > 1 indicating population growth. Contour maps were produced using the plot3D library (version 1.1, Soetaert, 2016).

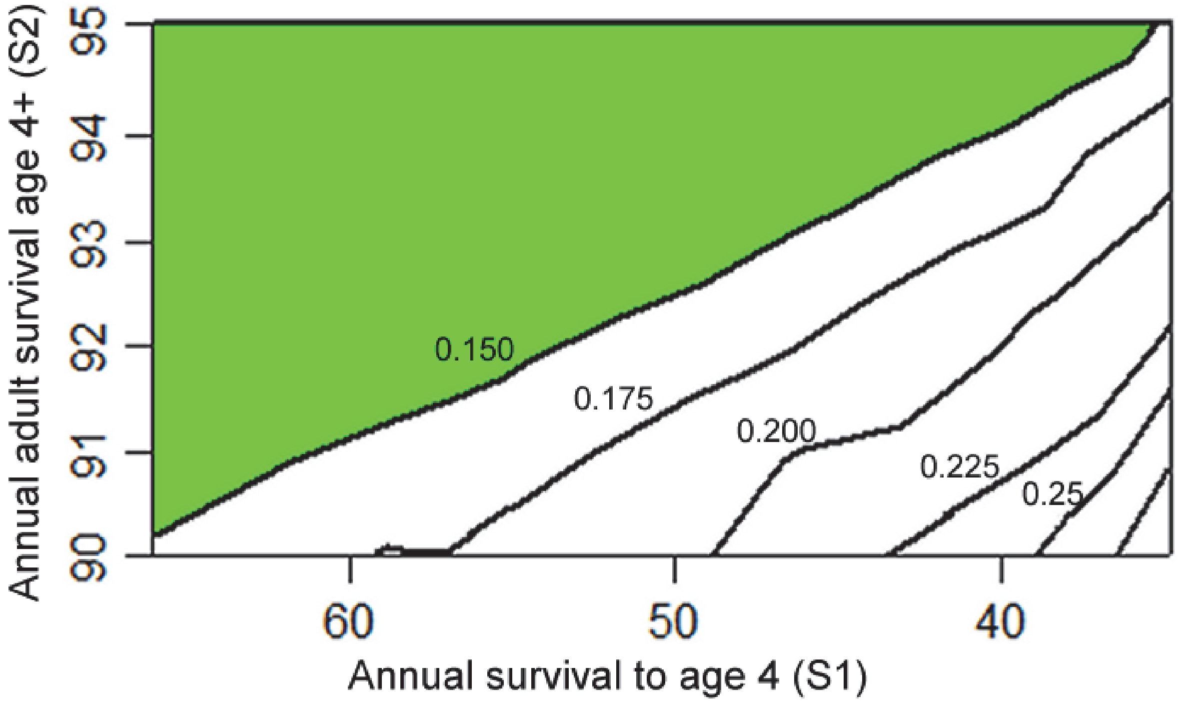


Figure 11.2. Contour lines for k =1 for different levels of modelled productivity (females fledged per occupied territory). Any combination of S1 and S2 to the left of the contour is compatible with k > 1. This is shown as the green shaded area for a productivity of 0.15. S2 (adult territorial bird survival at age 4 +) is annual, whereas S1 (pre-breeding survival after tagging) is for approximately the first four years, and values are given as percentages (e.g. S1 40 = 40 %).

A mean k of 1 (stability) as plotted (Figure 11.1 & 11.2) however, would have resulted in some simulated populations in which k was below 1. This was evaluated and the evaluation is described in Figure 11.3, where the contours were the numbers of simulations (out of 1,000) in which k was above 1.

Figure 11.3 shows that, for low levels of productivity, the chance of a population growth rate > 1 is not high even though the mean growth rate is > 1. For example, the yellow contour for a productivity of 0.15 in Figure 11.3 approximated to the location of the k = 1 contour in Figure 11.2, for the same level of productivity. However, only 600 of 1,000 simulations under these conditions resulted in a value of k > 1. So, although on average, this combination of survival rates and productivity would result in population expansion there was considerable uncertainty about this outcome.

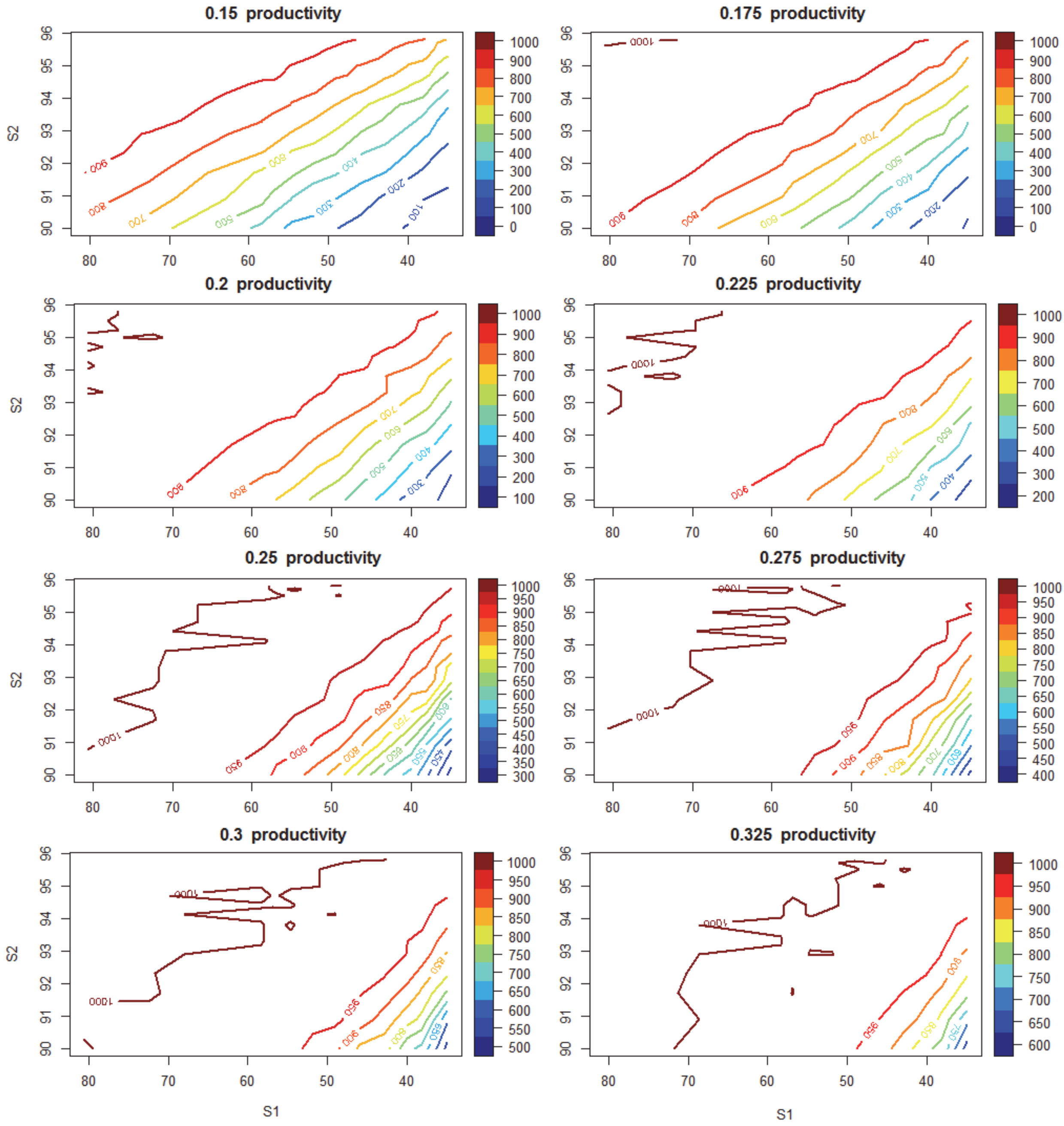


Figure 11.3. Contour lines for a count of k >1 in 1,000 modelled simulations of survivorship (S1 and S2) for different levels of productivity (females fledged per occupied territory). The colour-coded strapline on the right illustrates the number of simulations in 1,000 in which k > 1.

11.5 Discussion

The modelling showed that with the estimated 'natural' survival rates of young (up to 4 y old) even with relatively low productivity and relatively low adult (4 +) survival rates, a Scottish golden eagle population was expected to grow and that there was a high probability of this outcome. The estimated natural survival rates were unexpectedly high (see section 6 and references therein, and *cf* Whitfield et al. 2004a, 2006, 2008a).

By contrast, the survival rates of young eagles, even after accounting for varying assumptions around the extent of the illegal killing involved in the stopped no malfunction tags showed that any prospect for a stable or increasing population became increasingly reliant on relatively high reproductive output and high adult (4+) survival, and greater uncertainty in the probability of such an outcome as such reliance increased.

In the population dynamics of large raptors, as k-selected species, the most influential demographic rate on population abundance and status is the survival of breeding adults, followed by the survival of pre-breeding young birds in the years after fledging, with reproductive output being the least influential (e.g. Whitfield *et al*. 2004a, 2008a, Newton *et al*. 2016). Nonetheless, the survival of pre-breeding young birds can be critical in the long-term conservation and population status of large raptors (e.g. Penteriani *et al*. 2005, 2006, 2008).

For example, conservation efforts are typically focussed on protecting by legislative designation the relatively predictable areas occupied by breeding pairs (and so this protection can minimise adverse effects on breeding adult survival). Yet this focus is an inadequate conservation strategy in isolation because it ignores that young raptors range far and wide after dispersing and are more vulnerable to anthropogenic activities on survival; because these birds rely on areas away from protected sites (e.g. Ferrer 2001, Watson & Whitfield 2002, van Eeden 2017). Several studies have shown that while in theory adult survival may be the key demographic rate for large raptor populations, in practice the survival of young (pre-adult) birds can be the most influential rate (Penteriani *et al*. 2005, 2006, 2008).

Satellite tagging in Scotland has confirmed in detail that many young golden eagles disperse widely after leaving their natal (parents') territory (e.g. Weston 2014; and see Annex 1). One consequence of this dispersal was predicted by Whitfield *et al*. (2004b) before satellite tagging of young eagles started in Scotland. Such that, as 'killing zones' are restricted to certain areas of the wider golden eagle distributional range but that these areas coincide with rich prey availability and the absence of territorial birds, dispersing young birds originating well away from the area of illegal killing may be drawn into an 'ecological trap' (Whitfield *et al*. 2004b). In this 'trap' they may be killed well away from their natal area and before they have had a later (year(s)-hence) chance to return closer to their natal area to occupy a breeding territory through the 'pull' of natal philopatry.

There were several examples of this phenomenon among the tagged eagles (Tables 2.1 and 2.3), notably a bird which dispersed from the Southern Uplands but which afterwards disappeared (stopped no malfunction) in the Highlands. Such an 'ecological trap' through persecution can spread the demographic effect of illegal killing away from the areas where it is conducted. The damaging extent of the spread depends on the dispersal behaviour of young eagles from any particular natal region and so, the number of dispersing birds (and their frequency of temporary settlement: see Weston 2014) in the 'ecological trap' area. If the number of dispersing eagles caught in the trap is relatively low then the adverse effect on survival for the natal population will be relatively small, but if it is relatively high then the effect will be much greater. For example, the death of a single bird in an ecological trap which had dispersed from the Southern Uplands where the population is in poor status and breeding birds few would be consequently higher for the natal population than for, say, the death of a single bird originating in Argyll.

From these results we would expect that in some parts of Scotland (assuming carrying capacity of territories has still not been reached there) which are relatively unaffected by the relatively localised effects of illegal killing then the population would be expected to be growing. In some parts, if carrying capacity has been reached we would expect the inherent capacity for population growth to be manifest by an increasing number of adult 'floaters' and, possibly, an effect on adult survival through increasing competition for a territory. The relative effect for these parts of Scotland would be conditional on how many young birds used the areas away from their natal region during juvenile dispersal where they were at risk of being killed, and were killed before they had an opportunity to return to their natal region.

Assuredly, for instance, we would not expect the population on the Western Isles (Outer Hebrides) to be affected, and so it should have a continued capacity to grow, because genetic analyses have shown that dispersal from the islands is rare (Ogden *et al*. 2015) (also confirmed by satellite tagging: see Figure 3.1). This seems to be due to the large expanse of sea (The Minches) separating the Western Isles and acting as a geographical barrier to movement.

By contrast, and given how many of the tagged birds with suspicious end fates originated in territories which were in the central and eastern Highlands (section 2, Tag Metadata: Table 2.3) we would expect the demographic effect of illegal killing to fall most heavily on 'populations' in these regions (which also coincided with where many of the clusters of suspicious tag fates occurred: section 4, Cluster Analysis). While breeding productivity is typically high in these regions, reflecting the high live prey availability (Whitfield *et al*. 2008a) we would expect, from the explorations in this section, that this would not be sufficient to counteract completely the marked effect of illegal killing as inferred from the satellite tagging of young eagles.

Overall, we would expect that the effect of killing young golden eagles revealed by this project would not be evident in some regions of Scotland and would be restricted to parts of the central and eastern Highlands. We would expect, therefore, that in several regions of Scotland away from the central and eastern Highlands the breeding population has continued to expand since the 2003 National Survey, although it may well be at or close to reaching carrying capacity (and so superficially stable on counts of occupied territories) in some parts.

Our evaluation from viewing and analysing many data sources is that persecution of golden eagles associated with grouse moor interests, while still prevalent in some areas (as indicated by this report: sections 4, 8 & 9) has relaxed in other areas of the same regions where unfavourable conservation status was largely ascribed to such persecution previously (*cf* Whitfield *et al*. 2003, 2004a, b, 2006, 2008a). In these regions, fundamentally, there is much greater intrinsic potential for population expansion than other regions elsewhere in Scotland due to high breeding productivity (Whitfield *et al*. 2006, 2008a); but there is obviously still a major ongoing and persistent persecutory problem in some parts of the central and eastern Highland regions which will continue to prevent the golden eagle population from reaching its natural national potential.

We would also expect, therefore, that there may have been some recovery in the Scottish regions (NHZs) of the central and eastern Highlands where the species' conservation status was previously unfavourable due largely to illegal persecution (Whitfield *et al*. 2006, 2008a). But we would also expect, when there is still locally frequent killing of young eagles in some parts of these regions (many of which involve 'locally produced' birds), that this recovery is still not complete. These areas probably continue to hold great potential for relatively rapid expansion through high productivity (Whitfield *et al*. 2006, 2008a) from abundant live prey availability. And, apparently (from the present report) should have high natural survival rates of pre-breeding eagles. Nevertheless, we expect that the continued illegal killing of golden eagles in some places, given its intensity there, will likely still have caused a continued (after many decades: Whitfield *et al*. 2008a) absence of breeding birds from several potential territories.

The 2015 National Survey data for golden eagles have yet to be published, but have been reported on preliminarily through a press release[12]. While this press release reports an increase to over 500 occupied territories from the previous (2003) total of 442, we also note that the results of expansion appear to be 'uneven' regionally, and that recovery is least evident in the eastern Highlands. Our analyses, at least superficially, given that the 2015 data have yet to be published, would appear to be broadly in agreement.

Overall, our analyses would indicate that the persecution of young eagles is continuing to suppress the national golden eagle's population potential, in the central and eastern Highlands, and is still hampering overall recovery from historic, widespread persecution.

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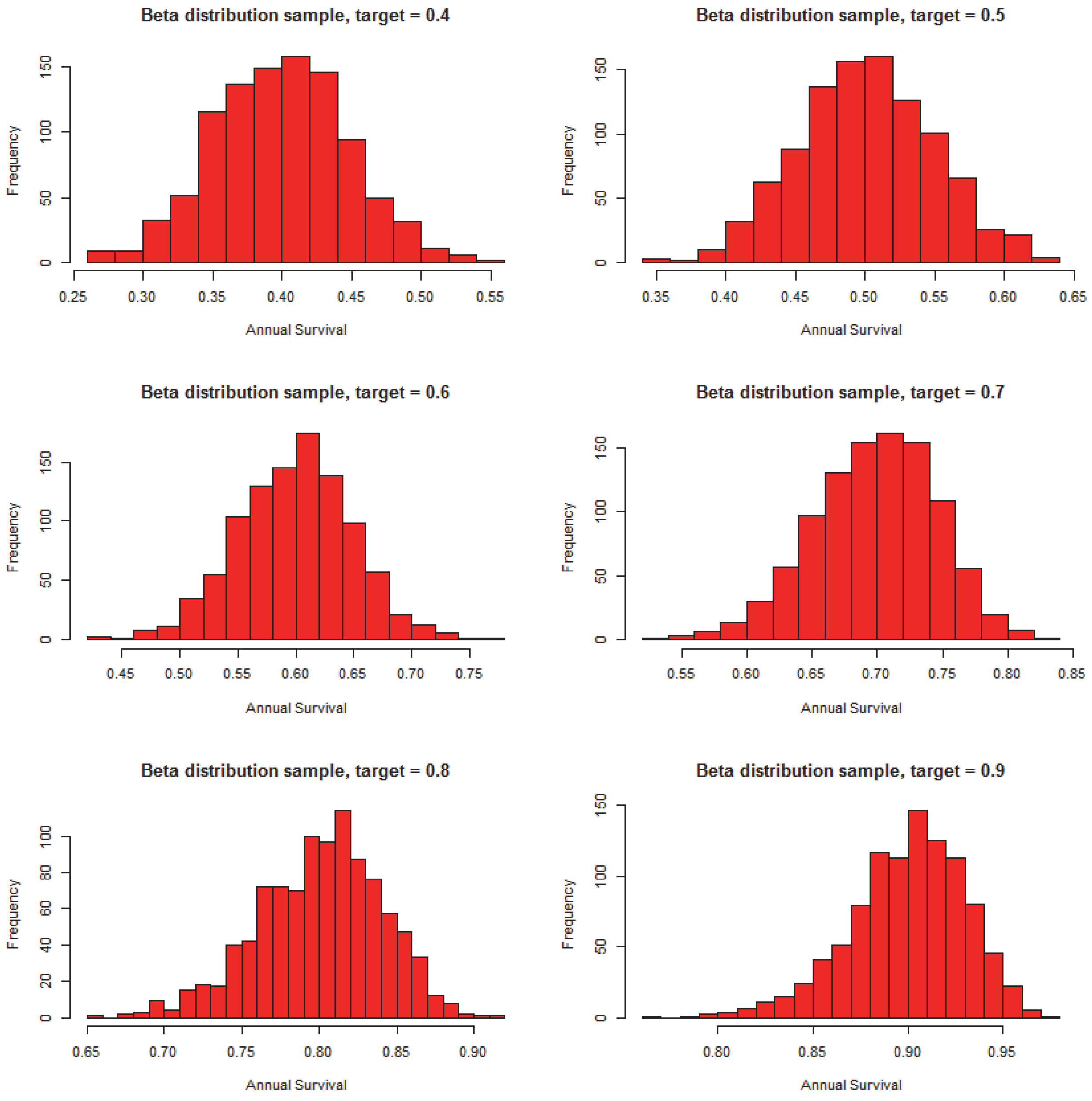
[12] https://www.rspb.org.uk/our-work/rspb-news/news/432959-welcome-rise-in-scotlands-golden-eagle-population-according-to-fourth-national-survey

Appendix 11.1. Demonstration of survival rate random sampling.

Survival rates were sampled from Beta distributions. The Beta distribution has two parameters: a and b. If the target mean is 0.9 the values of a and b are 0.9 and 0.1 respectively; for a target mean of 0.4 they are 0.4 and 0.6 respectively. As a test six mean survival rates were modelled using 1,000 random samples from a beta distribution (Figure A11.1). The target means were 0.4, 0.5, 0.6, 0.7, 0.8 & 0.9. The sample means were 0.399, 0.501, 0.599, 0.6985, 0.801 and 0.900. The survival to age 4 with only natural mortality was 0.806 (95 % CL 0.657 to 0.989). The sampled distribution matched this range quite closely (Figure A11.1).


Beta distribution sample, target = 0.4

Beta distribution sample, target = 0.5

Beta distribution sample, target = 0.6

Beta distribution sample, target = 0.7

Beta distribution sample, target = 0.8

Beta distribution sample, target = 0.9

Figure A11.1. Probability distributions for six mean annual survival rates. 1,000 random values were obtained using the rbeta function in R.

12. CONCLUSIONS

In previous sections we have described several subsidiary conclusions, as they related to each section's subject matter. Please refer to these materials, as they went beyond the questions posed by the original project brief in pursuance of answering further questions which arose during analyses.

In this final section our conclusions refer to the original Introduction section (section 1) which described the primary project objective and the related questions/objectives which were within the project's brief.

The primary aim of this report was encapsulated by the Cabinet Secretary's instruction; for analyses to examine if there was a pattern of suspicious activity surrounding the 'disappearance' of many satellite tagged golden eagles.

In addressing this primary aim, our analyses indicated:

There was a pattern of suspicious activity surrounding the 'disappearance' of many satellite tagged golden eagles, from many lines of evidence. There were many such 'disappearances'. The high number was inexplicable without accepting that they were largely due to human intervention: at least many or most of the tagged birds which 'disappeared' were probably killed by people. These high numbers of likely killings were significantly associated with <u>some</u> grouse moor areas and contemporaneous evidence of confirmed persecution.

As in section 1 (Introduction), subsumed within and related to the primary aim there were several objectives/questions within the project brief which we addressed:

1. Is there a significant spatial pattern in tagged eagle 'losses'? Are losses greater in specific parts – regions/land-uses/close-locations?

There was a significant spatial pattern, and these were greater in specific parts of Scotland (mostly located within the central and eastern Highlands) associated with <u>some</u> grouse moors and places where other illegal persecution events had been recorded contemporaneously. There was no connection with wind farm locations.

2. Are these losses greater than we might expect from observed movements (i.e. are more birds lost in some areas because there is a preference to be there)?

The losses ('disappearances') of suspicious tag fates were greater than expected from observed movements. In sharp contrast, non-suspicious tag fates were not different from expectations of observed movements. The many 'disappearances' were largely due to human intervention (people killing tagged birds).

3. How reliable are the transmitters, and what is the expected lifespan?

Modern tags appeared to be reliable: many tags on young Scottish eagles inexplicably 'failed' prematurely before an expected 3 y lifespan and the high sudden failure rate was not replicated in any other study. The high sudden failure rate of many Scottish tags added further to the conclusion that their termination was due to people; acting in destructive ways at a scale beyond any other source we could discover elsewhere. Several lines of evidence indicated that tag reliability had little or no role in the many 'disappearances' recorded.

4. Is there any evidence that the tags harm the birds or influence their behaviour?

No substantive evidence was found for harm, on many levels, from individuals' behaviour, post-mortem examinations, through to, critically, vital population rates.

5. What is the estimated loss of 'young-tagged' eagles to natural and other causes?

'Natural' survival rates were high: higher than recorded by any other study, and if even they were non-additive/compensatory (to a degree) they clearly showed that tagging had no adverse effect on this critical demographic rate. The 'non-natural' causes had a statistically significant effect on survival rates, even if a generous proportion of the suspicious tag fates were assumed as not suspicious, but due to tag failure. For the tagged birds the survival estimates three years after tagging, attributed to all causes (including known killing or suspicion of killing), were half those derived from only natural deaths

6. What impacts are the non-natural losses of eagles having on the population regionally and nationally?

Overall, we conclude that a relatively large number of the satellite tagged golden eagles were probably killed, mostly on or near <u>some</u> grouse moors where there was also contemporaneous independent evidence of illegal persecution. This illegal killing had a marked effect on the survival rates of the young birds, so that we expect the potential capacity for the breeding golden eagle population continues to be suppressed in the environs of where the killing largely appeared to occur (in parts of the central and eastern Highlands of Scotland). This is after decades of continued suppression through illegal killing in these same areas of Scotland. Elsewhere in Scotland, beyond the spread that such illegal killing can have on young golden eagles, we expect the impacts to be much less and the intrinsic ('natural') capacity to expand may well have been realised since the last overview of regional conservation status.

As a final passing comment we can do no better than to repeat an observation made by the late, great and inspirational Jeff Watson in his foreword to Whitfield *et al*. (2008a):

"*Undoubtedly the highest priority of all is the need to address the illegal persecution that continues to affect eagle populations in the eastern and southern parts of the species' range. There can be no more urgent task than to eliminate this blight on the population of one of our most majestic birds*."

Dr Jeff Watson

Formerly Director of North Areas for SNH, and author of The Golden Eagle, published by T & AD Poyser.

At least for some parts of the species' range in Scotland we would note that an urgency of task is still required, nearly 10 years later.

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ANNEX 1: SUMMARY OF TAG SPATIAL USE AND FINAL FIX LOCATIONS

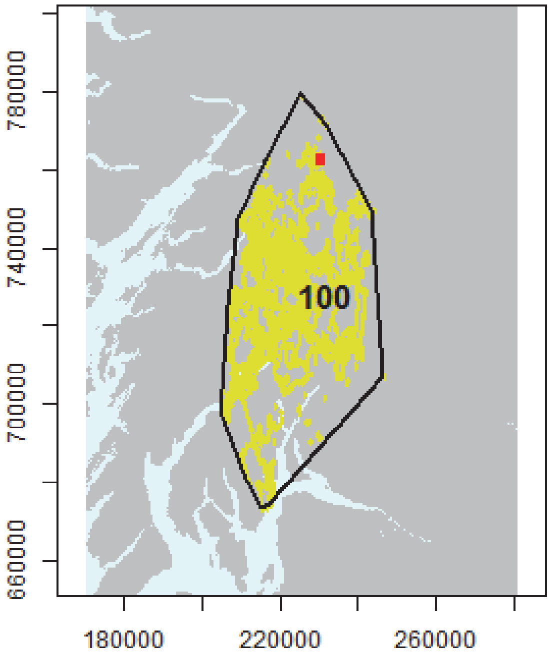
The overall movements of each tag are summarised by their minimum convex polygons (MCP) drawn around their locations. However, the tagged birds will not have visited everywhere in their MCPs so additional information is provided as 95 % kernel density maps (100 m pixel resolution).

Normally a kernel density map would be shaded to identify regions by their intensity of use. However, this inevitably results in a clear identification of the nest site for birds tagged as nestlings (Weston *et al*. 2013). Therefore, no intensity of use information is provided in such circumstances. A small number of tags were operational for only a period of days and even the 95 % kernel map identified the nest location. No maps are presented for these tags. Finally, the last location for each tag is marked by a red square.

The background of each map shows the land and sea. Maps are scaled in proportion to the size of the MCP: the spatial extent of a map is the size of a rectangle enclosing the MCP multiplied by 1.4. No map scale bar is given but the x and y coordinates are the OS grid (m) for the background so scale can be inferred from a map’s axes.

Following these maps, we tabulate the grid references for the final fixes for all tags which were not still transmitting as of 15 January 2017 (Table A2.1).

Tables 2.1 – 2.6 in the main text provide more metadata about tags and their deployment.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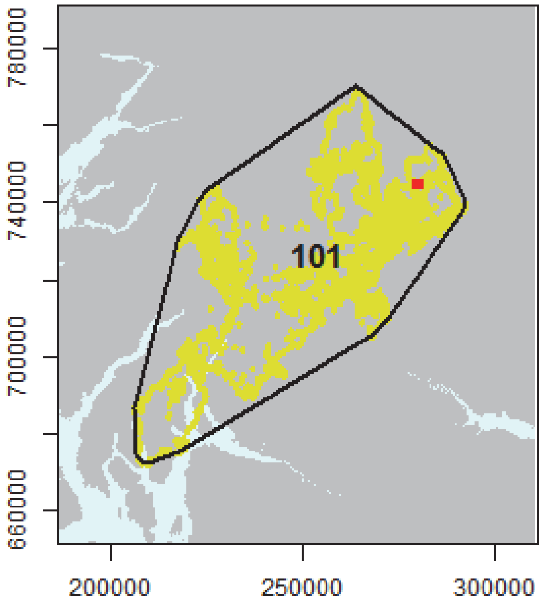
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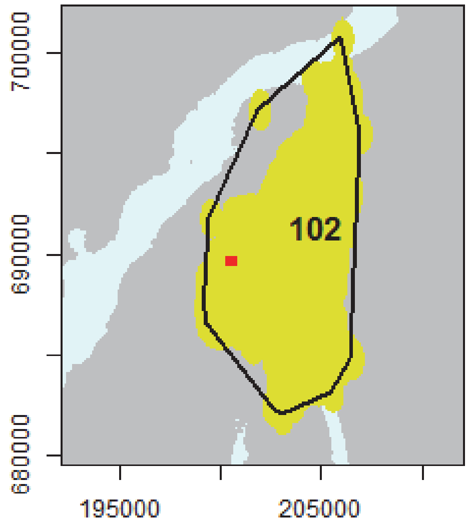
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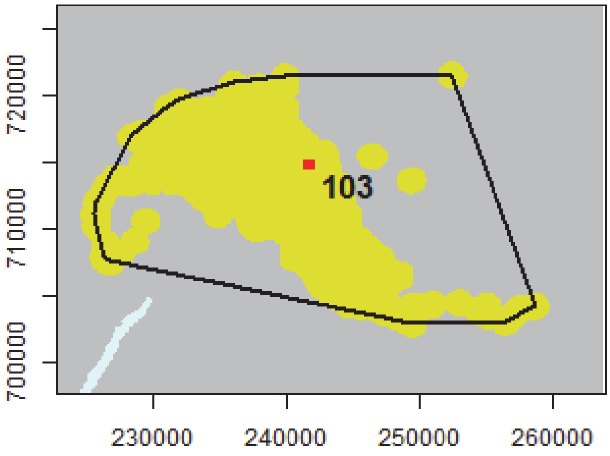
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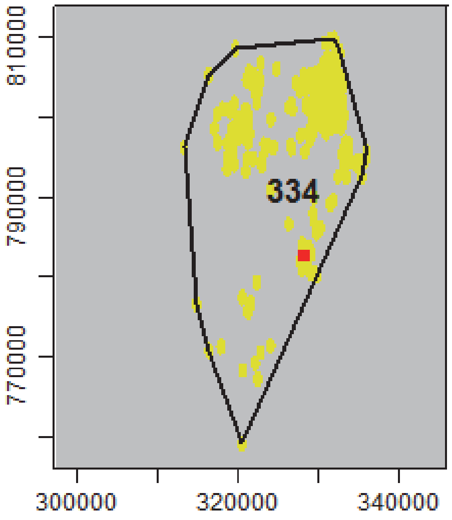
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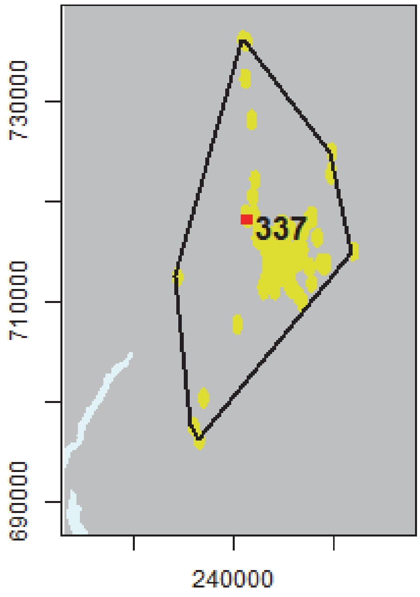
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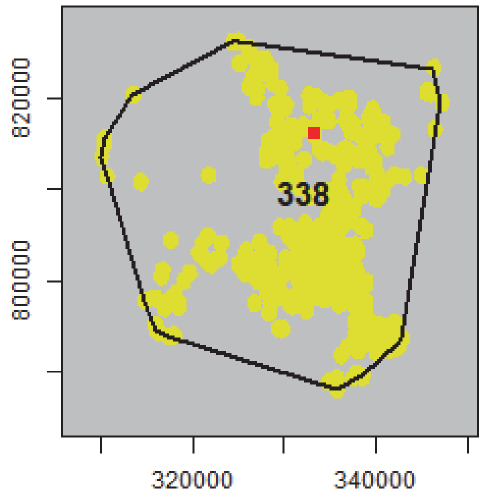

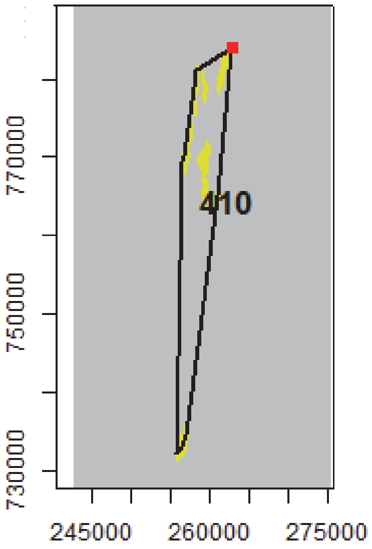

421 not shown because the map would identify the nest location

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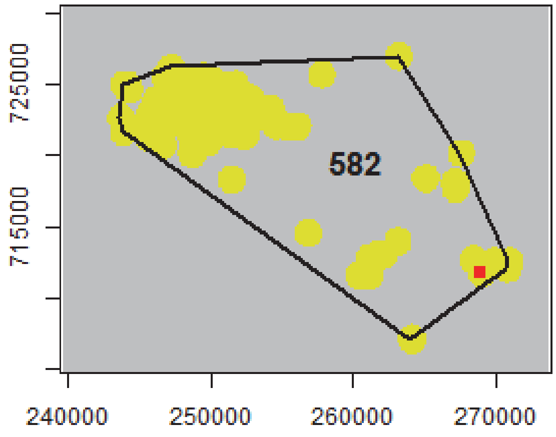

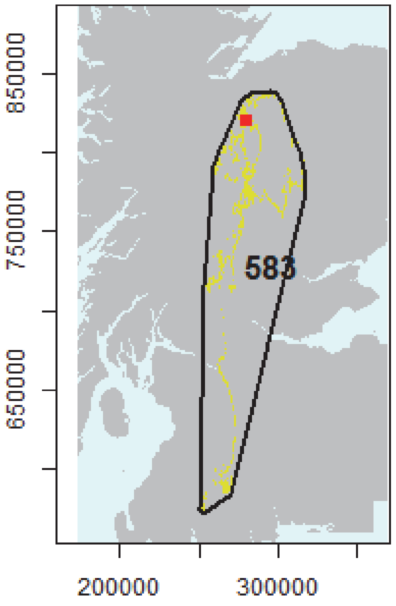

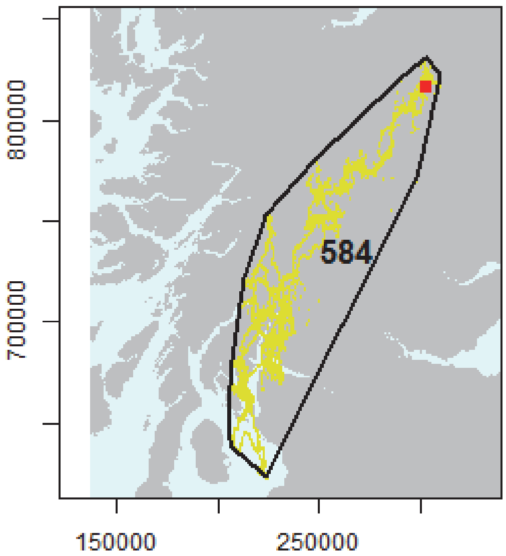
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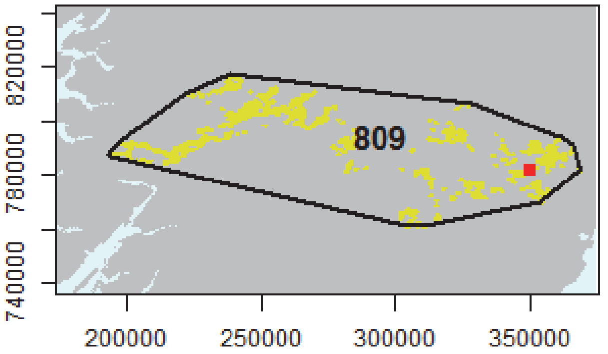
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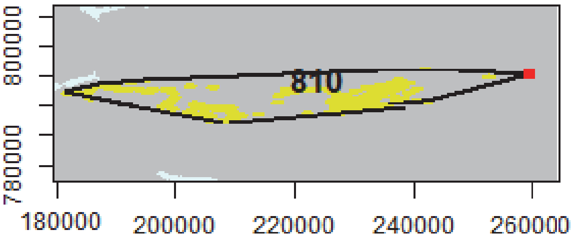
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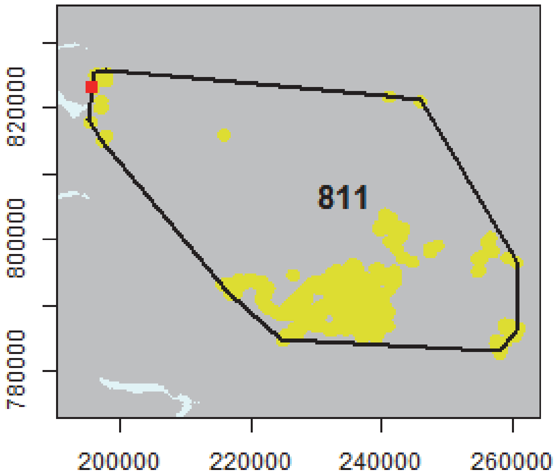
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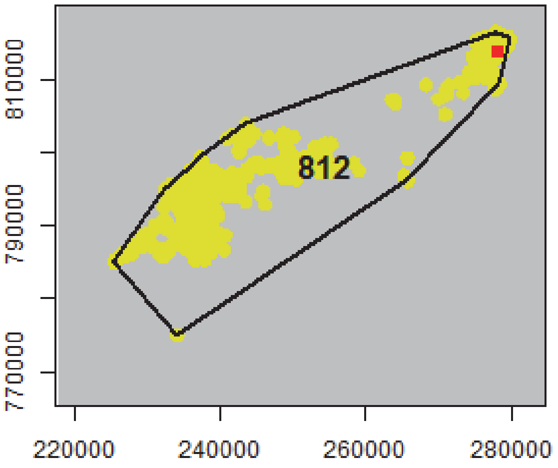
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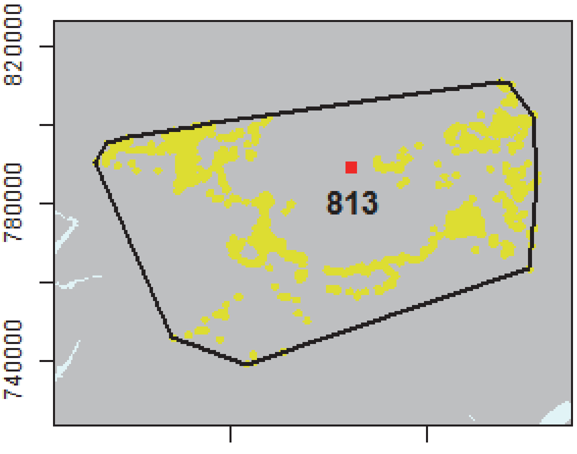
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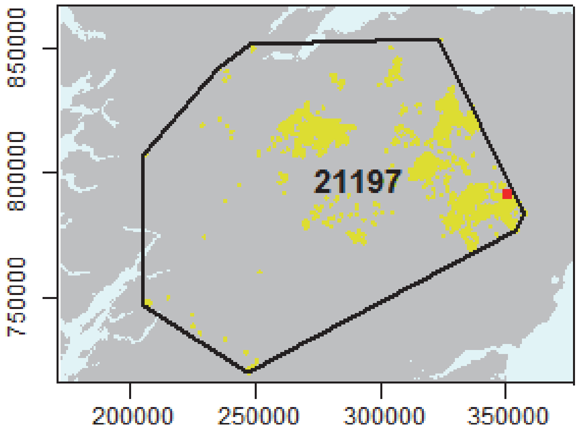
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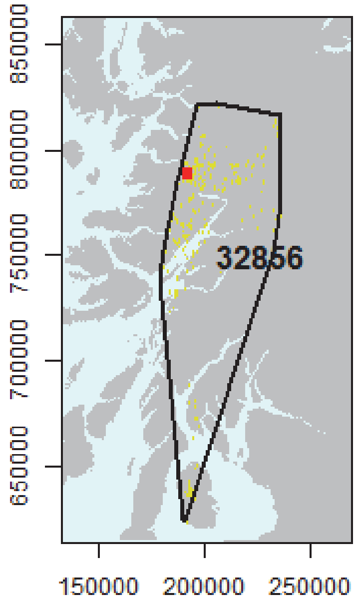
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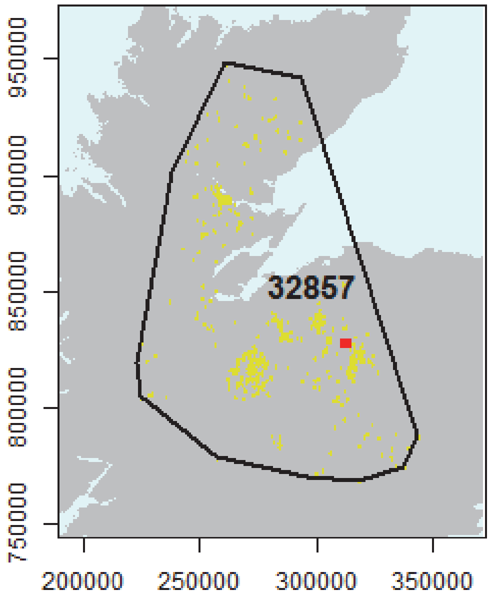
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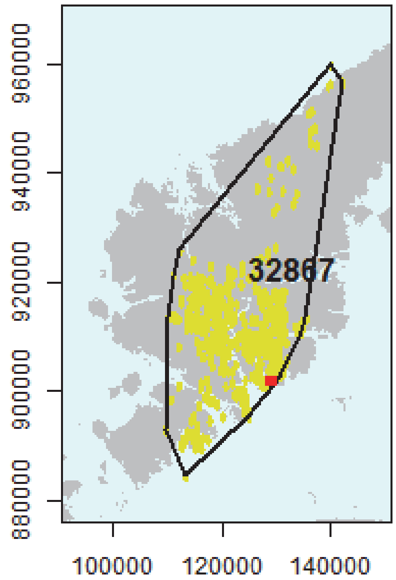
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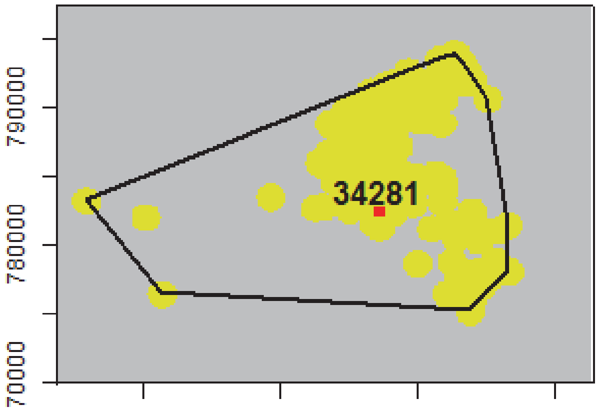
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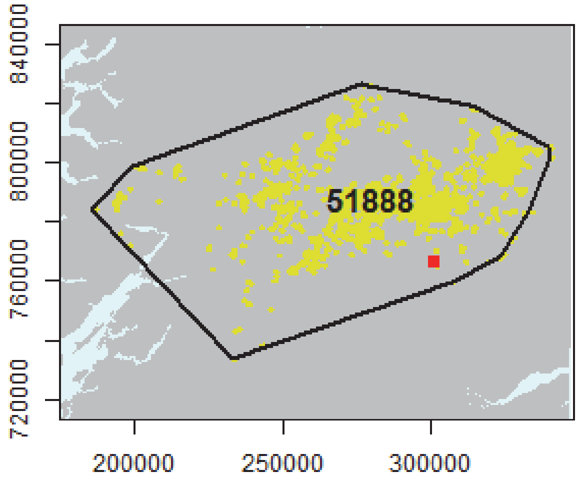
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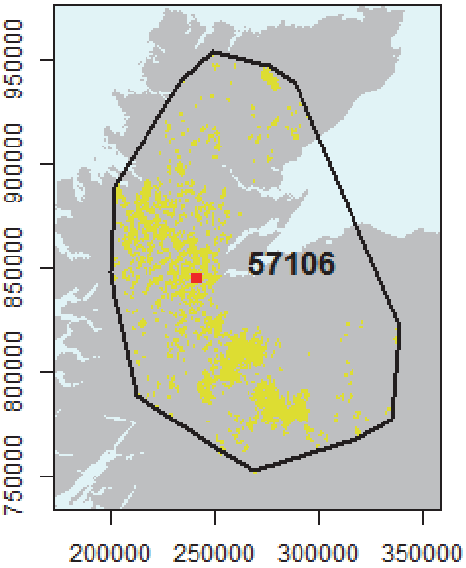
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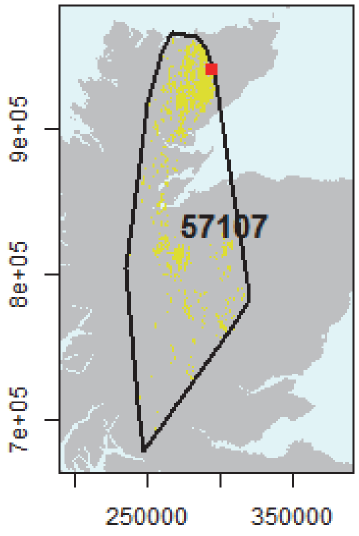

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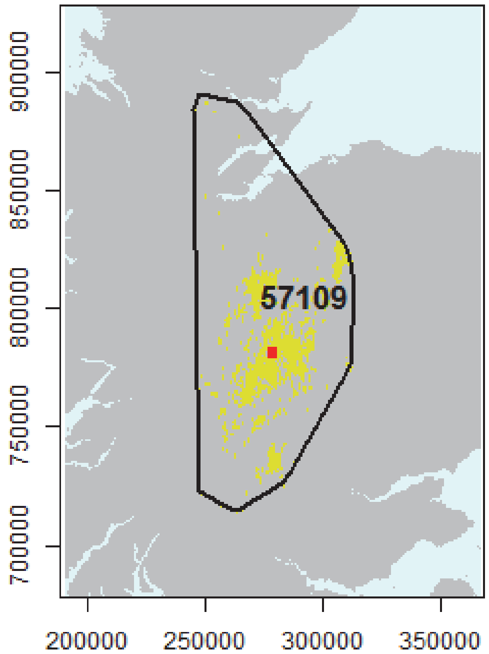

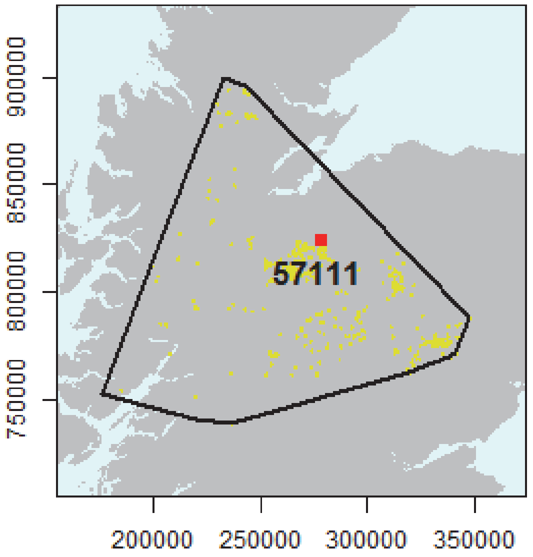

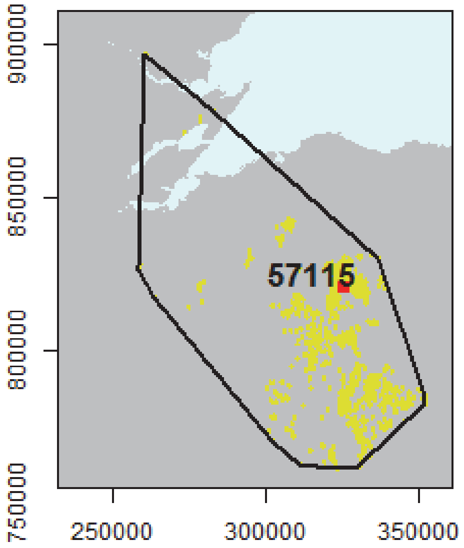

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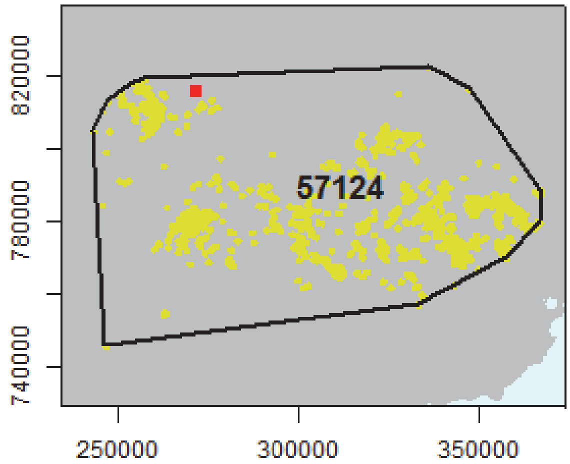
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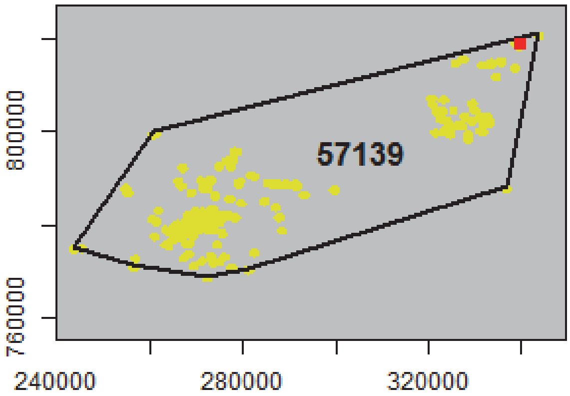
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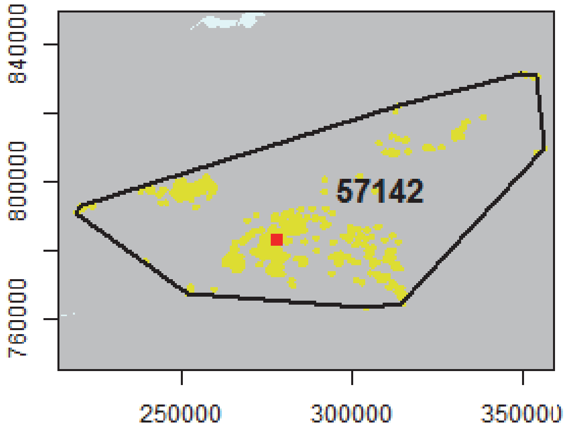
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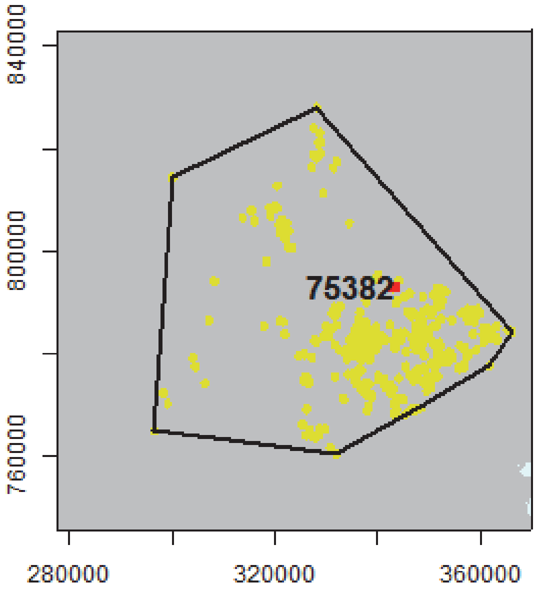
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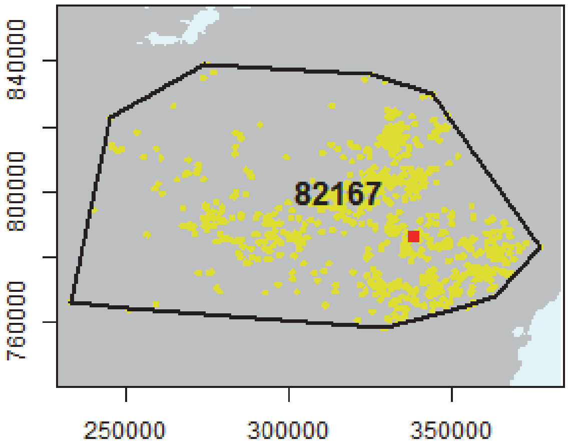
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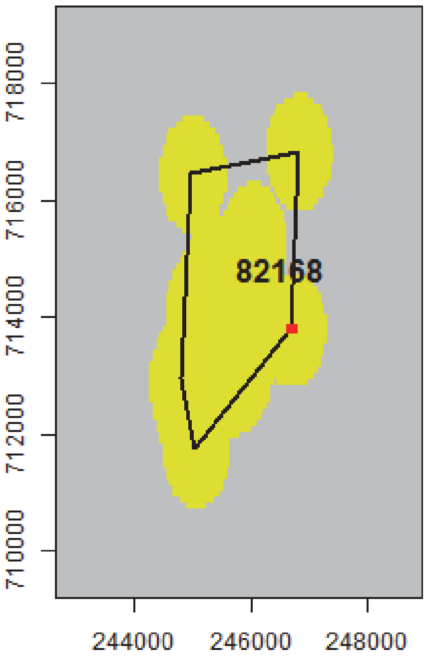
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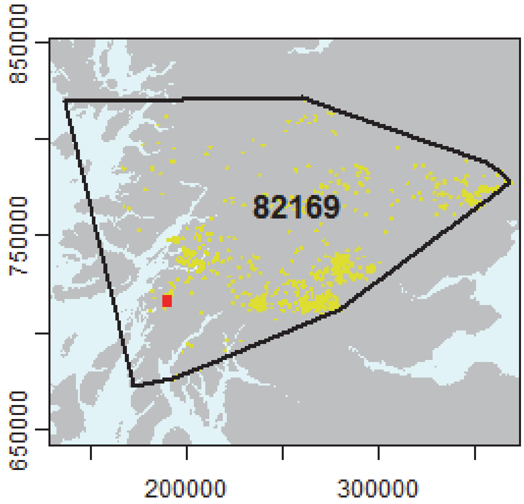
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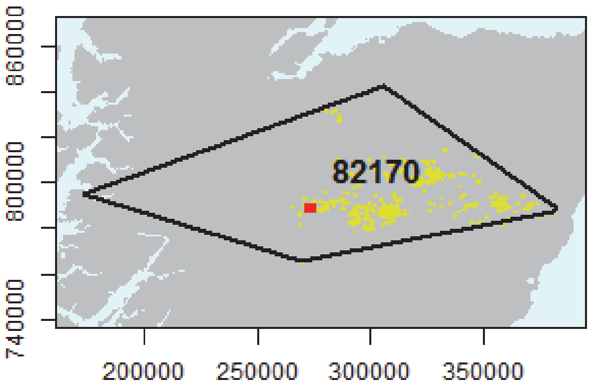
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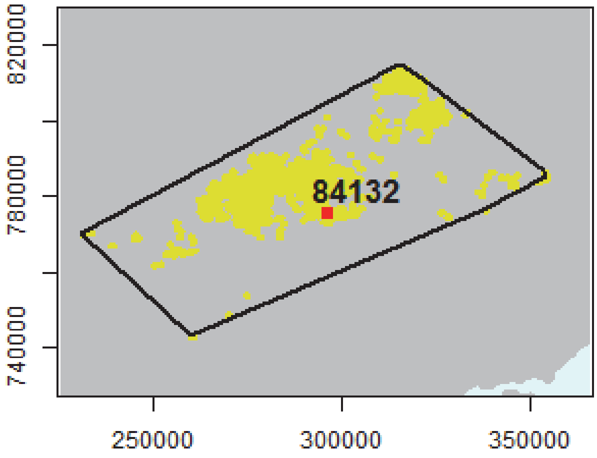
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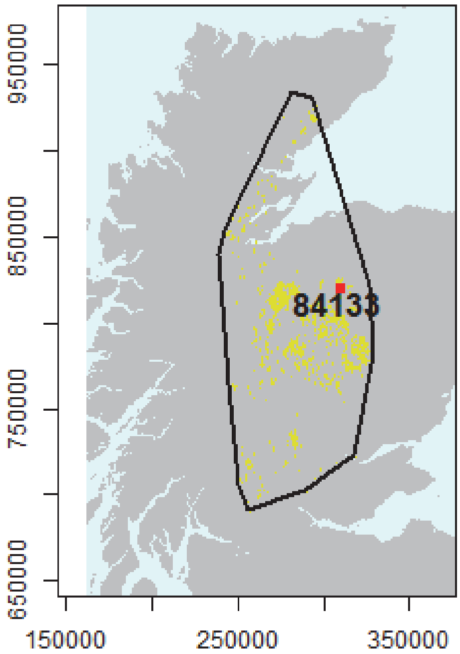
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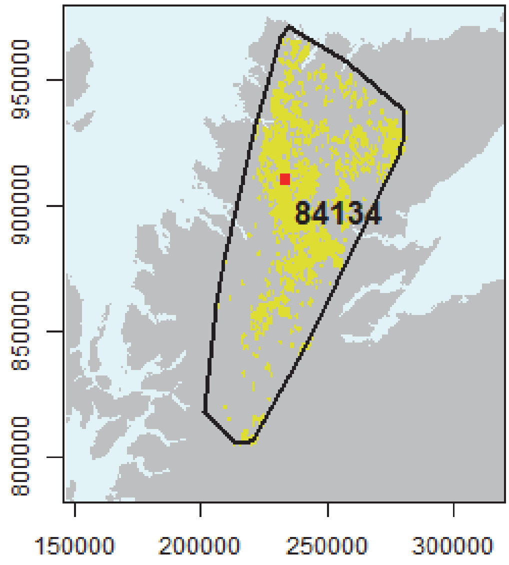
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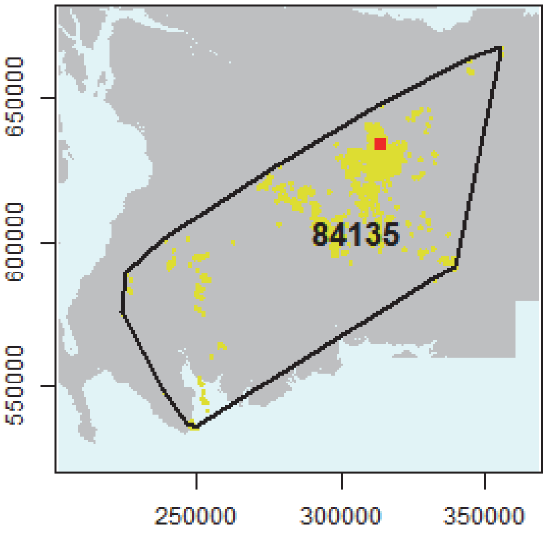
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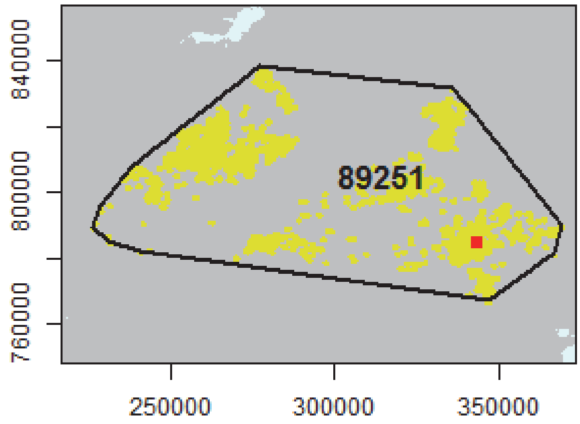
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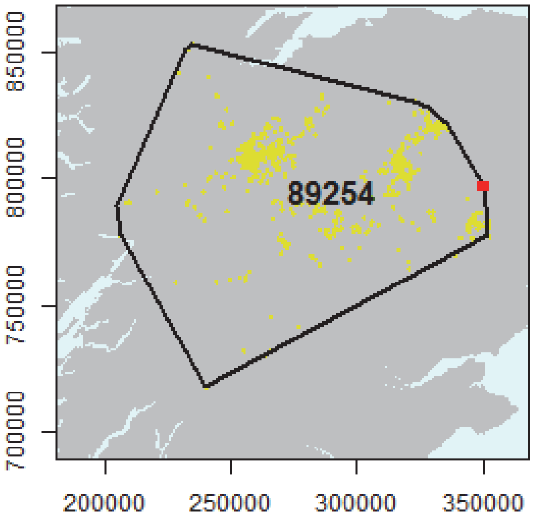
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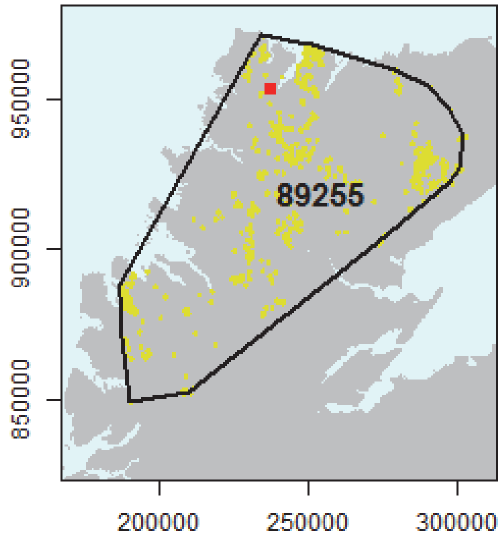
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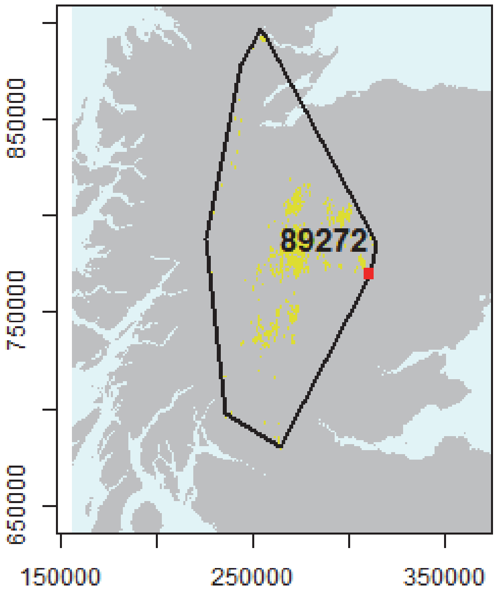
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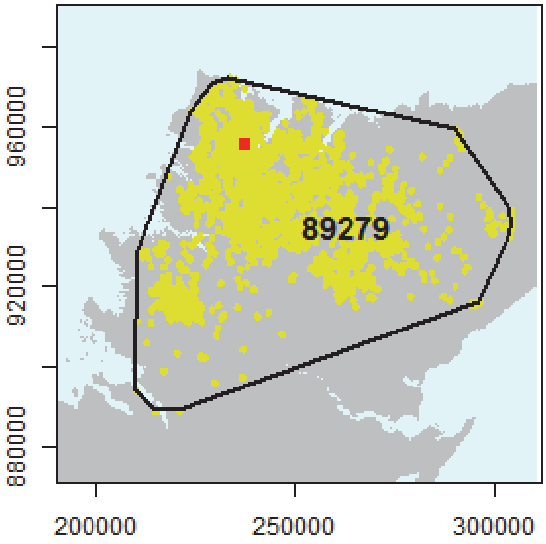
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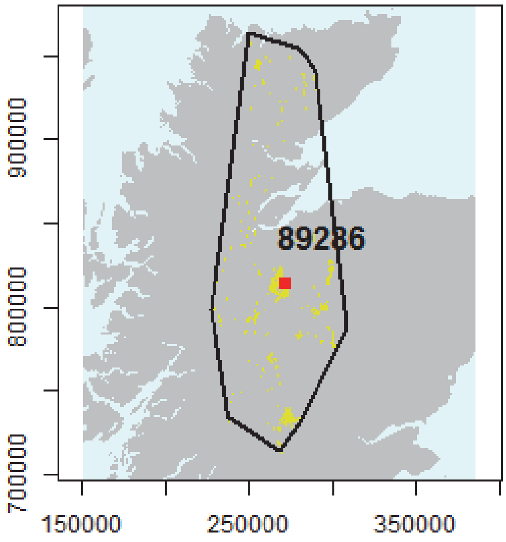
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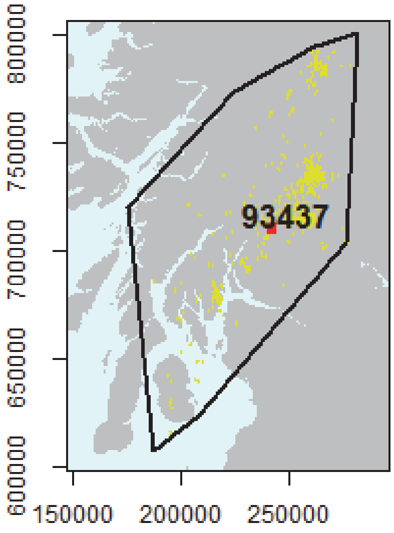
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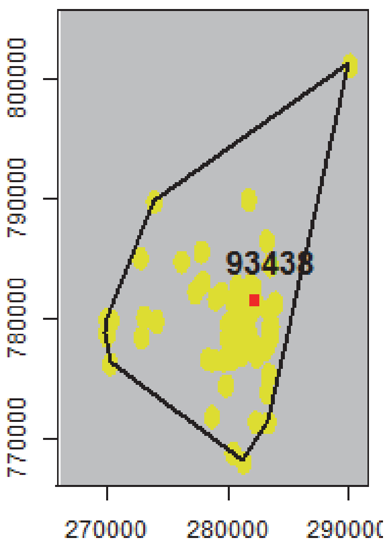
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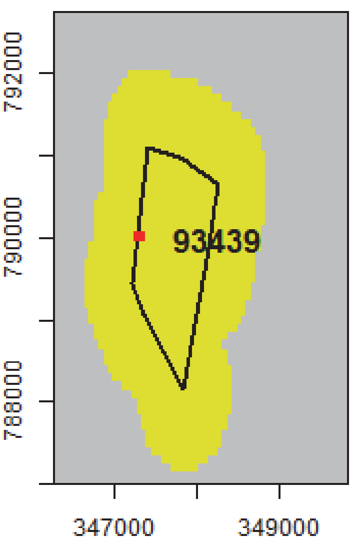
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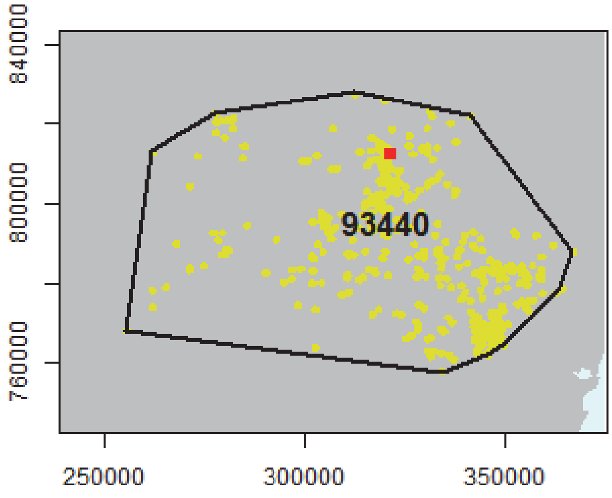
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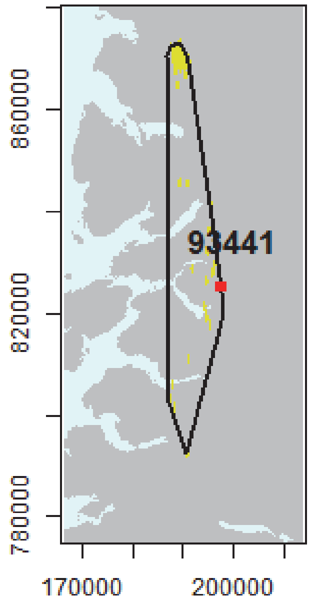
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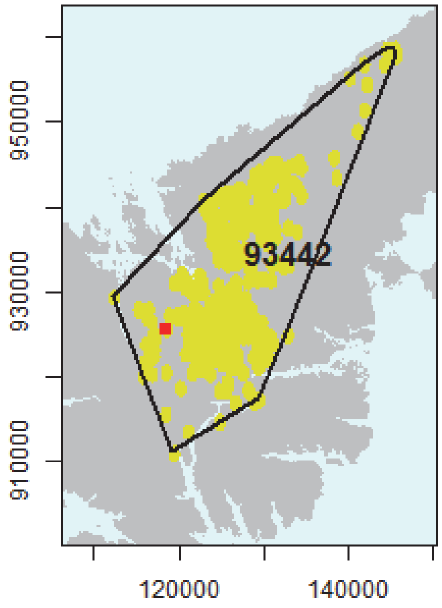
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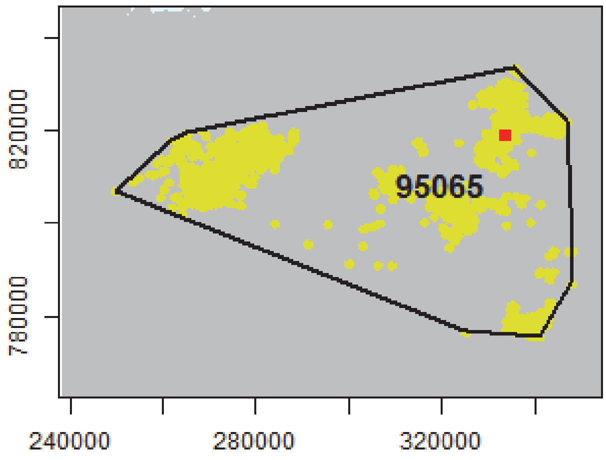
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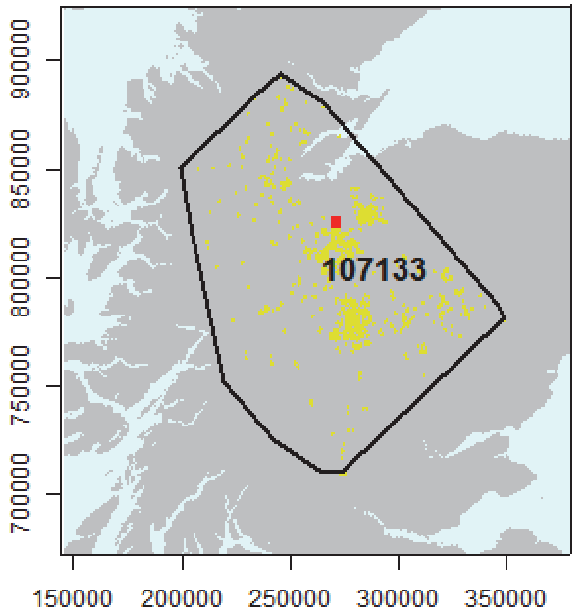
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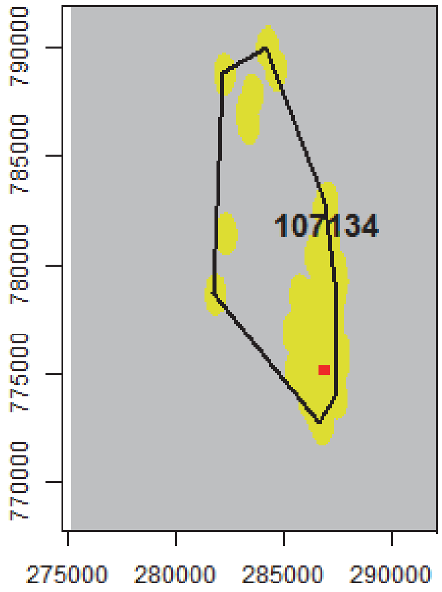
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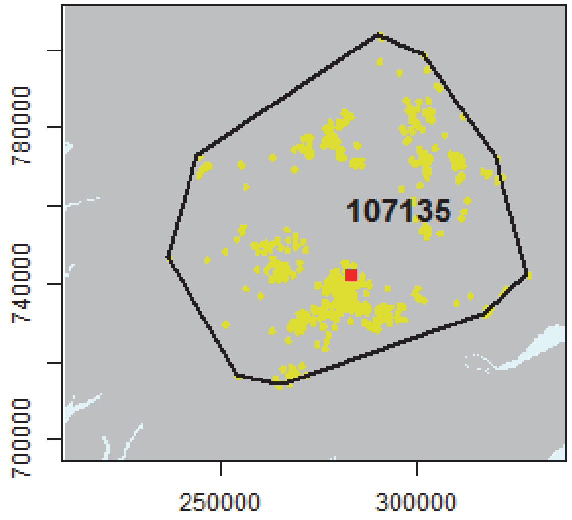
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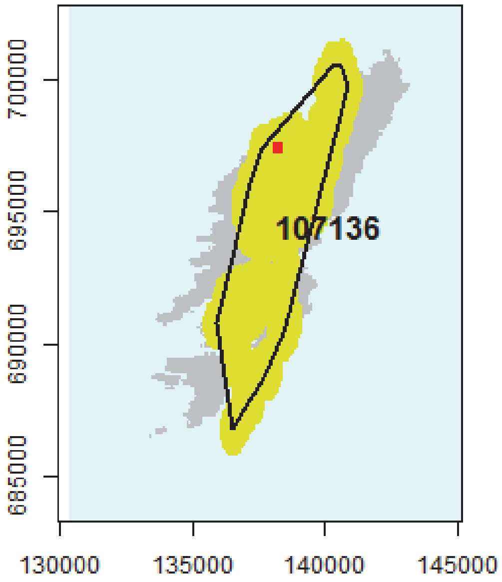
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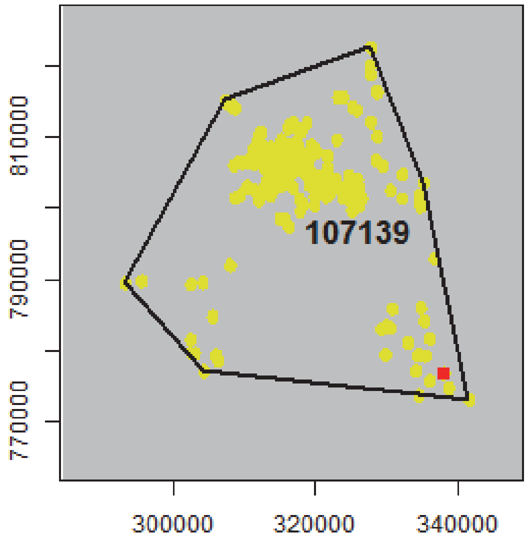
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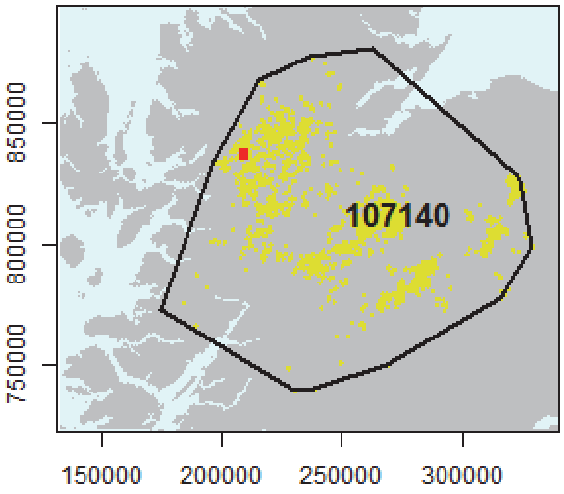
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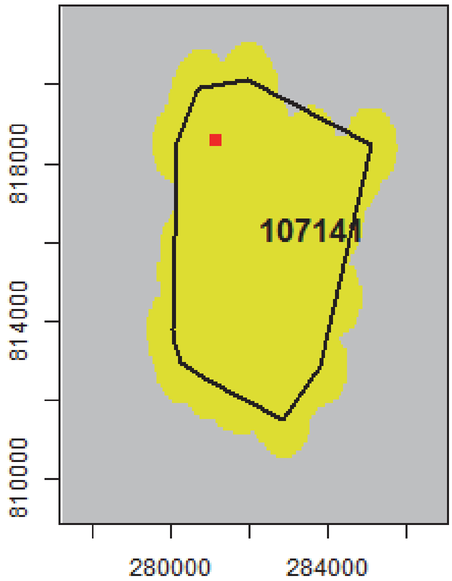
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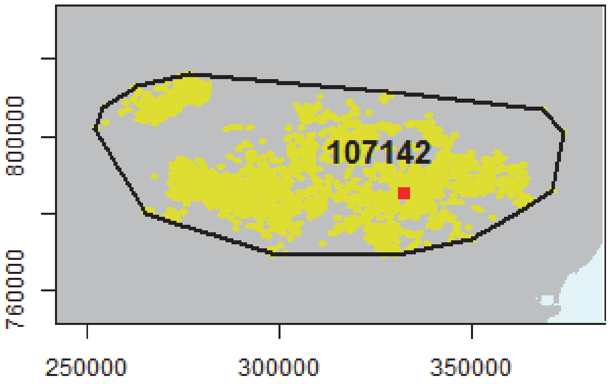
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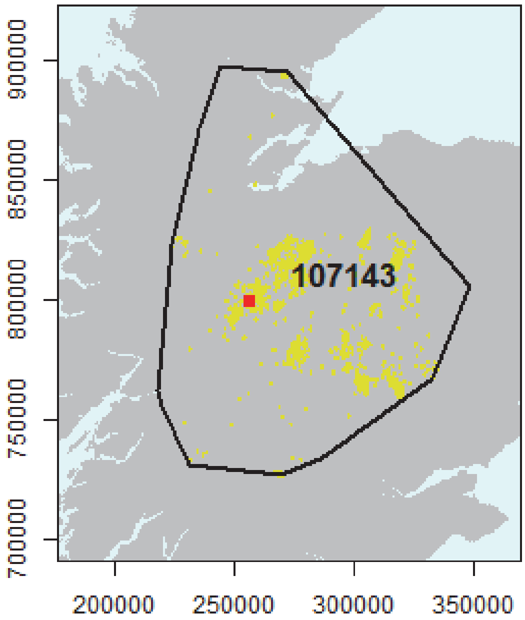
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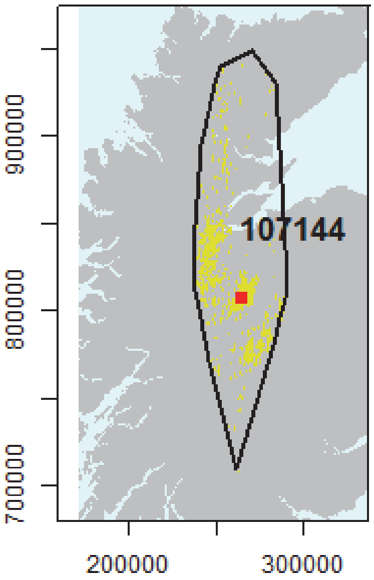
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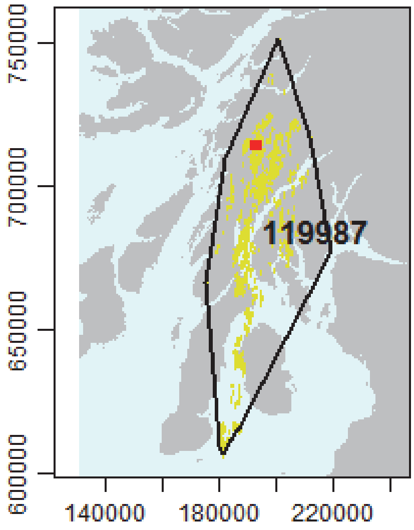
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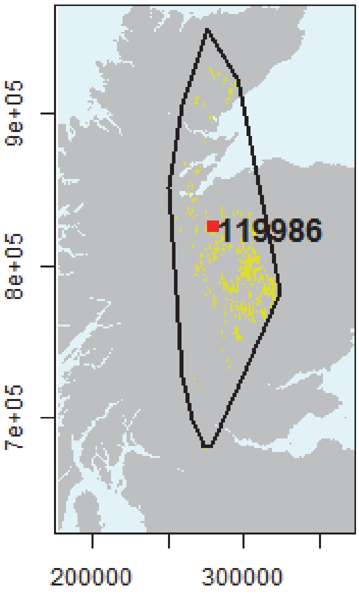
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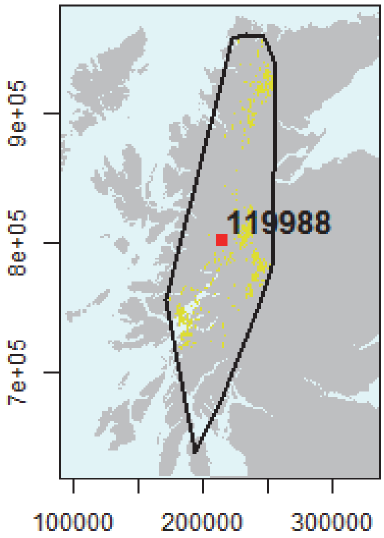
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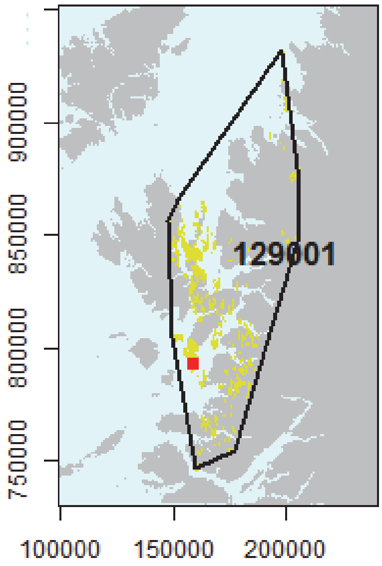
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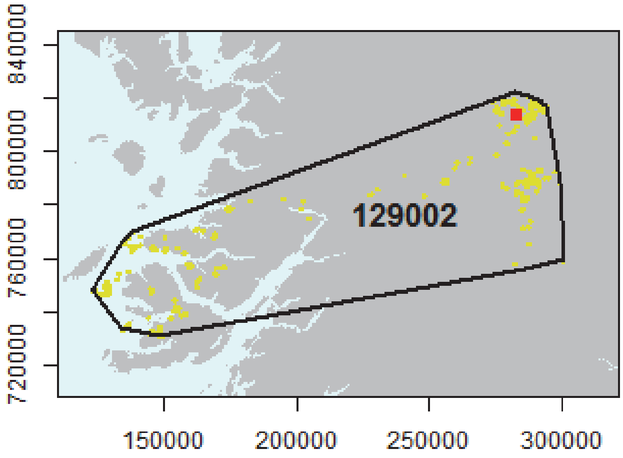
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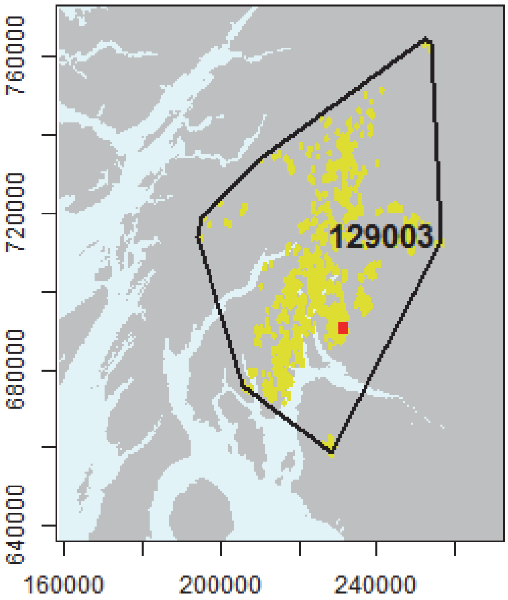
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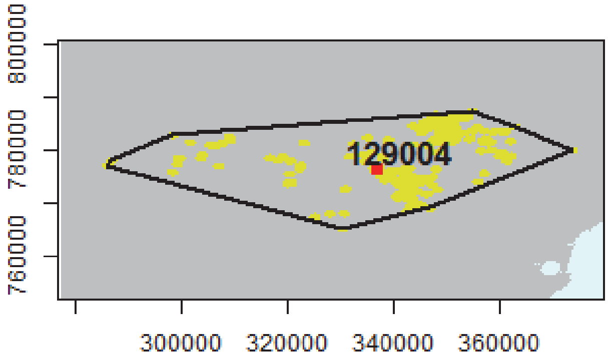
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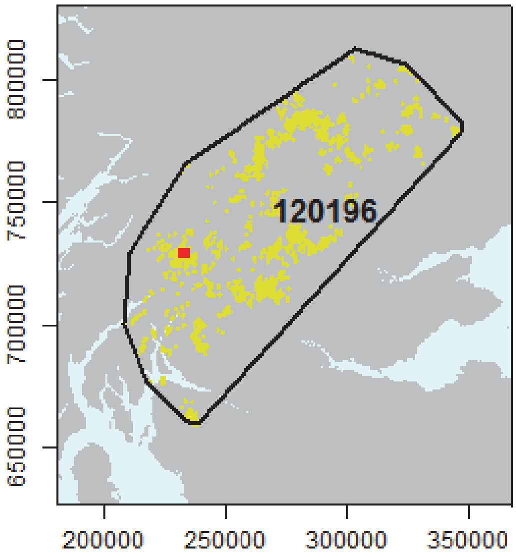
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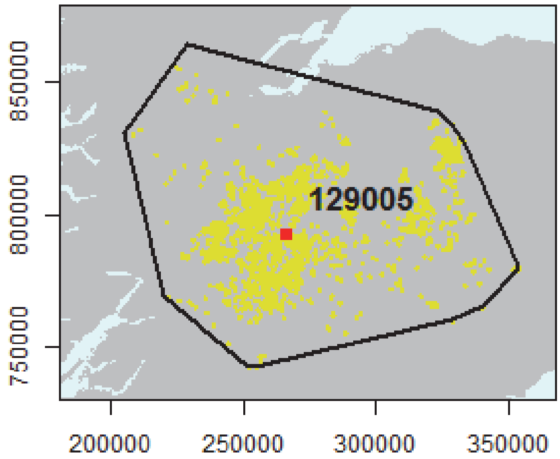

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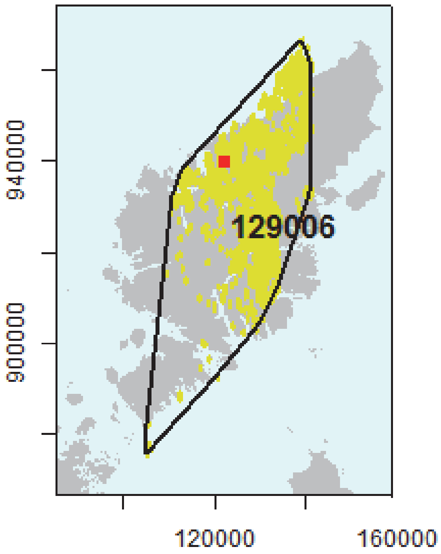

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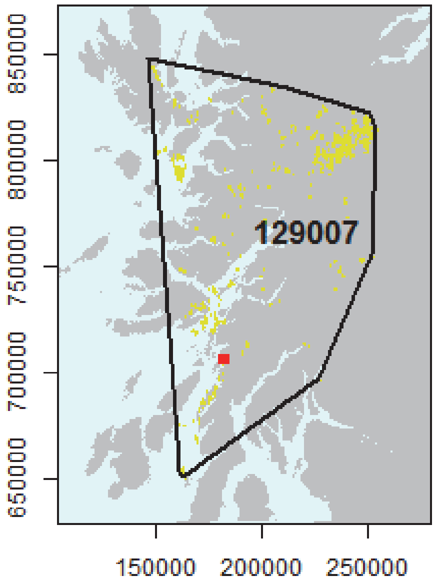

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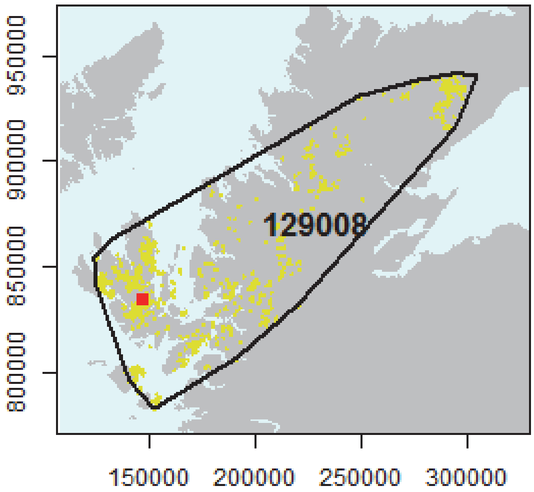

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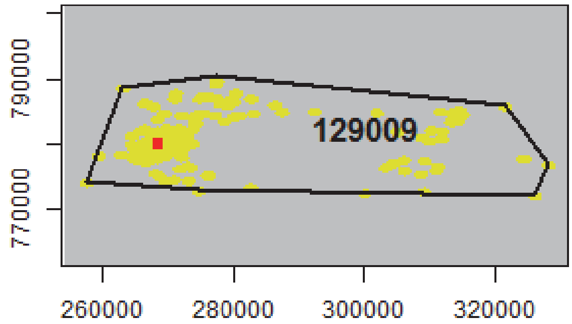

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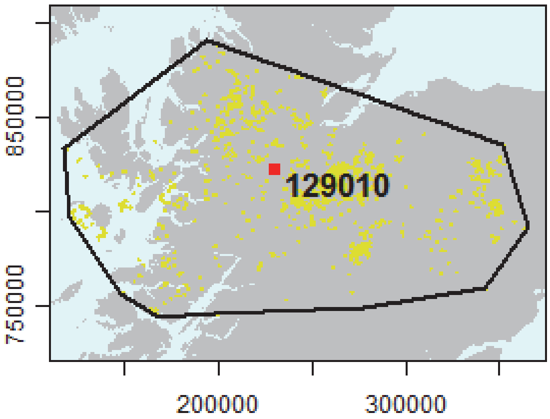

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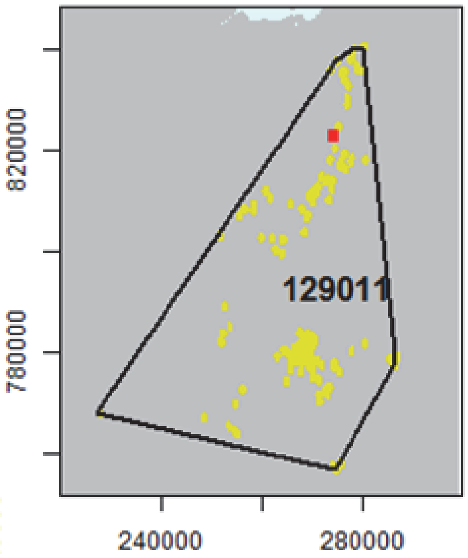
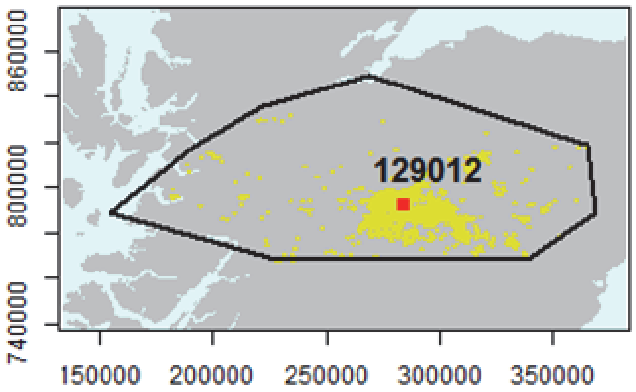
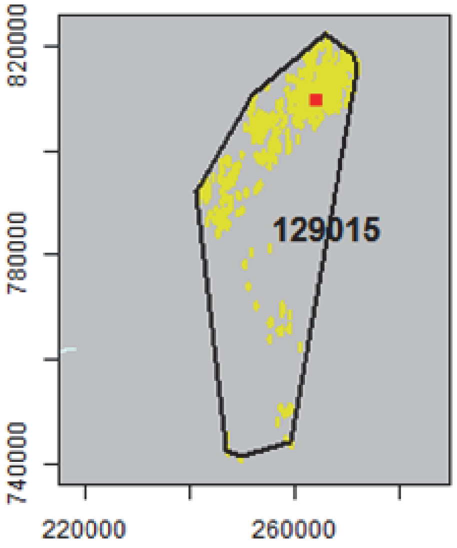
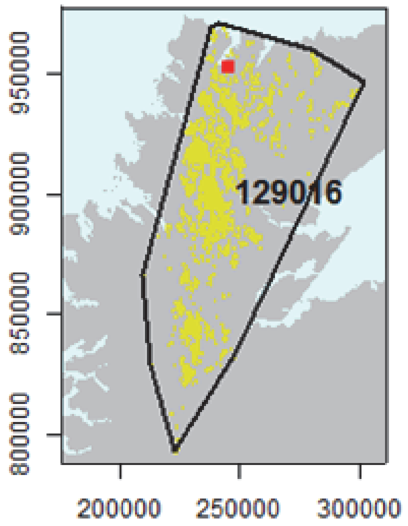
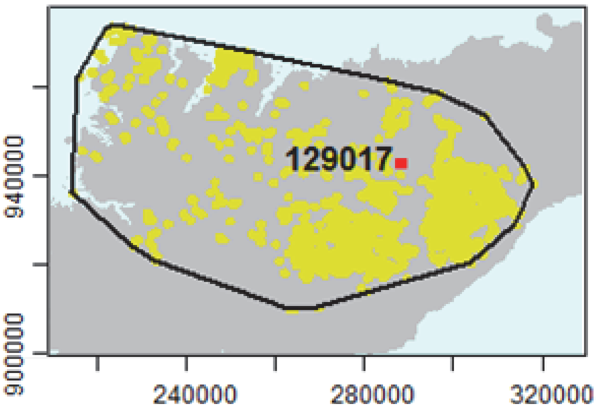


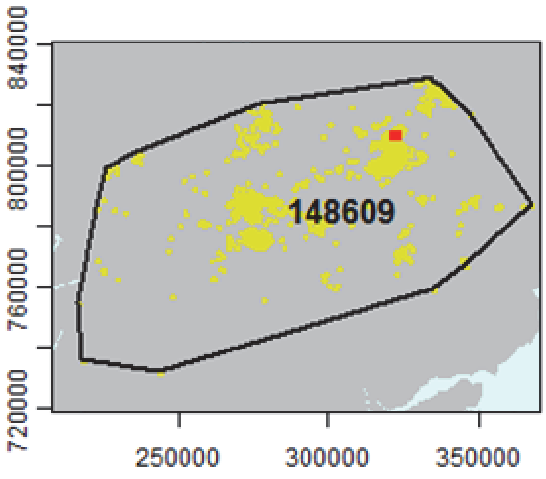


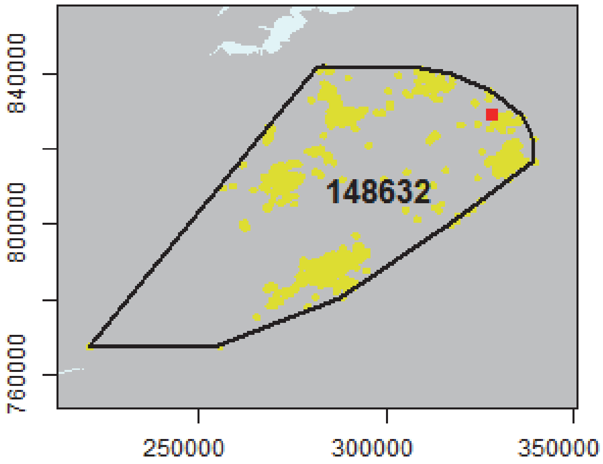


129014 not shown because the map would identify the nest location





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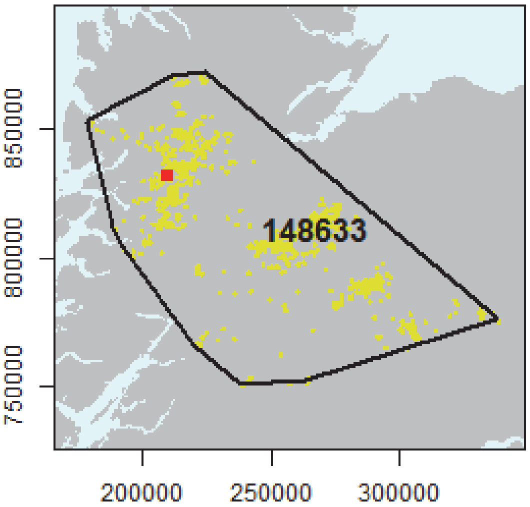
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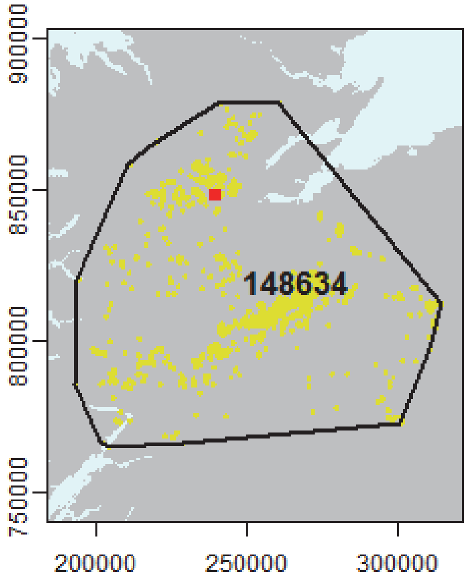
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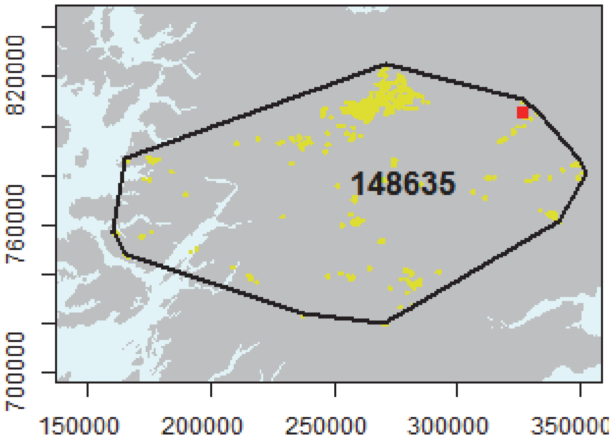
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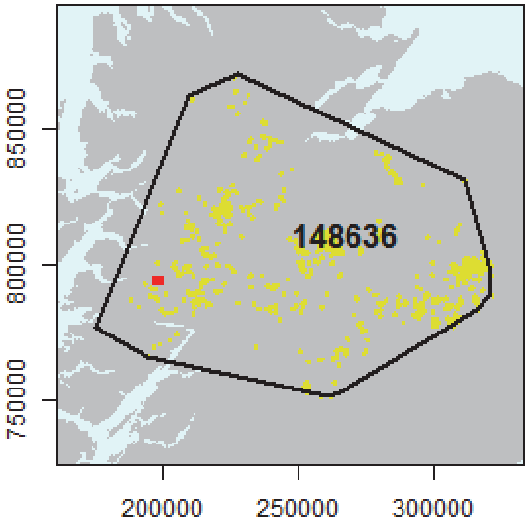
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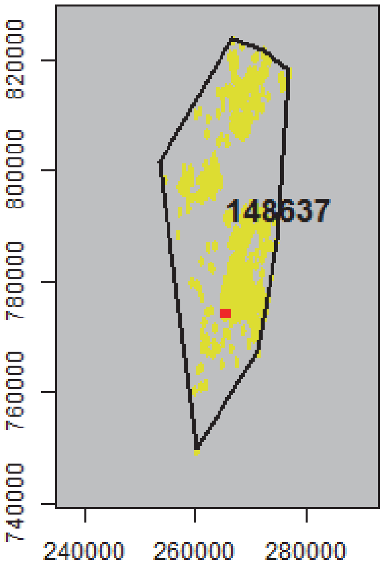
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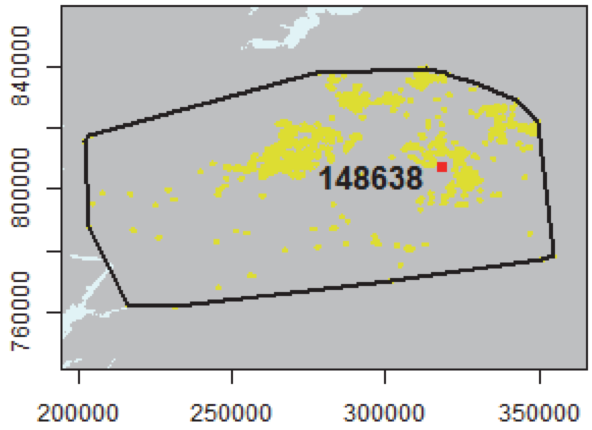
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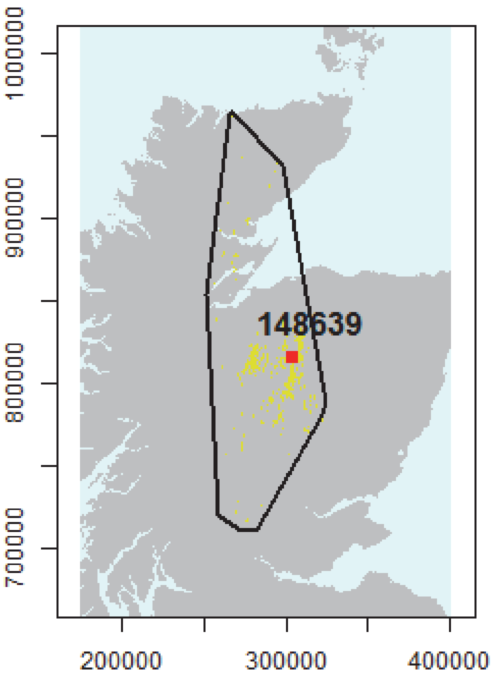
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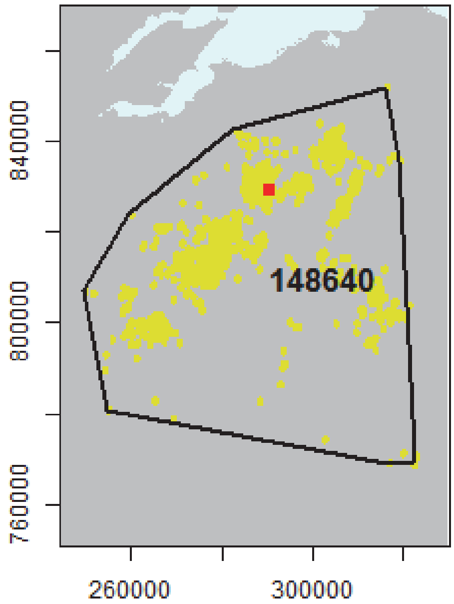
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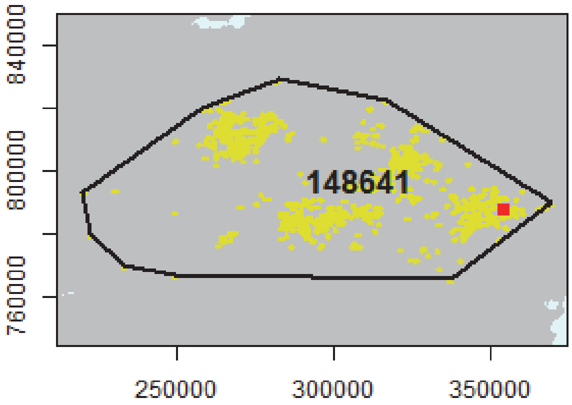
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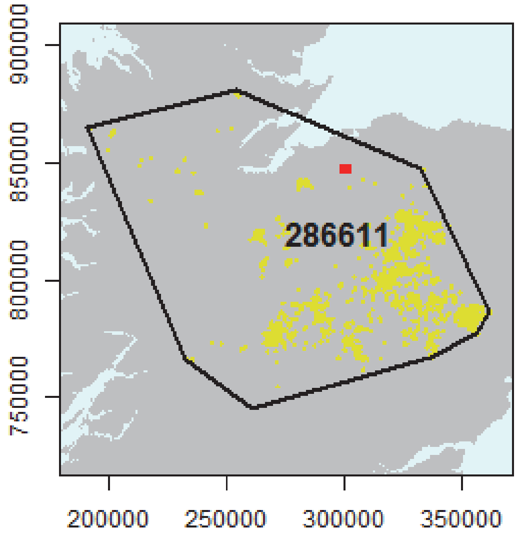
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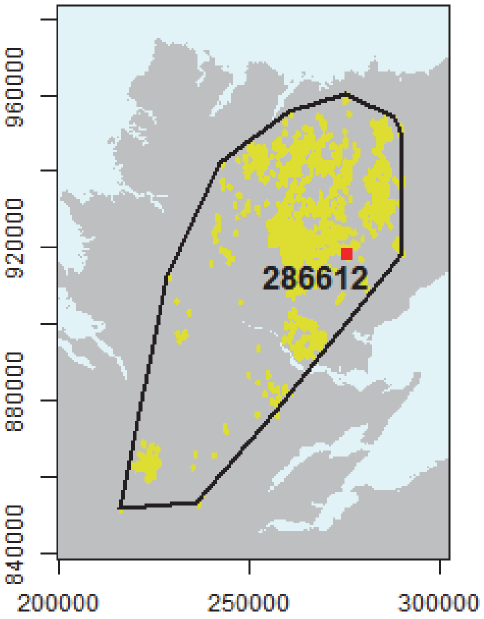
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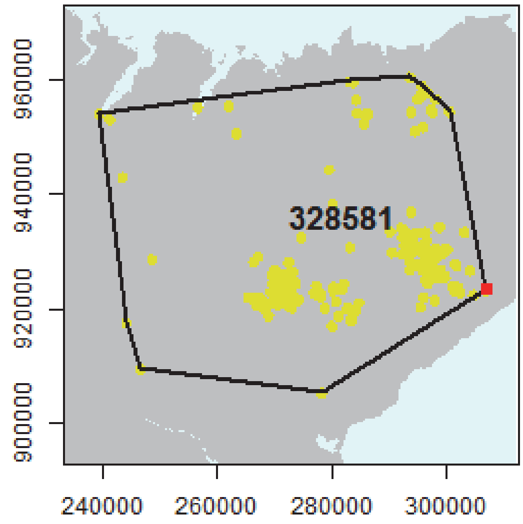
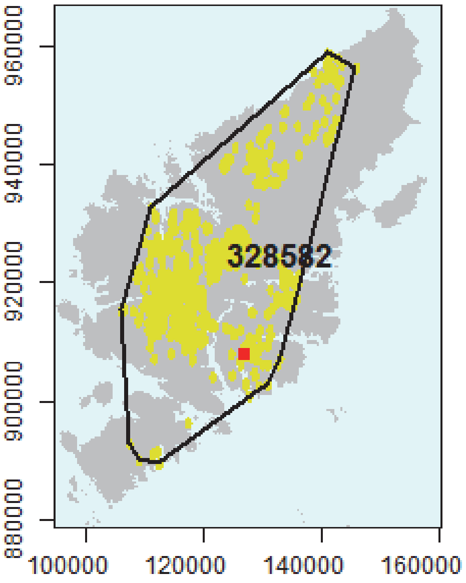
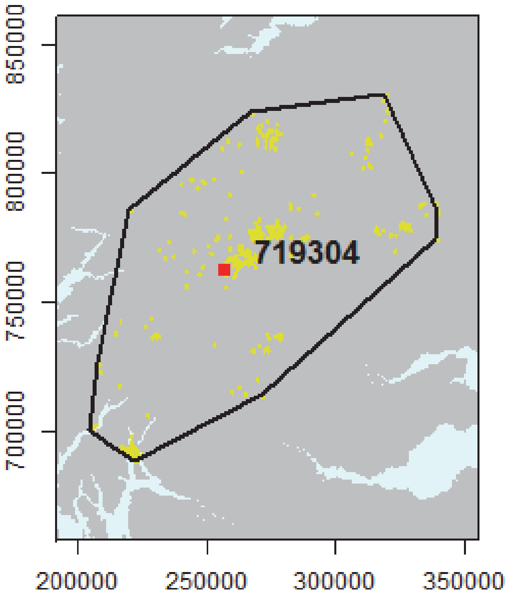
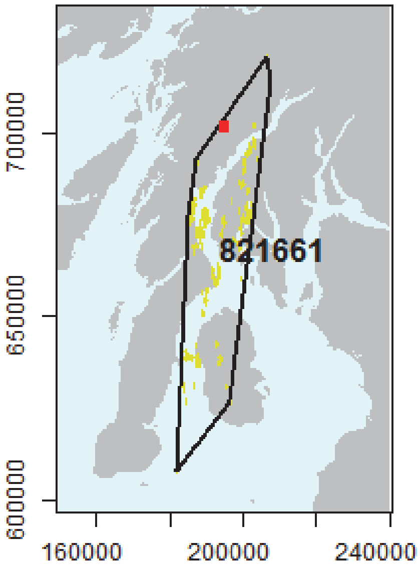
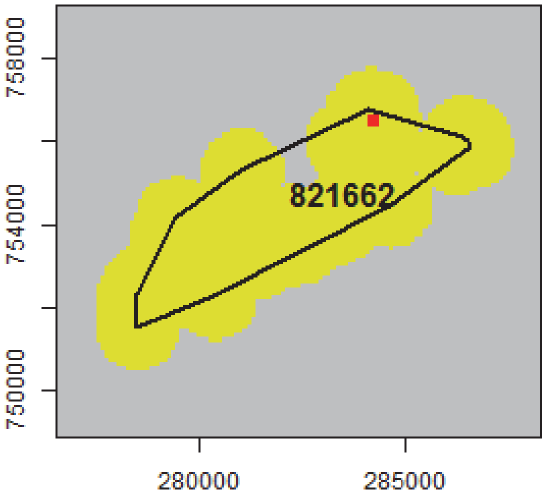




719301 not shown because the map would identify the nest location







821663 not shown because the map would identify the nest location

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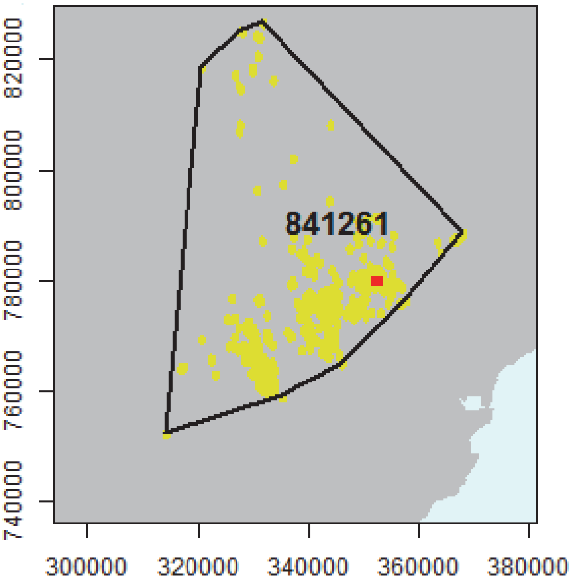

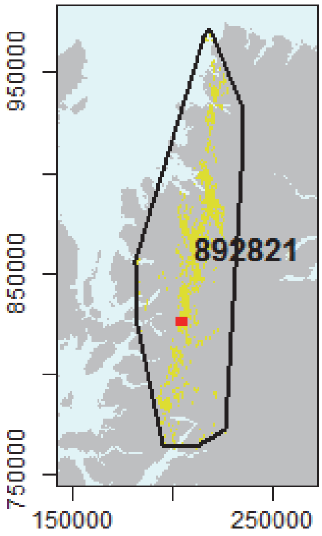

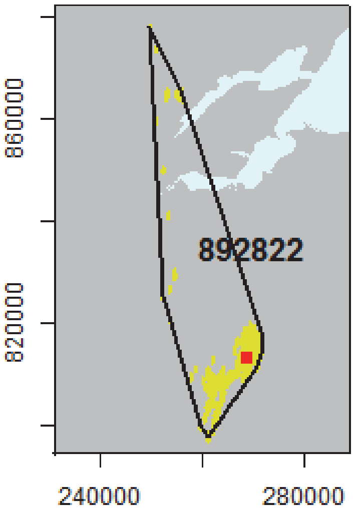

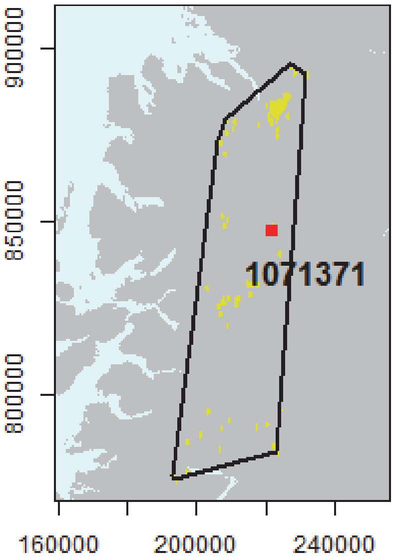

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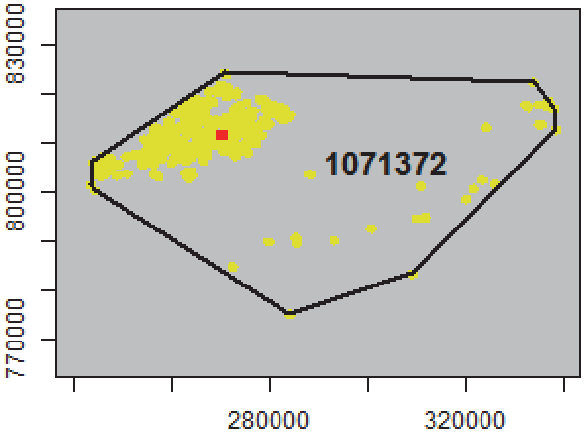


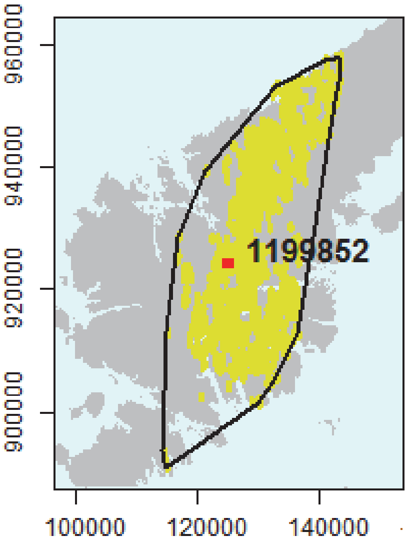


Table A2.1. Final fix locations for tags which were not transmitting at 15 January 2017, by tag model and assigned fate (see main text, section 2).

Tag model	Final X co-ordinate	Final Y co-ordinate	Tag fate
105GPS	253879	761921	Battery drained
105GPS	112496	923396	Battery drained
105GPS	131338	901897	Battery drained
105GPS	334112	786313	Battery drained
105GPS	248945	710419	Battery drained
105GPS	267574	713754	Battery drained
80NS	134199	912408	Battery drained
105GPS	81989	814176	Died - natural
105GPS	217251	695166	Died - natural
105GPS	306449	922604	Died - natural
70GPS	188281	719915	Died - natural
70GPS	188281	719915	Died - natural
70GPS	289121	775150	Died - natural
70GPS	199906	826185	Died - natural
70GPS	312485	941365	Died - natural
80NS	72507	801482	Died - natural
105GPS	276391	734687	Dropped - not suspicious
105GPS	194997	701728	Dropped - not suspicious
105GPS	284170	756444	Dropped - not suspicious
70GPS	280980	808493	Dropped - not suspicious
70GPS	231206	847552	Dropped - not suspicious
70GPS	235912	953791	Dropped - not suspicious
70GPS	277800	877800	Dropped - not suspicious
70GPS	284614	918409	Dropped - not suspicious
70GPS	187977	714429	Dropped - not suspicious
70GPS	356943	791654	Dropped - not suspicious
70GPS	230319	845248	Dropped - not suspicious
70GPS	227874	910433	Dropped - not suspicious
80NS	131018	932726	Dropped - not suspicious
80NS	252563	752942	Dropped - not suspicious
80NS	217844	703480	Dropped - not suspicious
80NS	287283	817579	Dropped - not suspicious
80NS	332982	806001	Dropped - not suspicious
80NS	318615	801917	Dropped - not suspicious
70GPS	356465	779914	Dropped - suspicious
105GPS	173212	788809	Killed
70GPS	333162	820715	Killed
70GPS	356067	781587	Killed
70GPS	352798	785056	Killed
70GPS	343001	770688	Killed
105GPS	347002	790025	Stopped - malfunction
105GPS	283291	781566	Stopped - malfunction
105GPS	207598	825185	Stopped - malfunction

Tag model	Final X co-ordinate	Final Y co-ordinate	Tag fate
105GPS	320535	812422	Stopped - malfunction
70GPS	344744	793023	Stopped - malfunction
80NS	306936	791919	Stopped - malfunction
105GPS	247371	713799	Stopped - no malfunction
105GPS	274005	785475	Stopped - no malfunction
105GPS	324657	827839	Stopped - no malfunction
70GPS	325335	778500	Stopped - no malfunction
70GPS	286772	782267	Stopped - no malfunction
70GPS	280437	818608	Stopped - no malfunction
70GPS	344470	789242	Stopped - no malfunction
70GPS	280598	823096	Stopped - no malfunction
70GPS	336163	776632	Stopped - no malfunction
70GPS	341681	776736	Stopped - no malfunction
70GPS	274200	816102	Stopped - no malfunction
70GPS	274557	790657	Stopped - no malfunction
70GPS	280527	824472	Stopped - no malfunction
70GPS	283259	742009	Stopped - no malfunction
70GPS	274352	814130	Stopped - no malfunction
70GPS	330088	819096	Stopped - no malfunction
70GPS	246888	799813	Stopped - no malfunction
70GPS	269956	825834	Stopped - no malfunction
70GPS	138087	697434	Stopped - no malfunction
70GPS	344659	782151	Stopped - no malfunction
70GPS	276662	781663	Stopped - no malfunction
70GPS	333765	820705	Stopped - no malfunction
70GPS	283219	741323	Stopped - no malfunction
70GPS	268975	825660	Stopped - no malfunction
70GPS	333365	820210	Stopped - no malfunction
70GPS	270966	809649	Stopped - no malfunction
70GPS	269190	826081	Stopped - no malfunction
70GPS	296001	775789	Stopped - no malfunction
70GPS	138467	793104	Stopped - no malfunction
70GPS	215803	802920	Stopped - no malfunction
70GPS	313490	807515	Stopped - no malfunction
70GSM	275066	820625	Stopped - no malfunction
70GSM	286910	744810	Stopped - no malfunction
80NS	280537	737463	Stopped - no malfunction
80NS	274822	744089	Stopped - no malfunction
80NS	125278	911115	Stopped - no malfunction
80NS	123680	918822	Stopped - no malfunction
80NS	170255	616555	Stopped - no malfunction

ANNEX 2: DETAILED RESULTS OF SPATIAL ANALYSES

ANNEX 2.1. Nearest neighbour sampling of all tags with no undetected tag failures

05/02/2017

R Libraries

```
library(knitr)
library(foreign)
library(plyr)
library(FNN)
library(qdapRegex)
```

Background

This analysis uses a random sampling algorithm to determine the probability of observing the known last known fixes (lkf) from satellite tags fitted to golden eagles that appeared to be functioning correctly prior to their final location. The analysis begins by reading in a CSV file of location data. Duplicate records have been removed, for example multiple locations from a roosting individual. Note that the same location, from one tag, will be retained on different days because the unique function examines the entire record and not just the location.

```
xylocs<-read.csv("xydata_nodups_Feb17.csv", as.is = FALSE)
```

Tag metadata

The metadata about the tags are loaded and used to create subsets for subsequent sampling. The data have a snmlf field in which 1 indicates a snmlf, other values are 0. The number of snmlfs is retained as qsus.

```
tagmeta<-read.csv("tagmetadatajan17.csv", as.is = FALSE)
attach(tagmeta)
qsus<-sum(tagmeta$snmlf)
```

Sampling effort

The subsequent random sampling is designed to preferentially select tags in the relation to the number of days of records, i.e. stratified random sampling. The Days field is the number of days between and a tag's last and first records. daysum is sum of days over all tags. Therefore, Days/daysum is the proportion of all tracked days allocated to a particular tag.

```
daysum<-sum(tagmeta$Days)
tagmeta$dayprop<-tagmeta$Days/daysum
```

Preparing sampling

The number of iterations is set, in this example to 5,000. The nndists data frame is created to store the results of the summary statistics of the NNDs. Another data frame, IDlist, is created to keep a record of which tags are sampled as a check that the stratified sampling is working correctly. Finally the random number seed is set to ensure reproducibility.

```
attach(xylocs)

## The following object is masked from tagmeta:
##     Days
```

```
iterations<-5000
rows<-iterations
nndists <- data.frame(min1=numeric(rows), q11=numeric(rows), med1=numeric(rows),
mean1=numeric(rows), q31=numeric(rows), max1=numeric(rows), min2=numeric(rows),
q12= numeric(rows), med2=numeric(rows), mean2=numeric(rows), q32=numeric(rows),
max2=numeric(rows), min3=numeric(rows), q13=numeric(rows), med3=numeric(rows),
mean3=numeric(rows), q33=numeric(rows), max3=numeric(rows), min4=numeric(rows),
q14=numeric(rows), med4=numeric(rows), mean4=numeric(rows), q34=numeric(rows),
max4=numeric(rows), min5=numeric(rows), q15=numeric(rows), med5=numeric(rows),
mean5=numeric(rows), q35=numeric(rows), max5=numeric(rows))
IDlist<-data.frame(matrix(ncol = qsus, nrow = rows))
set.seed(12345)
```

Random sampling

The sampling iterations are contained within a loop. The loop begins at 2 to leave space in row 1 of the nndist data frame for the 'real' data. A random sample of tag IDs, qsample, is drawn without replacement from the tag metadata. The number of tags sampled is set to qsus and tags are sampled with a probability that is in proportion to their relative number of days (dayprop). lst is a list of the sampled tag IDs. The list is sorted and stored in the IDlist data frame. The IDlist can be used at the end of the analysis to verify that tags were sampled appropriately. Tag locations, for those tags in the sample, are extracted from the full xylocs data frame into a smaller xylocsample data.frame (xylocs$ID %in% lst). A single location is selected next, at random, from each of the sampled tag's locations. This sampling is weighted to decrease the probability of sampling an early record. The samp_p field is calculated as dayno/(dayno + Days/4). The extracted record is stored in s2. Only the X & Y columns are retained in s2 meaning that it has two columns (X & Y) which are a single location from each tag in the sample list. NNDs are found for the locations in s2. In this analysis the first five nearest neighbours are identified. At this point each sampled tag has a list of its five NNDs. The five sets of NNDs are summarised (min, 1st quartile (q1), median, mean, 3rd quartile (q3) and max) and stored in nndo. nndo contains text which needs to be removed using the as_numeric2 funtion from the qdapRegex package. However, this function requires a space before a digit so the colon separator is first replaced by : followed by a space using the gsub function. Finally, the 30 nearest neighbour summary statistics (six for each of the five NNDs) is retained in the nndists data frame.

```
for (i in 2:iterations) {
   qsample <- tagmeta[sample(1:nrow(tagmeta),qsus,replace=FALSE,tagmeta$dayprop),]
   lst<-qsample$TagID
   IDlist[i-1,]<-lst[order(lst)]
   xylocsample<-xylocs[xylocs$ID%in% lst,]
   lstlen<-length(lst)
   s2<-data.frame(X=numeric(lstlen), Y=numeric(lstlen))
   for (a in 1:lstlen) {
      s <- xylocsample[ which(xylocsample$ID==lst[a]), ]
      samp_idx <- sample(seq_len(nrow(s)), 1, prob=s$samp_p)
      s2[a,] <- s[samp_idx,c("X","Y") ]
   }
   nnd<-knn.dist(s2,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
   nndo<-summary(nnd)
   nndo<-gsub("[:]",": ",nndo)
   tmp2<-as_numeric2(ex_number(nndo))
   for (j in 1:30) nndists[i,j]<- tmp2[j]
}
```

Real nearest neighbours

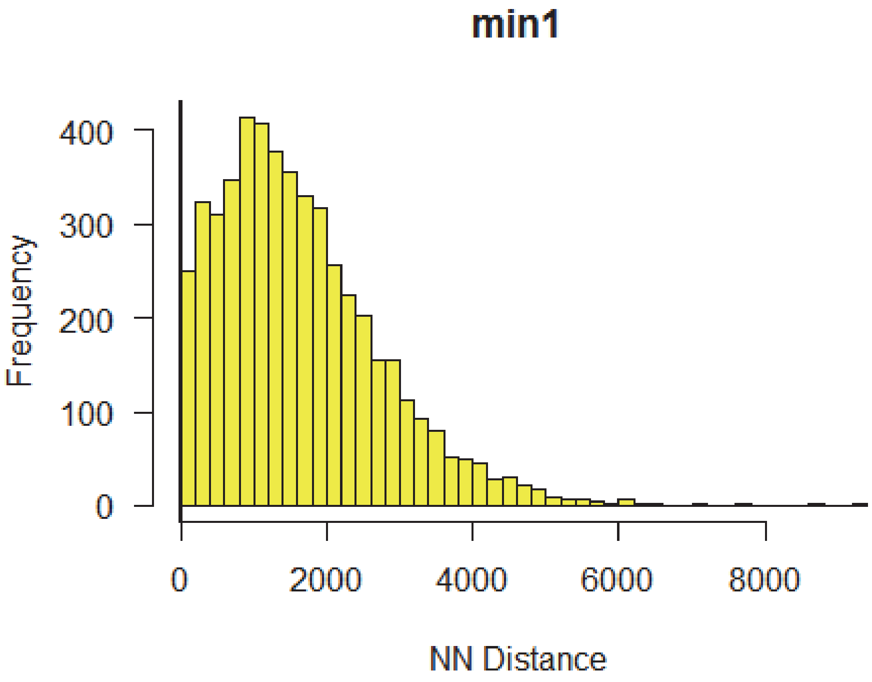
The final section finds the five NNDs for the snmlfs of tags that ceased to function with no prior indication of a fault with the tag. The process is the same as in the sampling iterations except that the tag metadata file is the source of the final X & Y fixes. Summary statistics are stored in the first row of the nndists data frame. The final step is storing the results in text files. The IDlist (list of sampled tags) has to be stacked prior to saving the list.

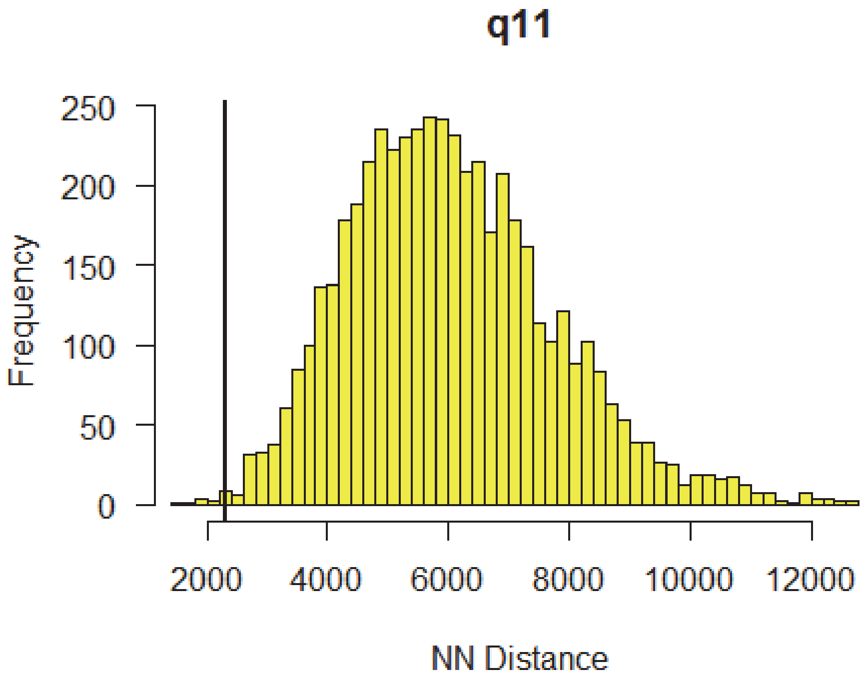
```
sx<-tagmeta[which(tagmeta$snmlf>0),c("FinX","FinY")]
nndx<-knn.dist(sx,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
nndo<-summary(nndx)
nndo<-gsub("[:]",": ",nndo)
tmp2<-as_numeric2(ex_number(nndo))
for (j in 1:30) nndists[1,j]<- tmp2[j]
write.table(nndists,file="nndistsalltags.txt",sep="\t")
IDcount<-stack(IDlist)
IDcount<-as.matrix(table(IDcount$values))
write.table(IDcount,file="nndistsalltags_n.txt",sep="\t")
```

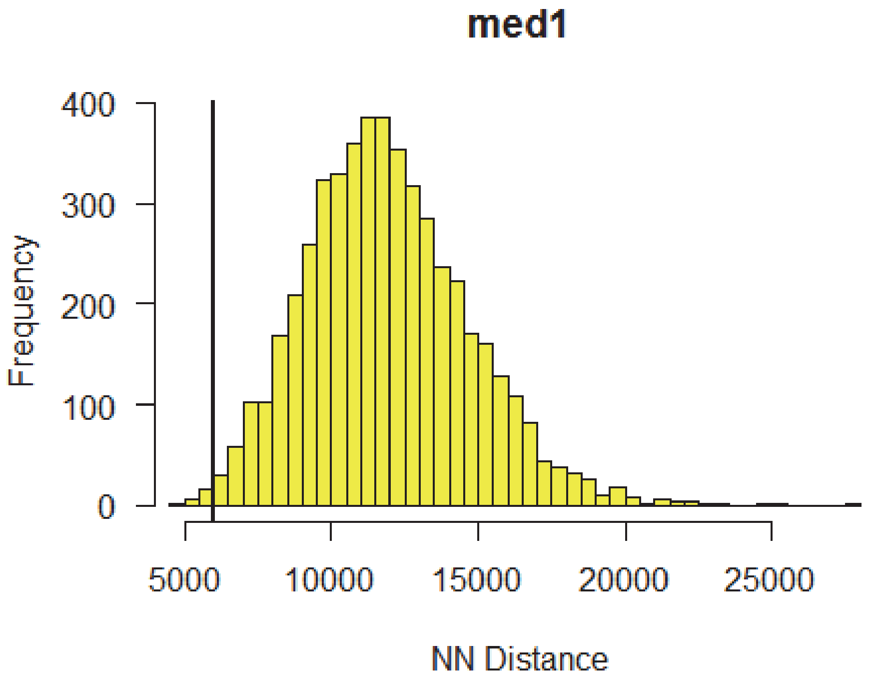
Plot the results

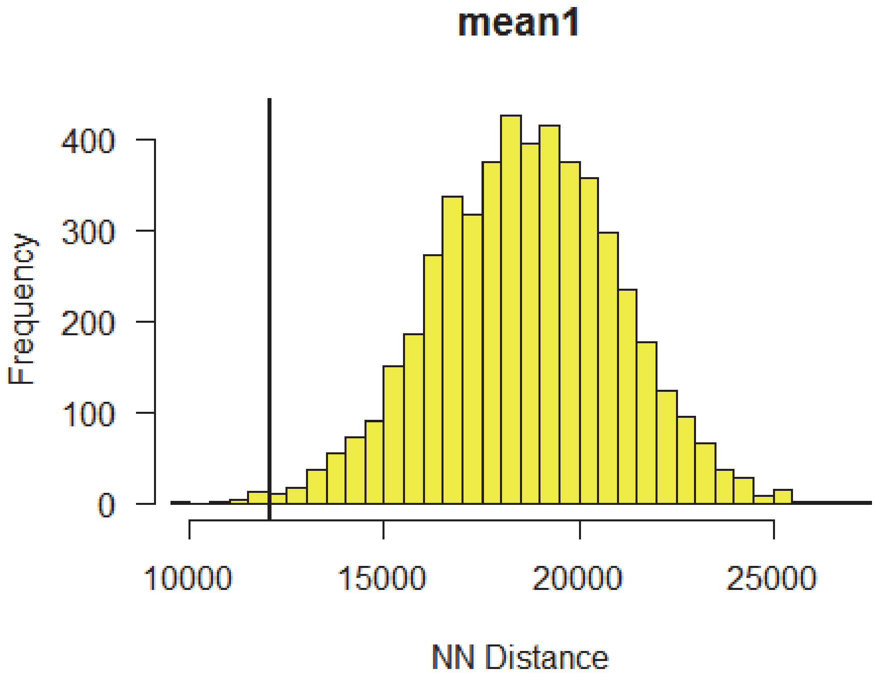
A frequency distribution is plotted for each nearest neighbour's sampling distribution and the real value is shown as a vertical black line.

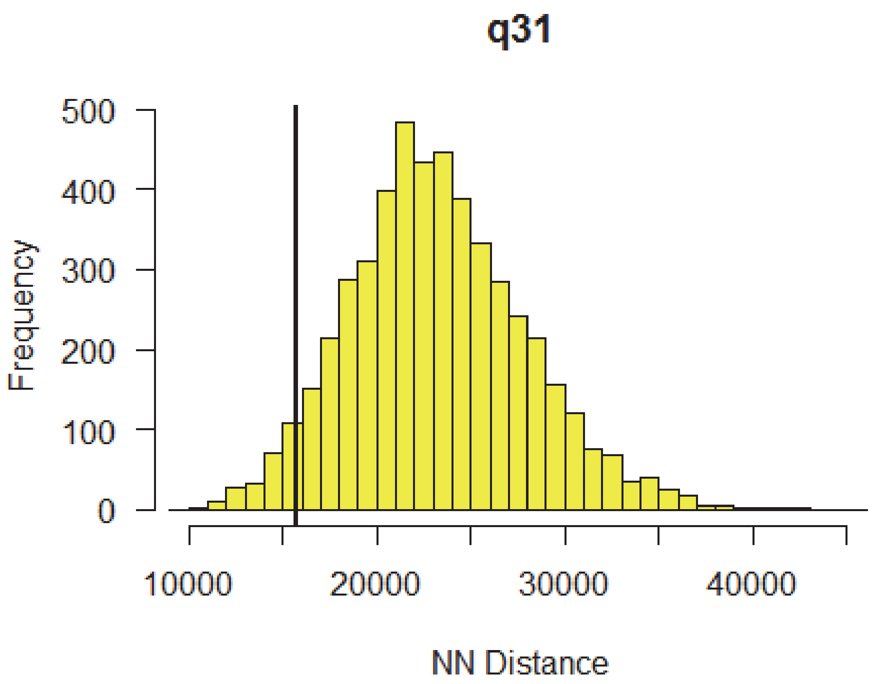
```
cnames<-names(nndists)
bins<-50
for (i in 1:length(cnames)) {
   title<-cnames[i]
   range<-round(range(nndists[,i]), digits=0)
   hist(nndists[,i], main=title, xlab="NN Distance", border="black", col="yellow",
xlim=c(range[1],range[2]), las=1, breaks=bins, prob = FALSE)
   abline(v=nndists[1,i],lty=1,lwd=2,col="black")
}
```

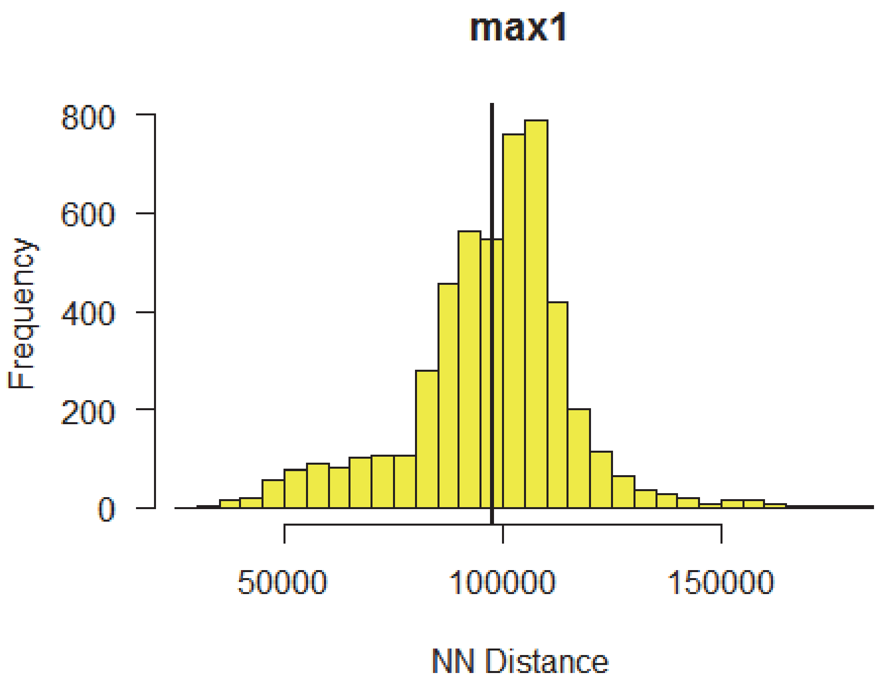

min1
Frequency
400
300
200
100
0
0
2000
4000
6000
8000
NN Distance

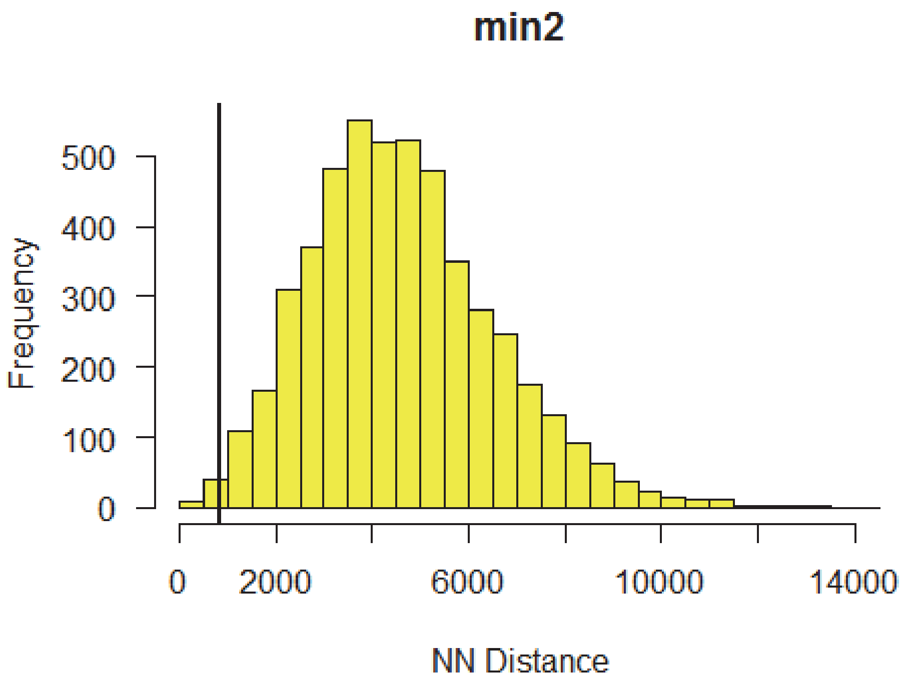

q11
Frequency
250
200
150
100
50
0
2000
4000
6000
8000
10000
12000
NN Distance

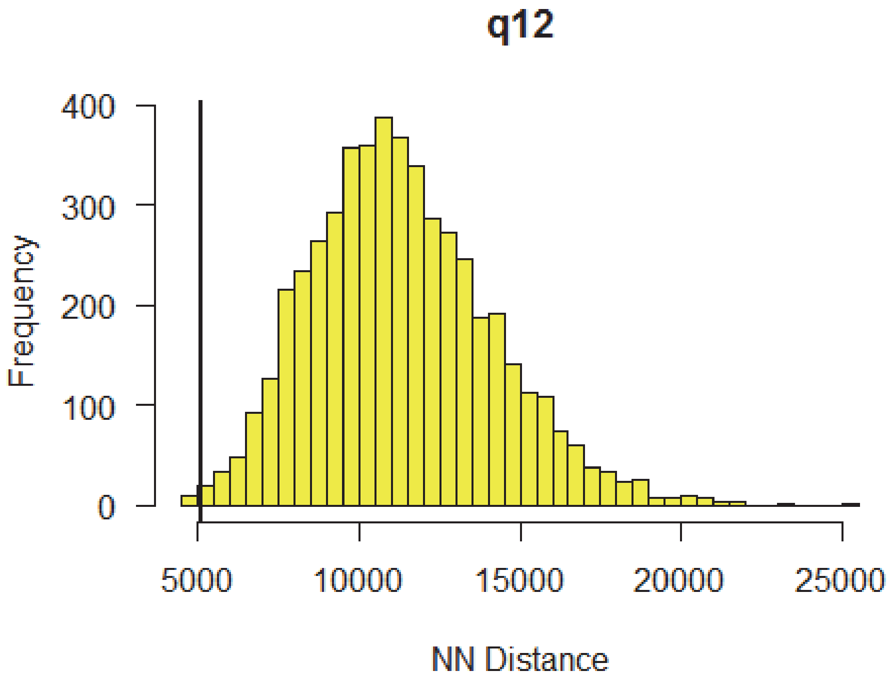

med1
Frequency
0
100
200
300
400
5000
10000
15000
20000
25000
NN Distance

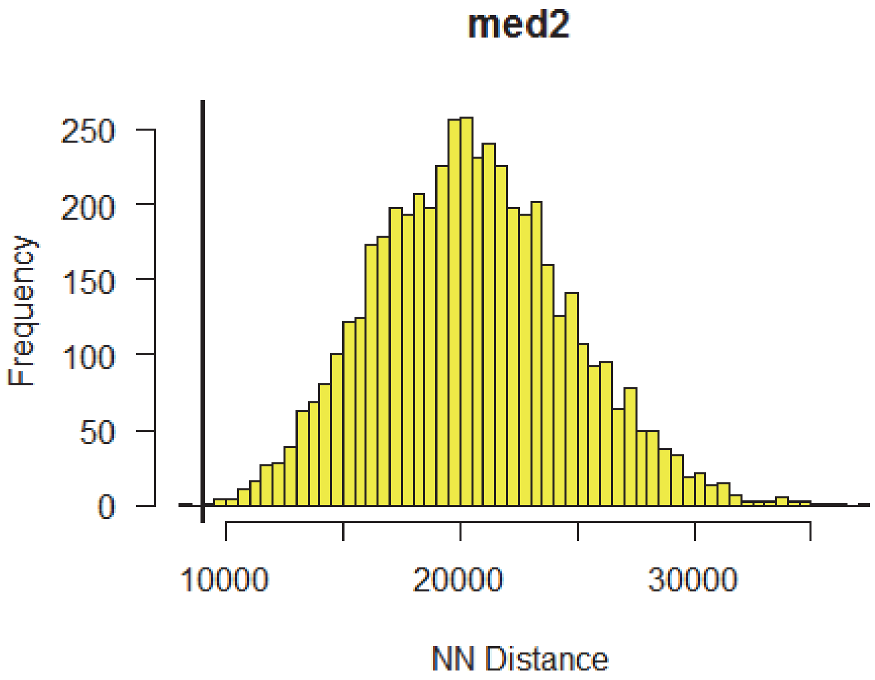

mean1
Frequency
0
100
200
300
400
10000
15000
20000
25000
NN Distance

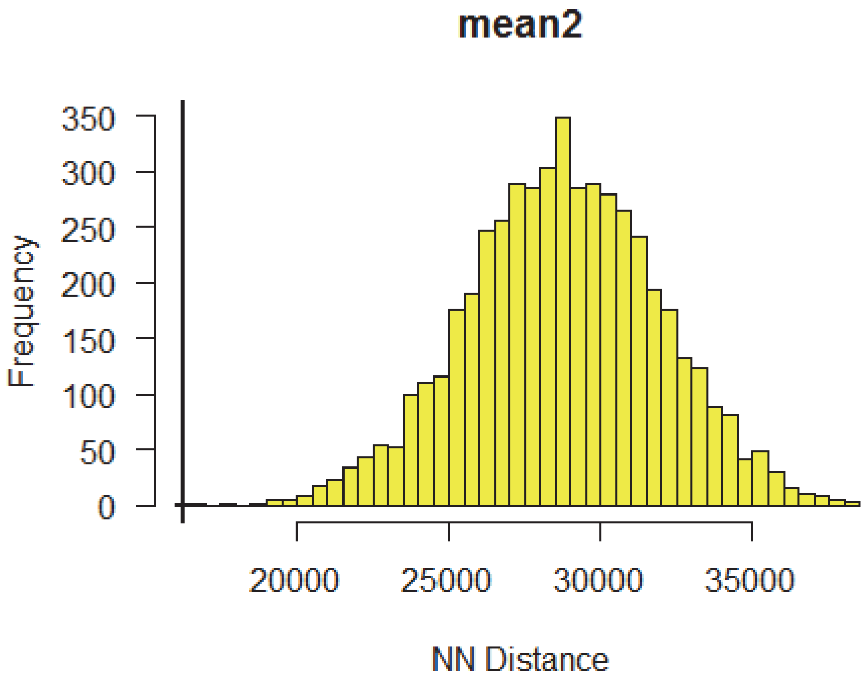

q31
Frequency
0
100
200
300
400
500
10000
20000
30000
40000
NN Distance


max1
Frequency
0
200
400
600
800
50000
100000
150000
NN Distance

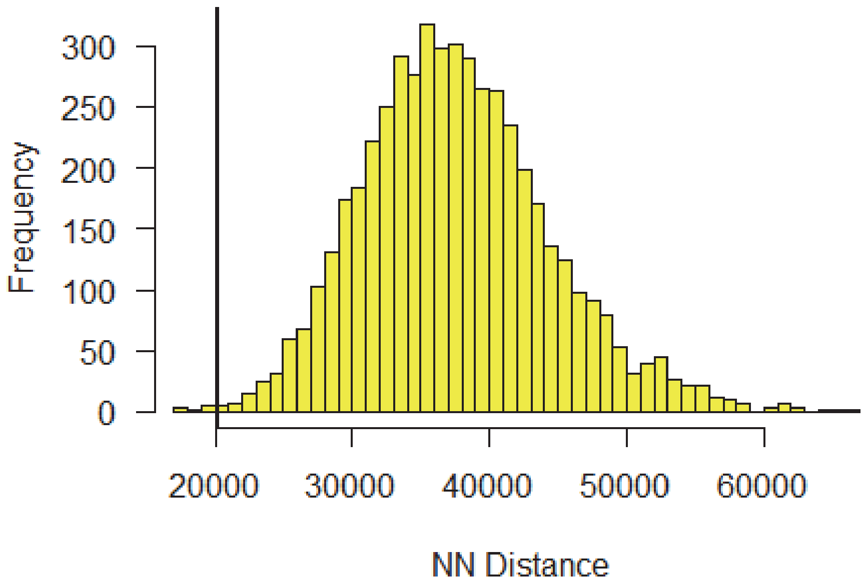

min2
Frequency
0
100
200
300
400
500
0
2000
6000
10000
14000
NN Distance


q12
Frequency
0
100
200
300
400
5000
10000
15000
20000
25000
NN Distance

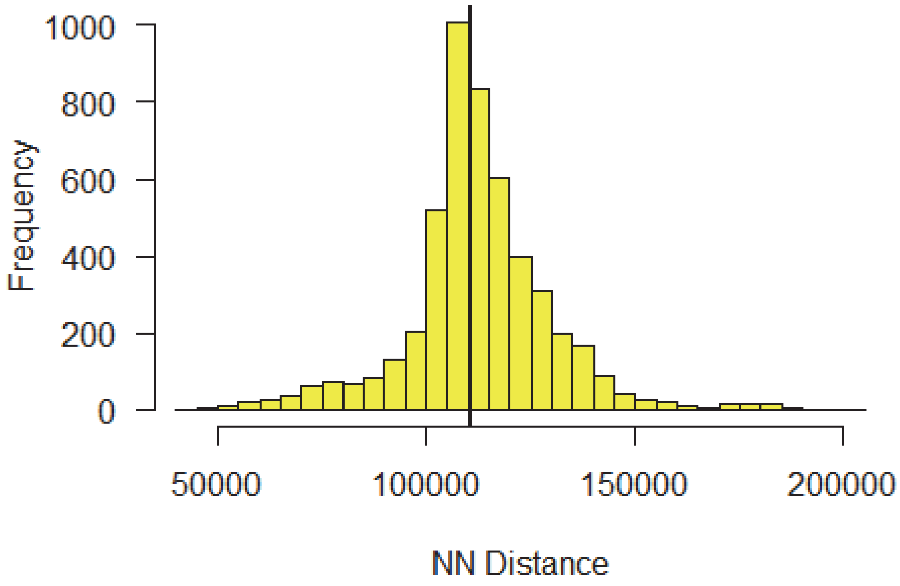

med2
Frequency
250
200
150
100
50
0
10000
20000
30000
NN Distance

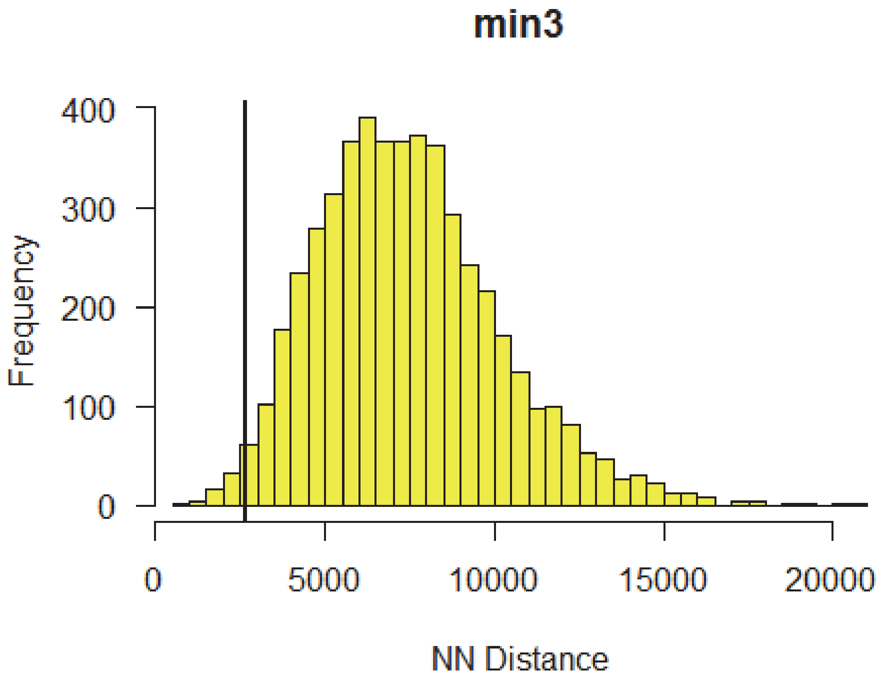

mean2
Frequency
350
300
250
200
150
100
50
0
20000
25000
30000
35000
NN Distance

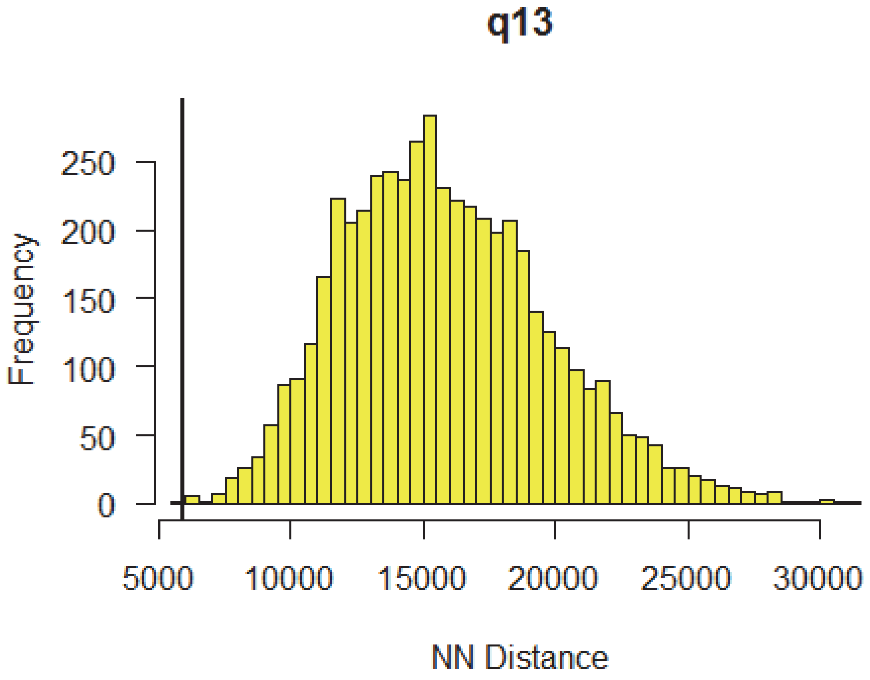
q32

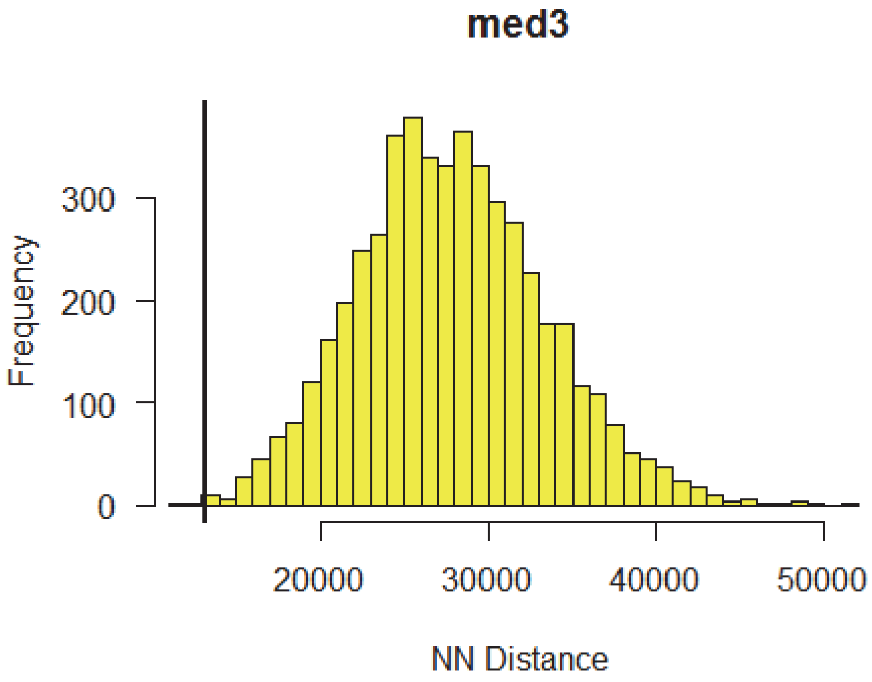

Frequency
300
250
200
150
100
50
0
20000
30000
40000
50000
60000
NN Distance

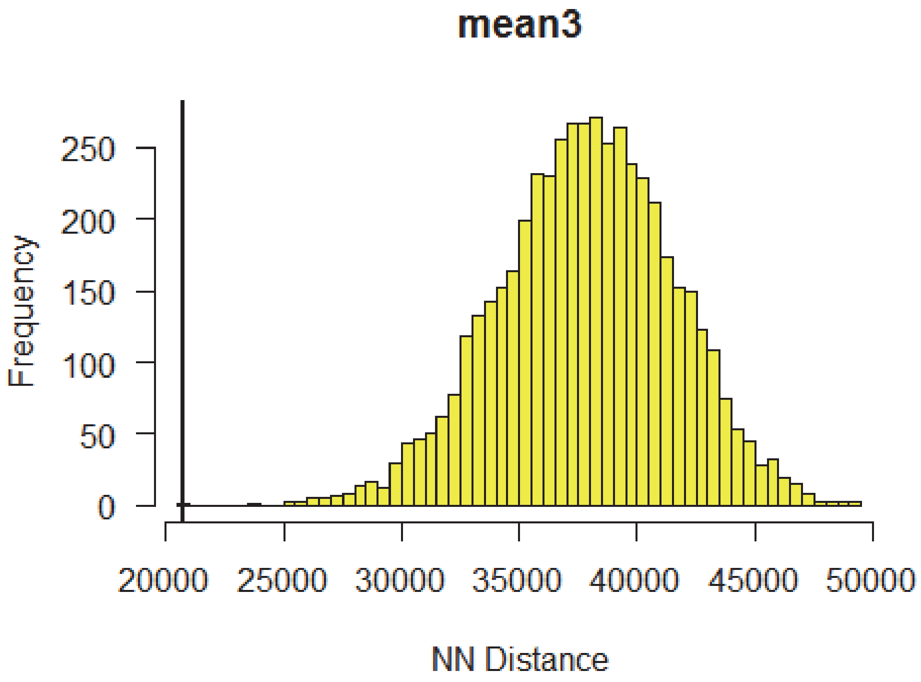
max2

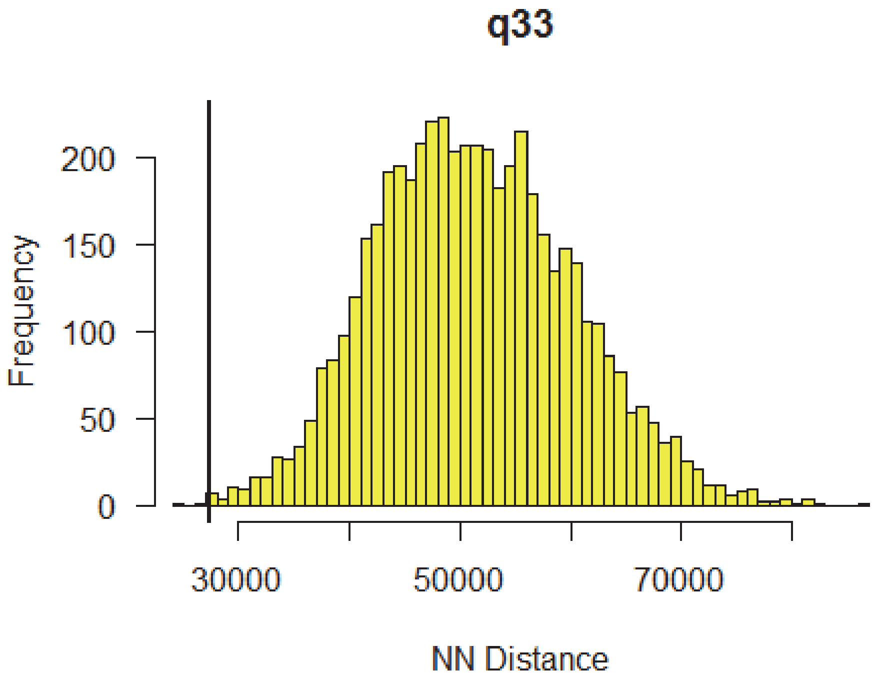

Frequency
1000
800
600
400
200
0
50000
100000
150000
200000
NN Distance

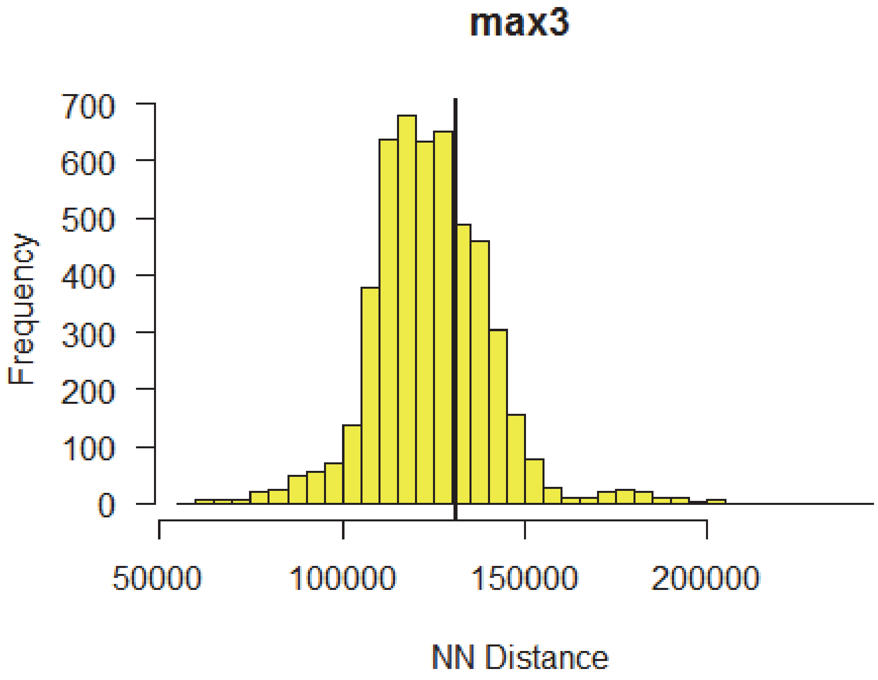

min3
Frequency
0
100
200
300
400
0
5000
10000
15000
20000
NN Distance

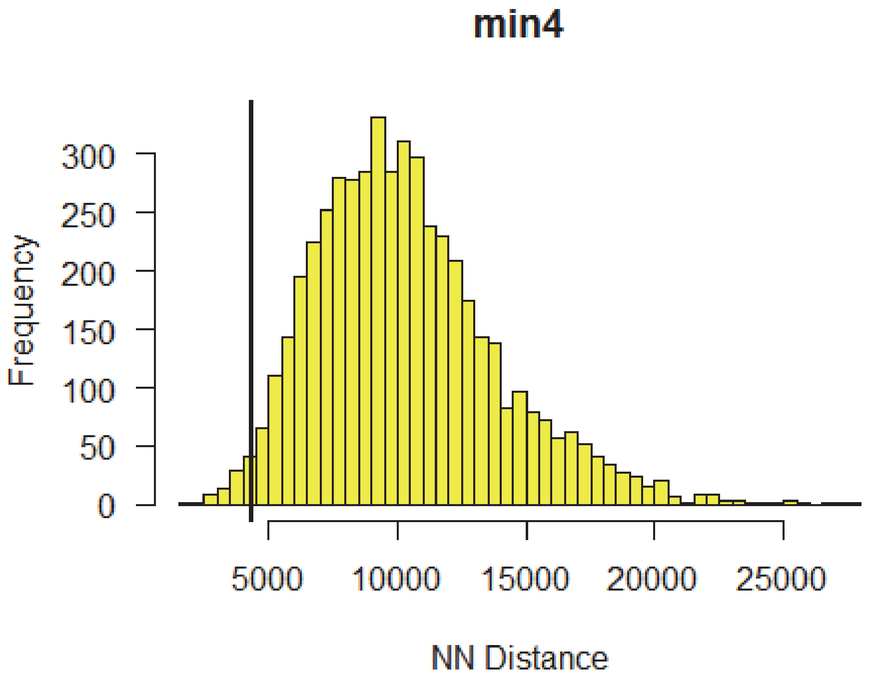

q13
Frequency
0
50
100
150
200
250
5000
10000
15000
20000
25000
30000
NN Distance

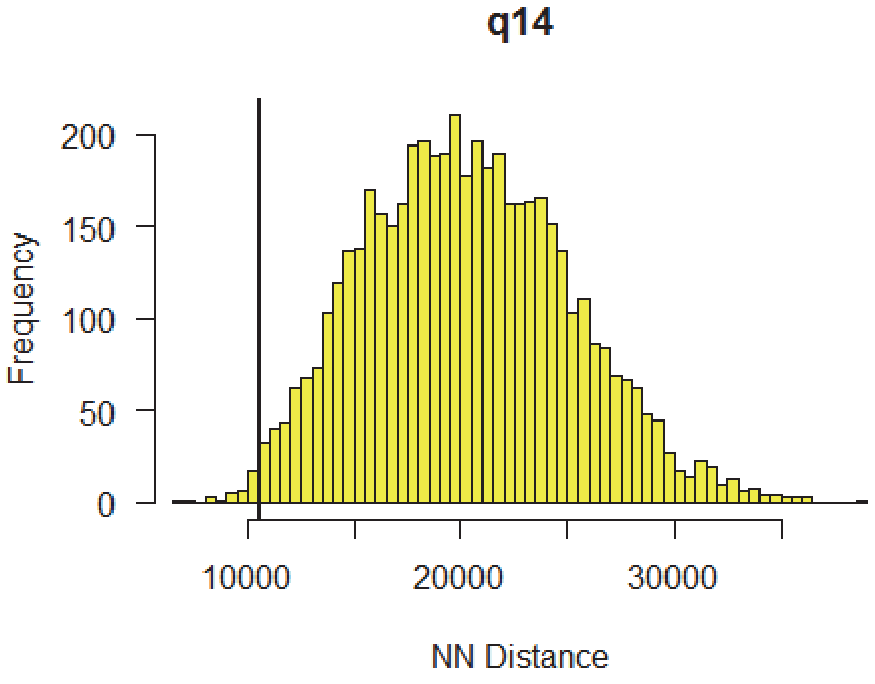

med3
Frequency
0
100
200
300
20000
30000
40000
50000
NN Distance


mean3
Frequency
0
50
100
150
200
250
20000
25000
30000
35000
40000
45000
50000
NN Distance

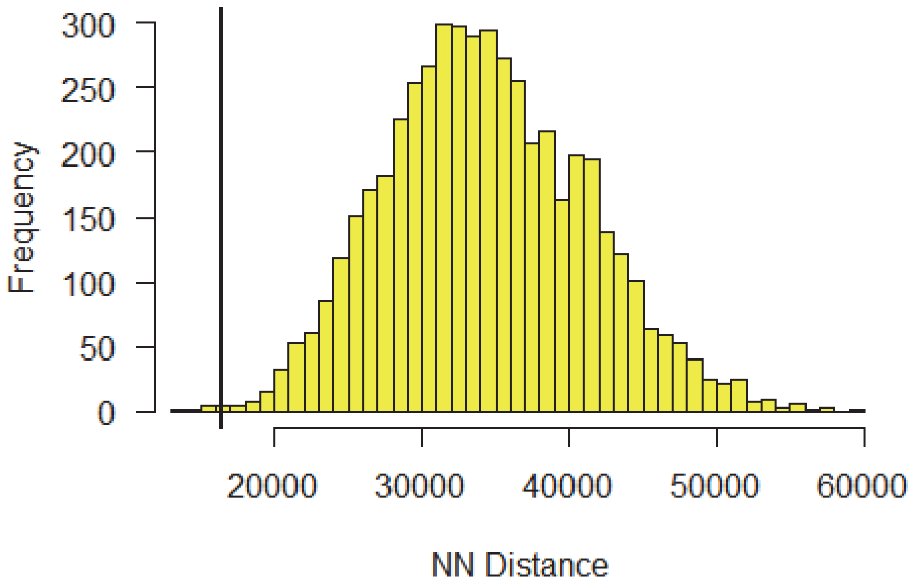

q33
Frequency
200
150
100
50
0
30000
50000
70000
NN Distance


max3
Frequency
700
600
500
400
300
200
100
0
50000
100000
150000
200000
NN Distance


min4
Frequency
0
50
100
150
200
250
300
5000
10000
15000
20000
25000
NN Distance

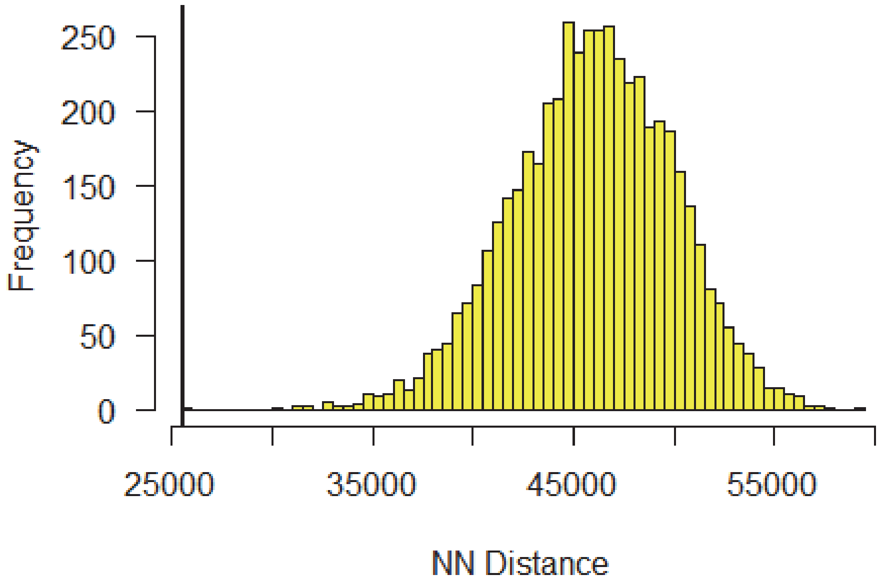

q14
Frequency
0
50
100
150
200
10000
20000
30000
NN Distance

med4

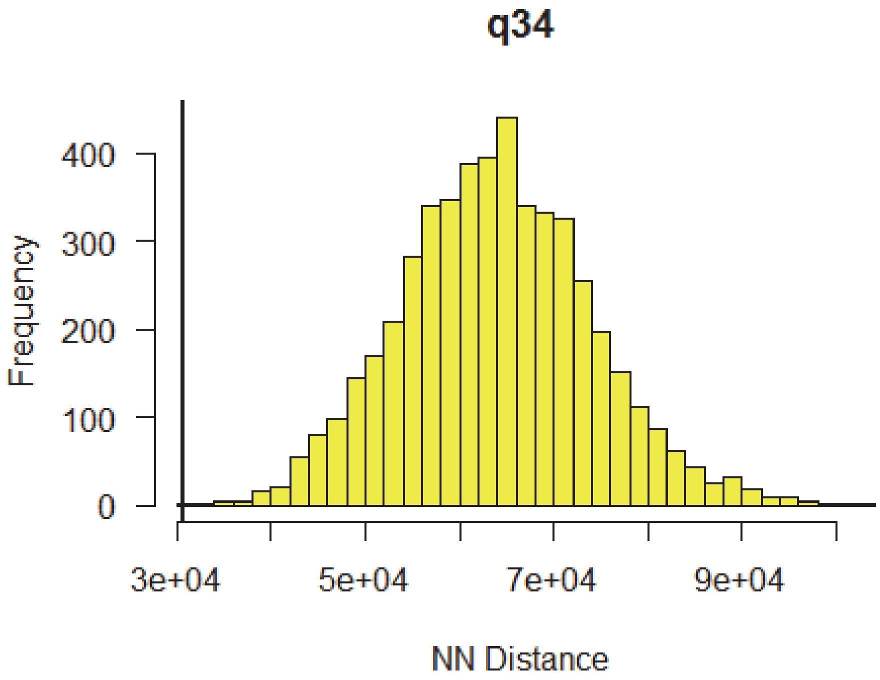


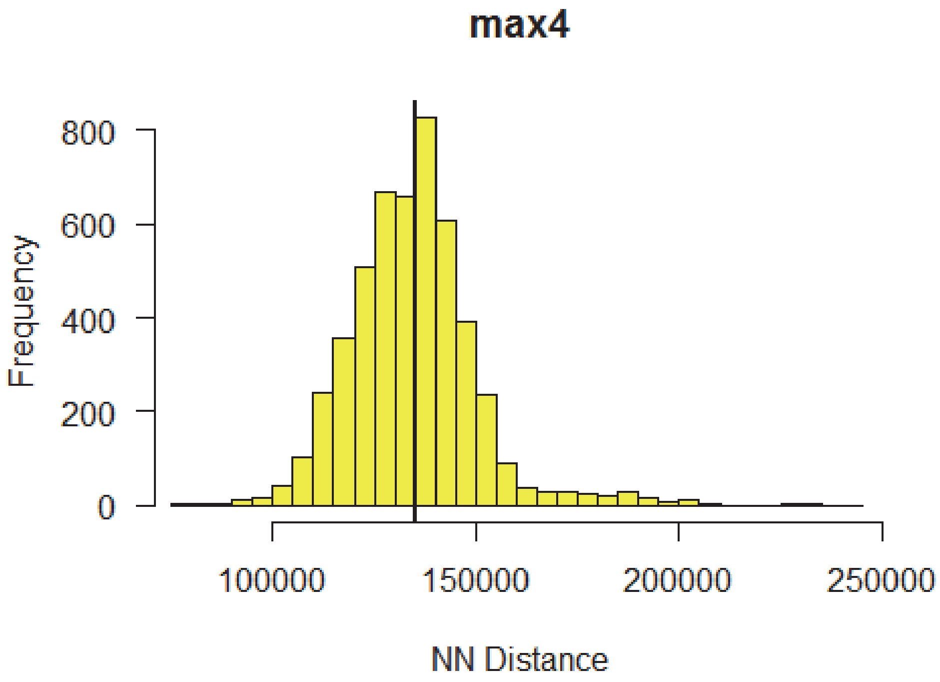
Frequency
300
250
200
150
100
50
0
20000
30000
40000
50000
60000
NN Distance

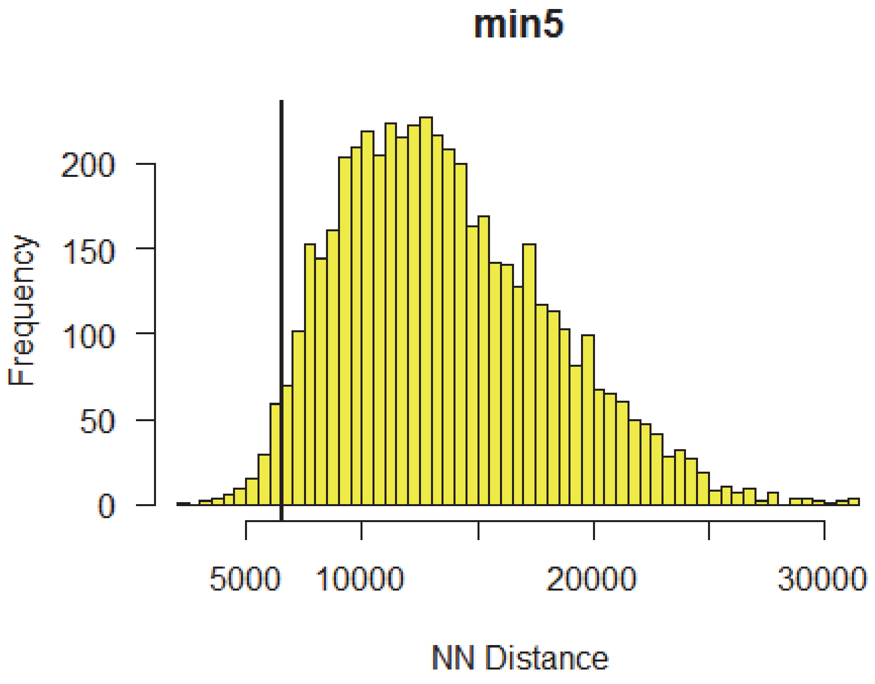
mean4

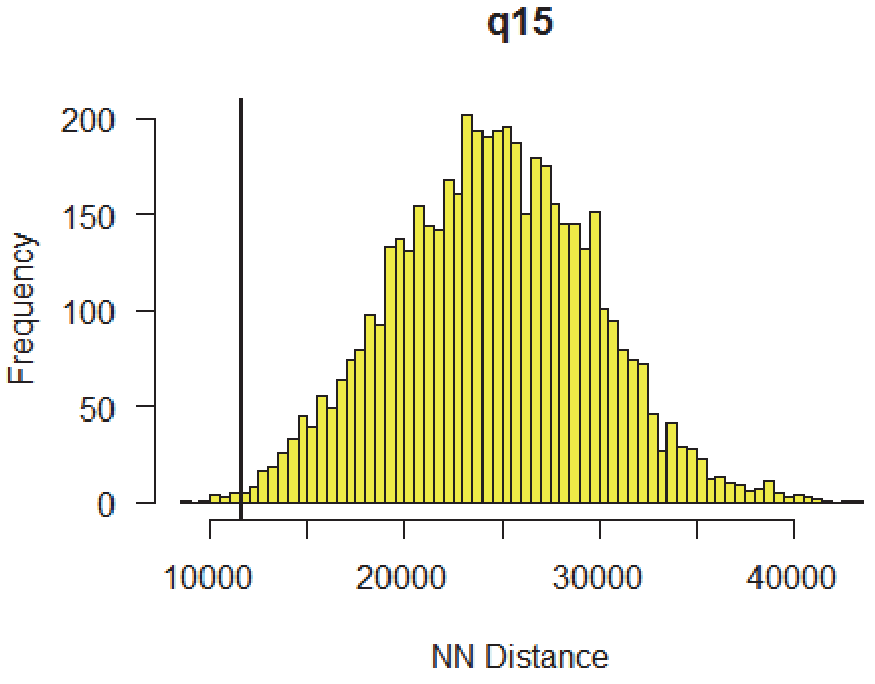


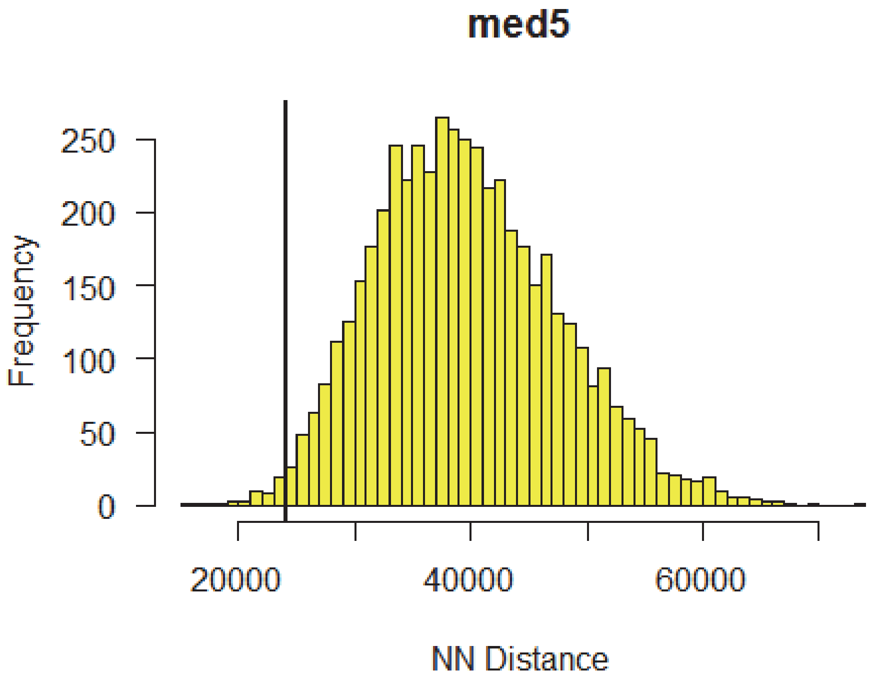
Frequency
250
200
150
100
50
0
25000
35000
45000
55000
NN Distance

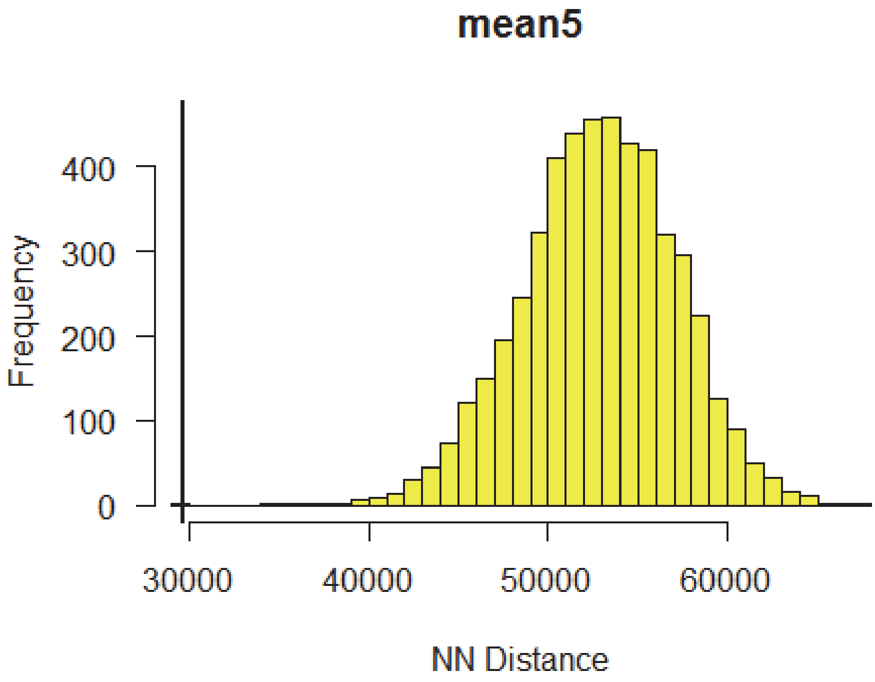

q34
Frequency
400
300
200
100
0
3e+04
5e+04
7e+04
9e+04
NN Distance

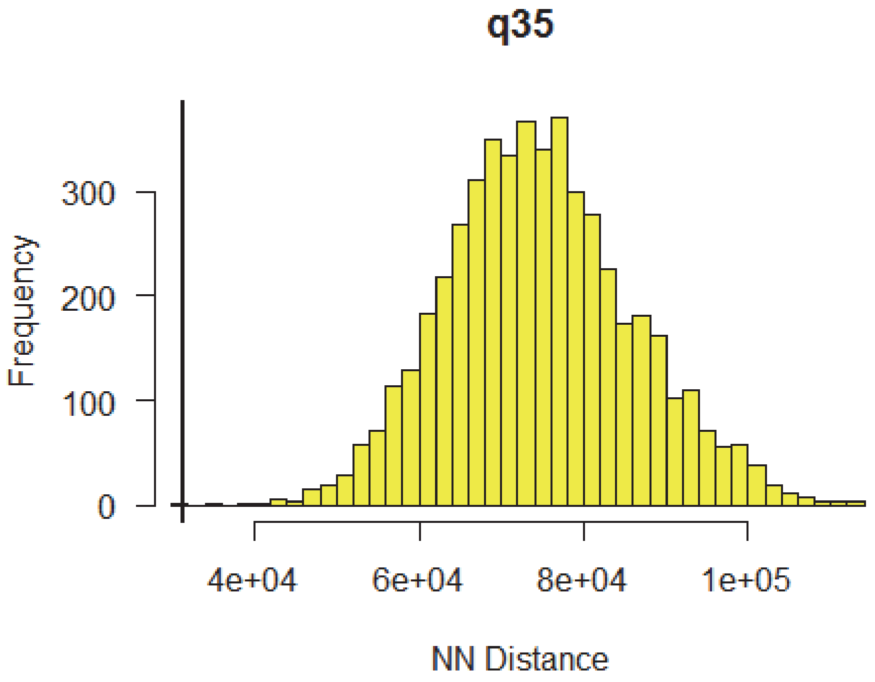

max4
Frequency
800
600
400
200
0
100000
150000
200000
250000
NN Distance

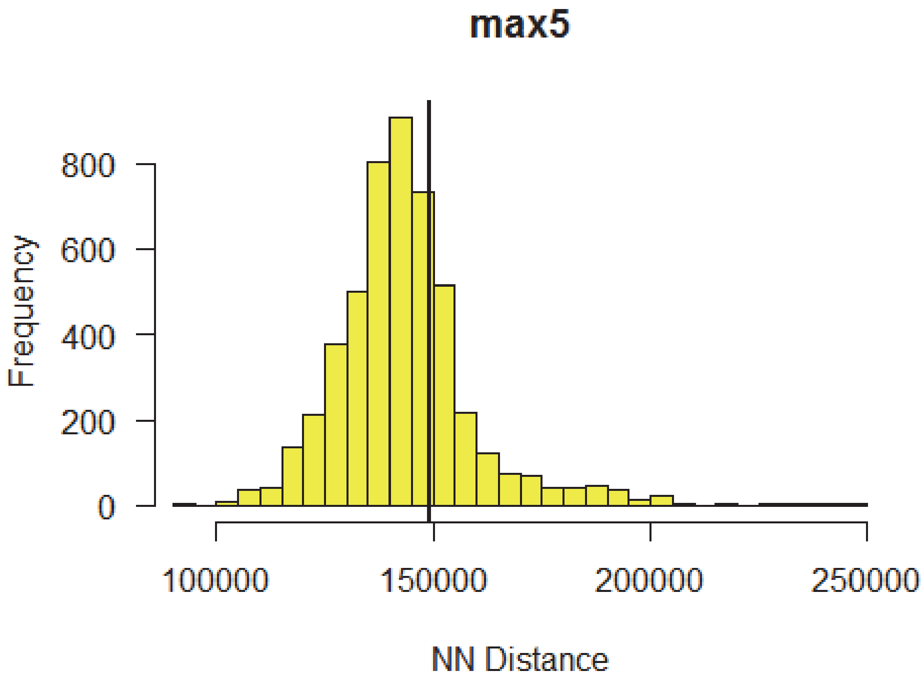

min5
Frequency
0
50
100
150
200
5000
10000
20000
30000
NN Distance


q15
Frequency
0
50
100
150
200
10000
20000
30000
40000
NN Distance


med5
Frequency
250
200
150
100
50
0
20000
40000
60000
NN Distance


mean5
Frequency
400
300
200
100
0
30000
40000
50000
60000
NN Distance


q35
Frequency
300
200
100
0
4e+04
6e+04
8e+04
1e+05
NN Distance


max5
Frequency
800
600
400
200
0
100000
150000
200000
250000
NN Distance

ANNEX 2.2. Satellite tag nearest neighbour sampling of all tags excluding killed birds with no undetected tag failures

05/02/2017

R Libraries

```
library(knitr)
library(foreign)
library(plyr)
library(FNN)
library(qdapRegex)
```

Background

See Annex 2.1

```
xylocs<-read.csv("xydata_nodups_Feb17.csv", as.is = FALSE)
```

Tag metadata

The metadata about the tags, excluding those related to tags fitted to birds known to have been killed, are loaded and used to create subsets for subsequent sampling. The data have a snmlf field in which 1 indicates a snmlf, other values are 0. The number of snmlfs is retained as qsus.

```
tagmeta<-read.csv("tagmetadatajan17nokilled.csv", as.is = FALSE)
attach(tagmeta)
qsus<-sum(tagmeta$snmlf)
```

Sampling effort

See Annex 2.1

```
daysum<-sum(tagmeta$Days)
tagmeta$dayprop<-tagmeta$Days/daysum
```

Preparing sampling

See Annex 2.1

```
attach(xylocs)

## The following object is masked from tagmeta:
##     Days

iterations<-5000
rows<-iterations
nndists <- data.frame(min1=numeric(rows), q11=numeric(rows), med1=numeric(rows),
mean1=numeric(rows), q31=numeric(rows), max1=numeric(rows),min2=numeric(rows),
q12= numeric(rows), med2=numeric(rows), mean2=numeric(rows), q32=numeric(rows),
max2=numeric(rows), min3=numeric(rows),q13=numeric(rows), med3=numeric(rows),
mean3=numeric(rows), q33=numeric(rows), max3=numeric(rows),
min4=numeric(rows),q14=numeric(rows), med4=numeric(rows), mean4=numeric(rows),
q34=numeric(rows), max4=numeric(rows), min5=numeric(rows),q15=numeric(rows),
med5=numeric(rows), mean5=numeric(rows), q35=numeric(rows), max5=numeric(rows))
IDlist<-data.frame(matrix(ncol = qsus, nrow = rows))
set.seed(12345)
```

Random sampling

See Annex 2.1

```
for (i in 2:iterations) {
    qsample <- tagmeta[sample(1:nrow(tagmeta),qsus,replace=FALSE,tagmeta$dayprop),]
    lst<-qsample$TagID
    IDlist[i-1,]<-lst[order(lst)]
    xylocsample<-xylocs[xylocs$ID%in% lst,]
    lstlen<-length(lst)
    s2<-data.frame(X=numeric(lstlen), Y=numeric(lstlen))
    for (a in 1:lstlen) {
        s <- xylocsample[ which(xylocsample$ID==lst[a]), ]
        samp_idx <- sample(seq_len(nrow(s)), 1, prob=s$samp_p)
        s2[a,] <- s[samp_idx,c("X","Y") ]
    }
    nnd<-knn.dist(s2,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
    nndo<-summary(nnd)
    nndo<-gsub("[:]",": ",nndo)
    tmp2<-as_numeric2(ex_number(nndo))
    for (j in 1:30) nndists[i,j]<- tmp2[j]
}
```

Real nearest neighbours

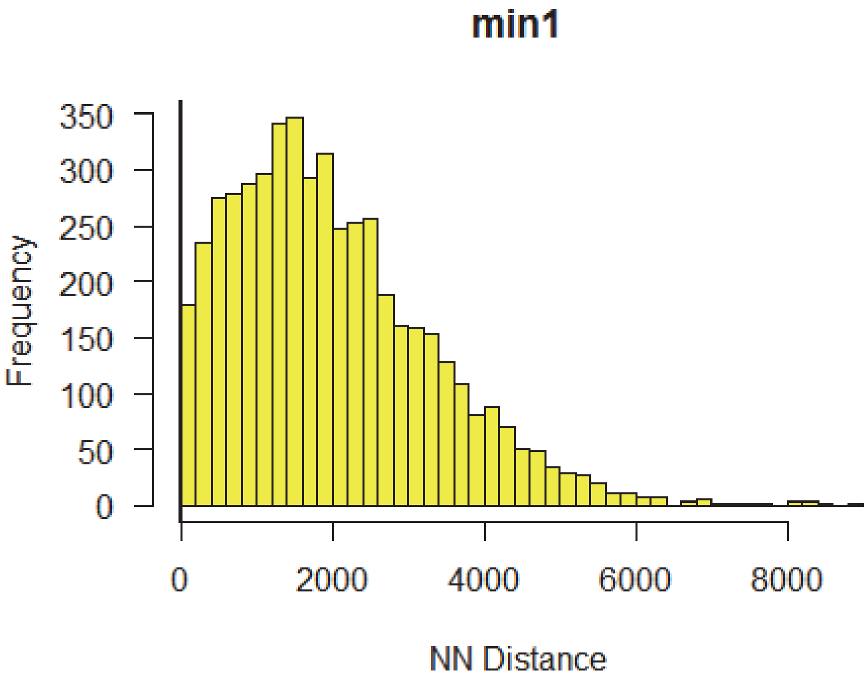
See Annex 2.1

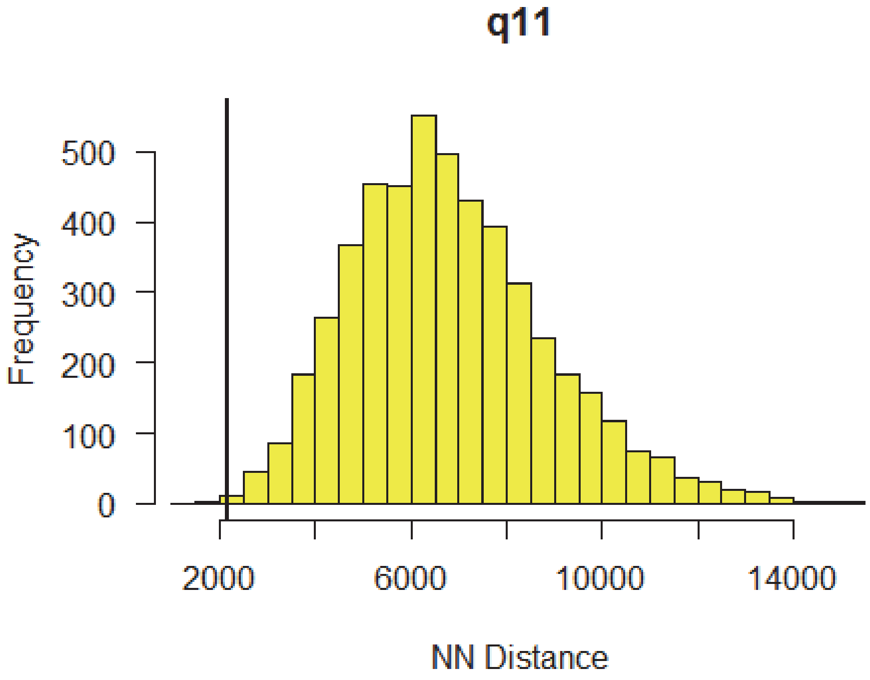
```
sx<-tagmeta[which(tagmeta$snmlf>0),c("FinX","FinY")]
nndx<-knn.dist(sx,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
nndo<-summary(nndx)
nndo<-gsub("[:]",": ",nndo)
tmp2<-as_numeric2(ex_number(nndo))
for (j in 1:30) nndists[1,j]<- tmp2[j]
write.table(nndists,file="nndistsalltagsnokills.txt",sep="\t")
IDcount<-stack(IDlist)
IDcount<-as.matrix(table(IDcount$values))
write.table(IDcount,file="nndistsalltagsnokills_n.txt",sep="\t")
```

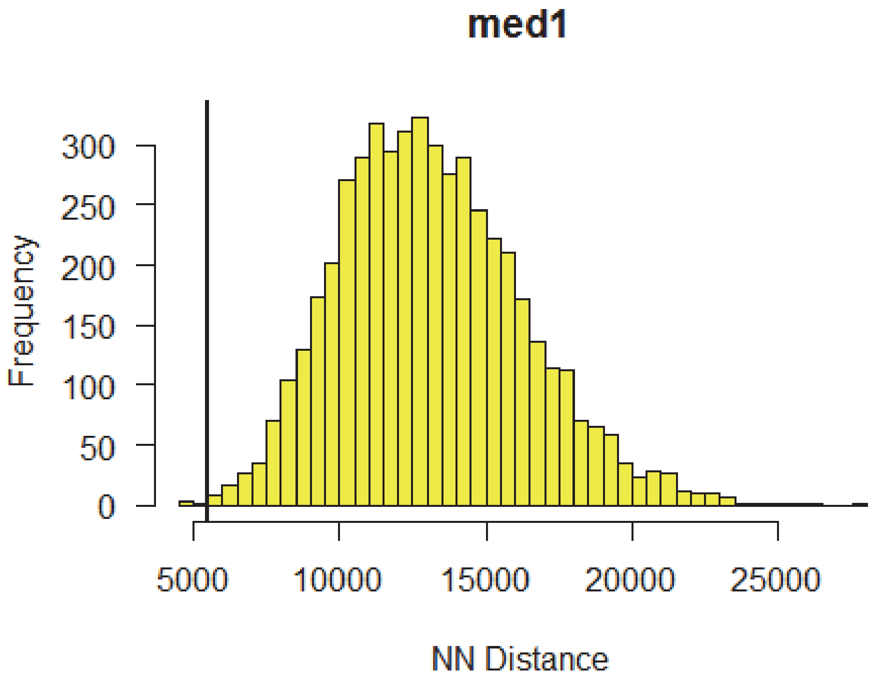
Plot the results

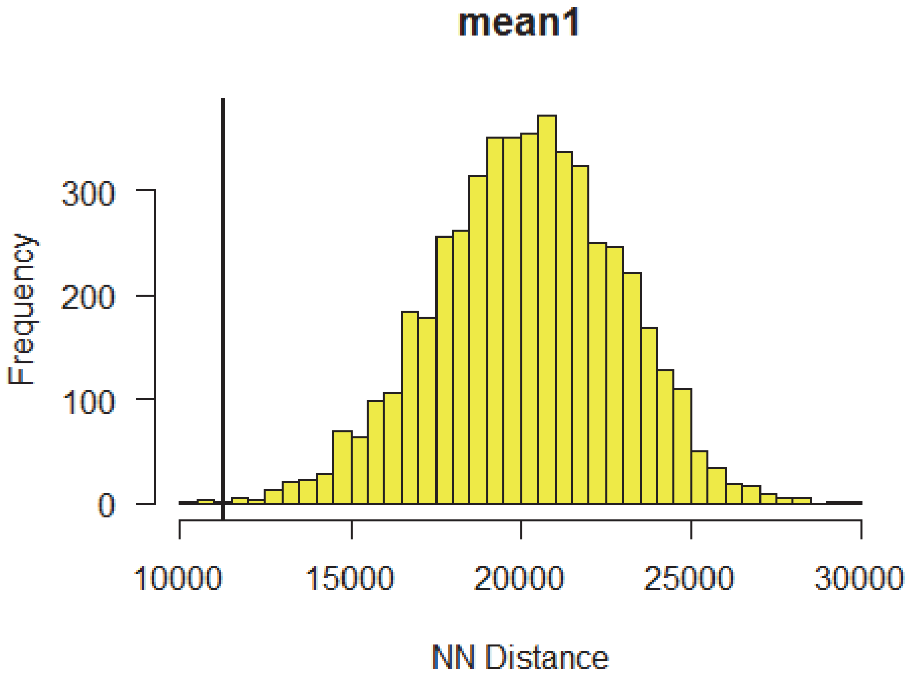
A frequency distribution is plotted for each nearest neighbour's sampling distribution and the real value is shown as a vertical black line.

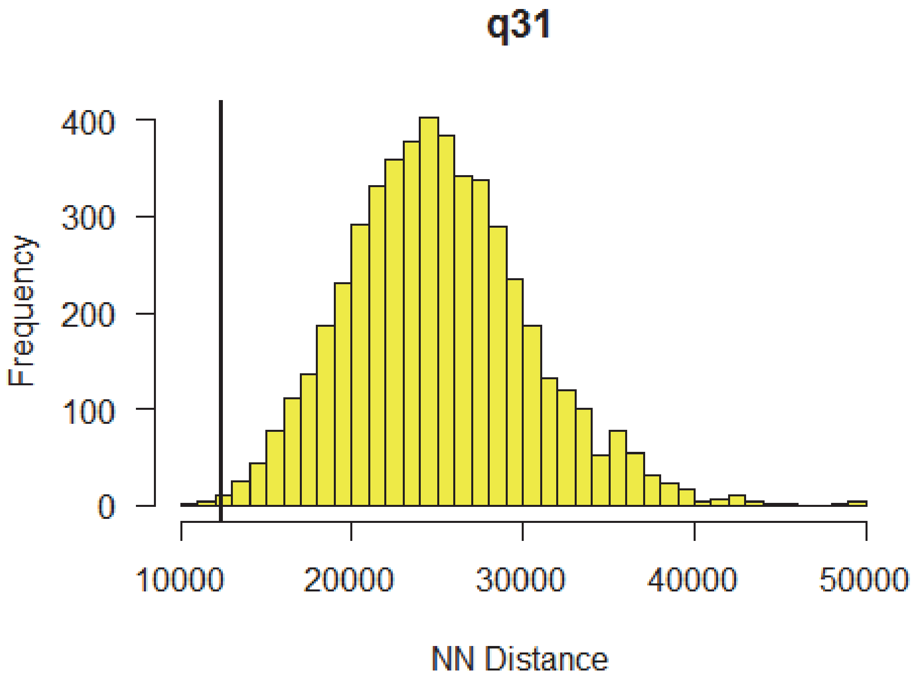
```
cnames<-names(nndists)
bins<-50
for (i in 1:length(cnames)) {
    title<-cnames[i]
    range<-round(range(nndists[,i]), digits=0)
    hist(nndists[,i], main=title, xlab="NN Distance", border="black", col="yellow",
xlim=c(range[1],range[2]), las=1, breaks=bins, prob = FALSE)
    abline(v=nndists[1,i],lty=1,lwd=2,col="black")
}
```

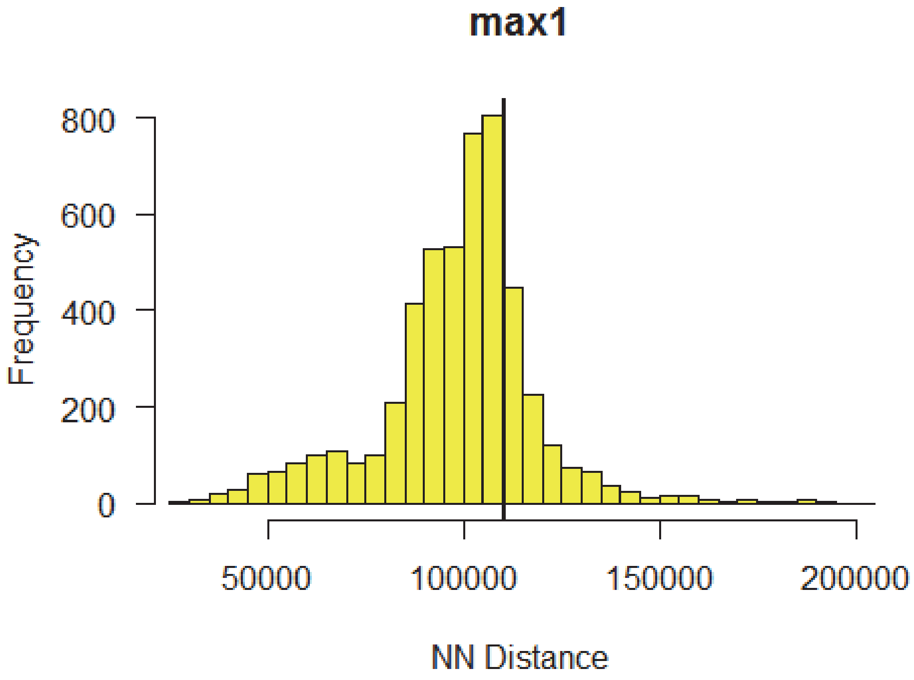

min1
Frequency
350
300
250
200
150
100
50
0
0
2000
4000
6000
8000
NN Distance

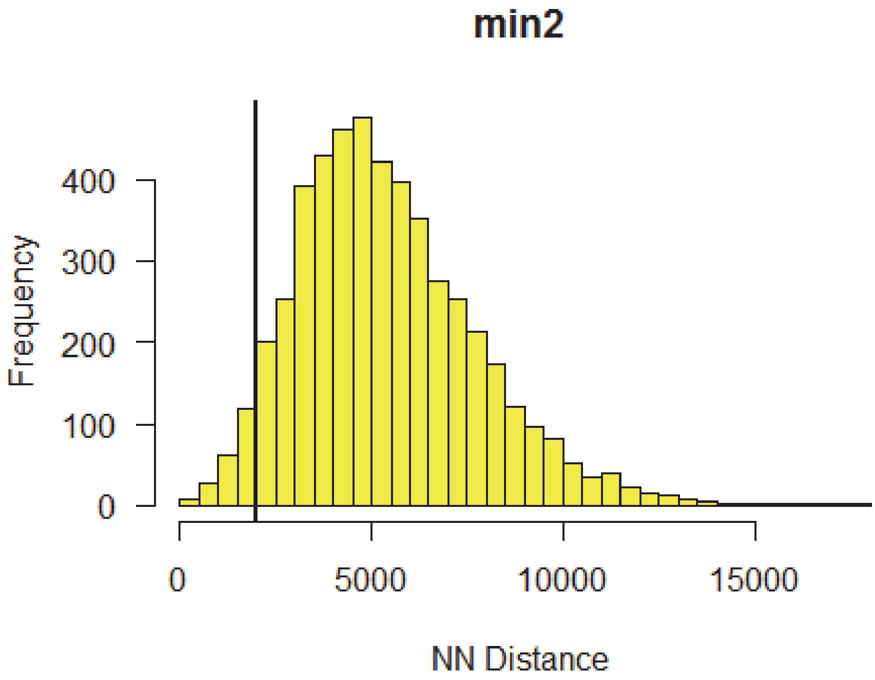

q11
Frequency
500
400
300
200
100
0
2000
6000
10000
14000
NN Distance

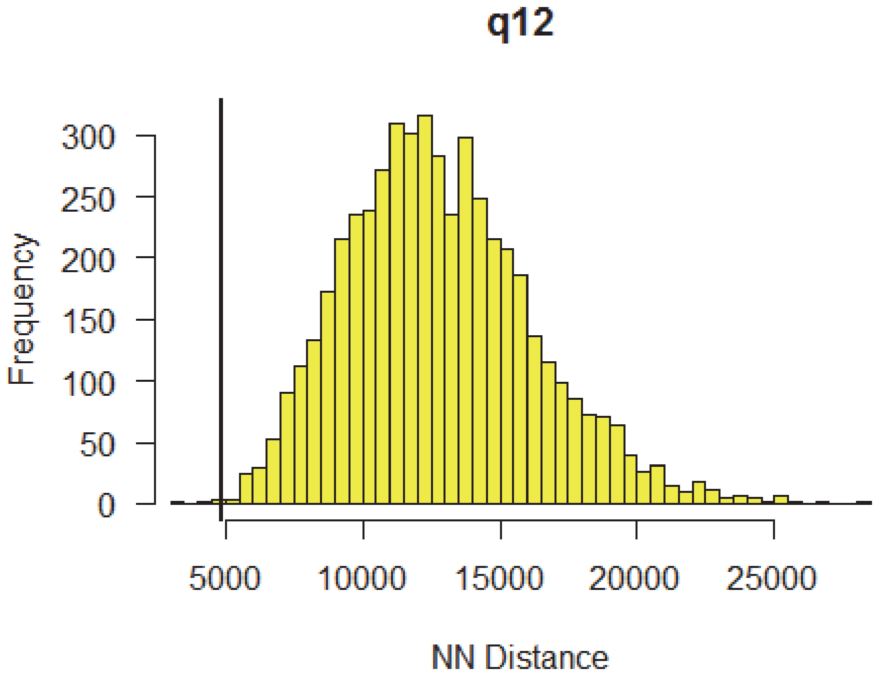

med1
Frequency
0
50
100
150
200
250
300
5000
10000
15000
20000
25000
NN Distance

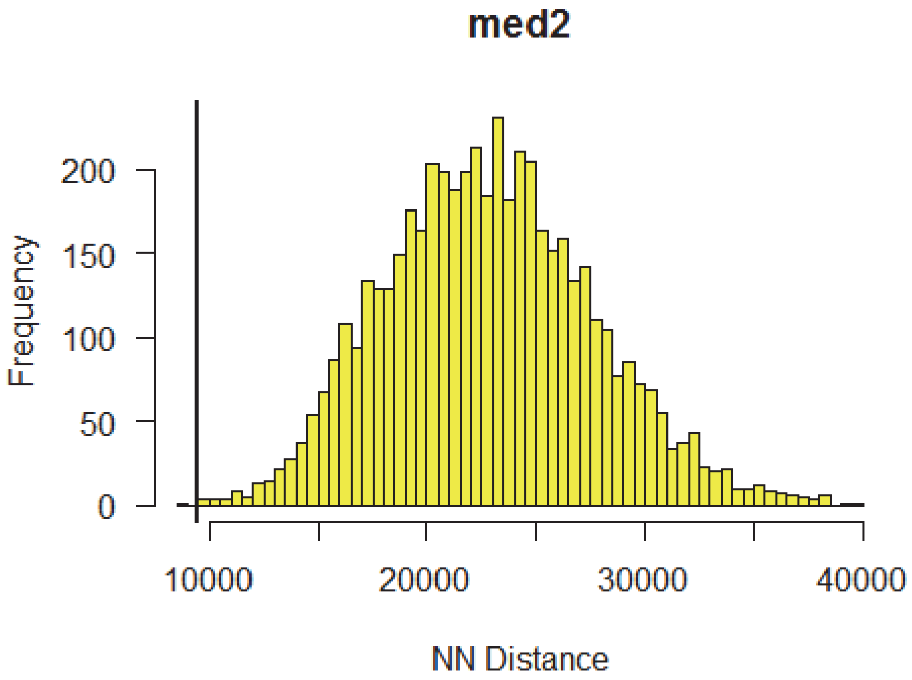

mean1
Frequency
0
100
200
300
10000
15000
20000
25000
30000
NN Distance

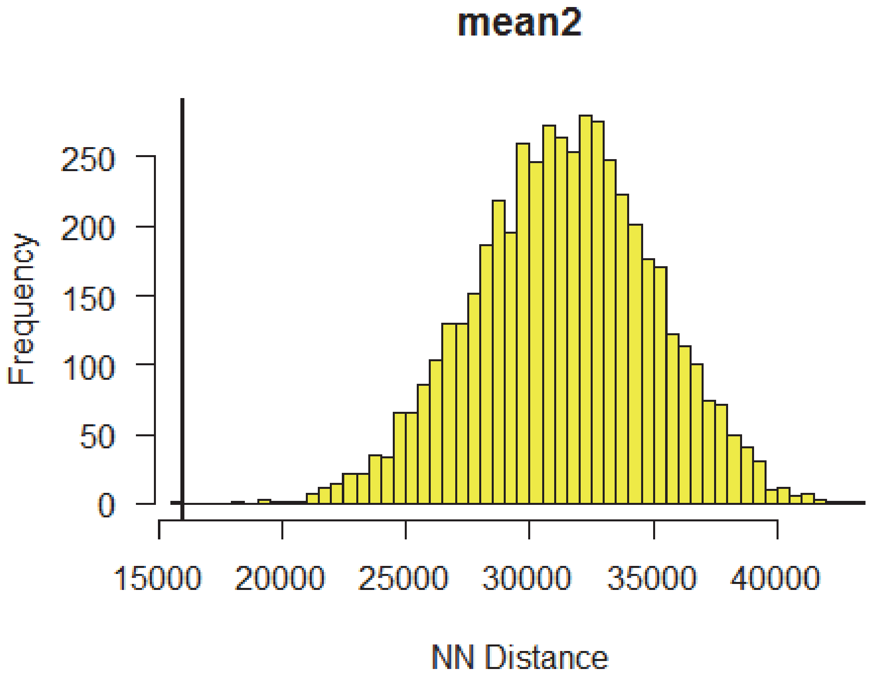

q31
Frequency
0
100
200
300
400
10000
20000
30000
40000
50000
NN Distance

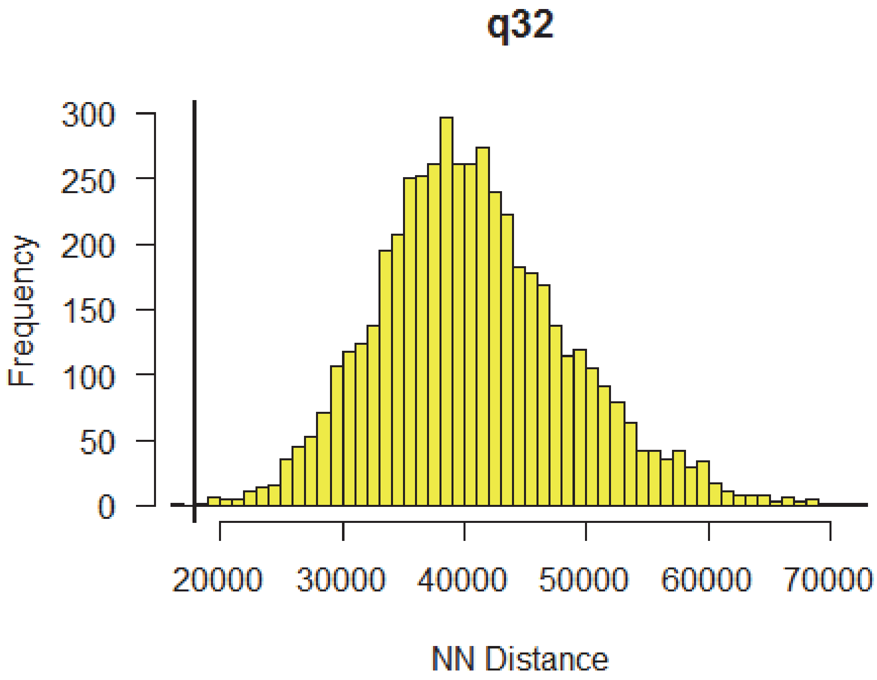

max1
Frequency
0
200
400
600
800
50000
100000
150000
200000
NN Distance

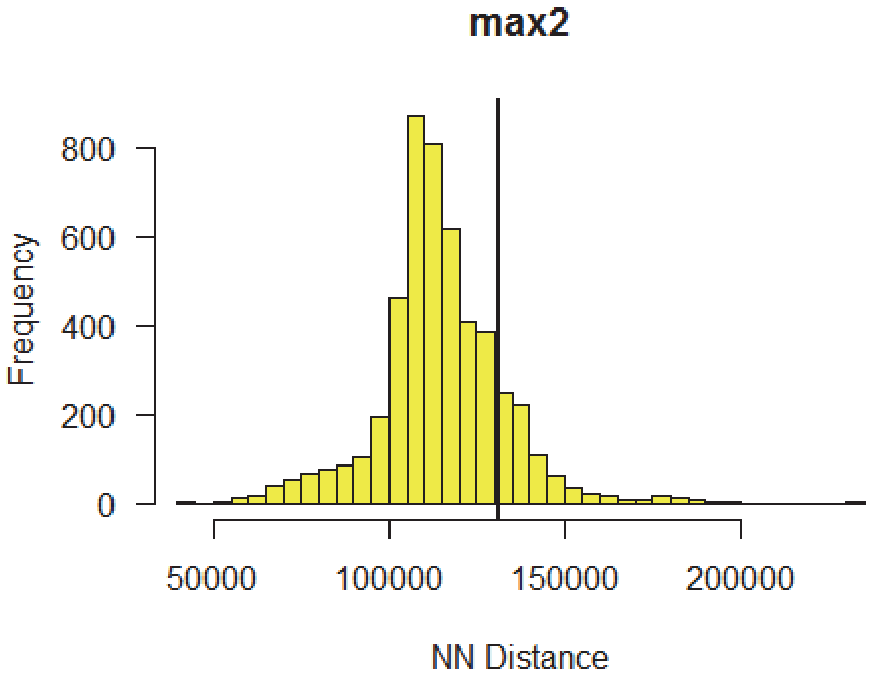

min2
Frequency
400
300
200
100
0
0
5000
10000
15000
NN Distance

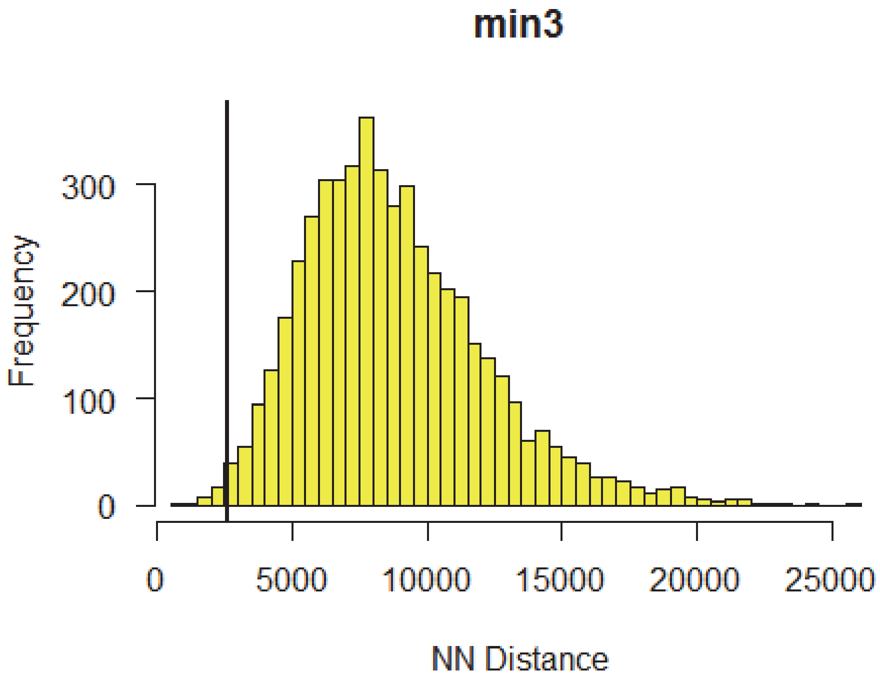

q12
Frequency
300
250
200
150
100
50
0
5000
10000
15000
20000
25000
NN Distance

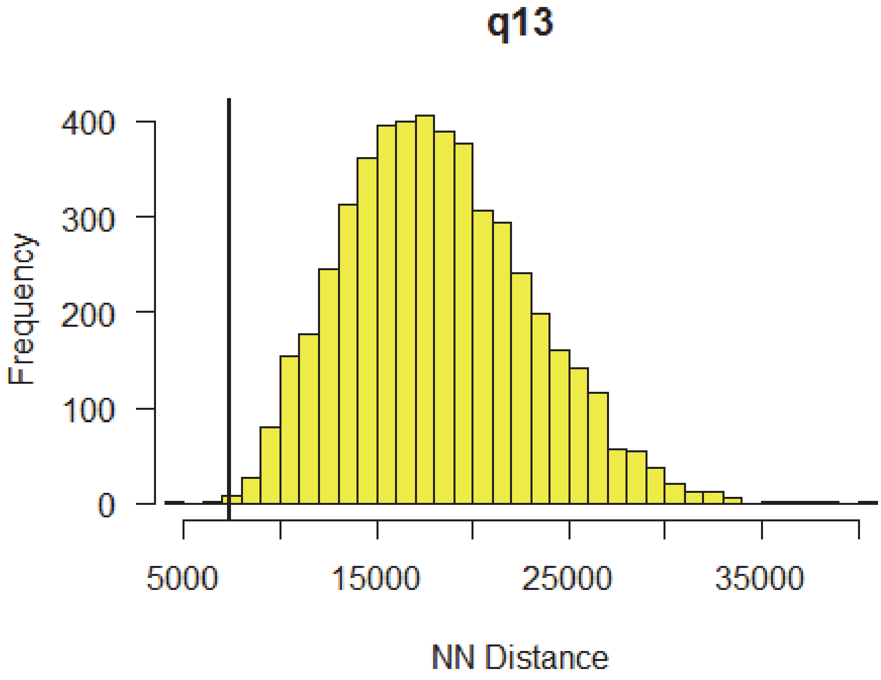

med2
Frequency
0
50
100
150
200
10000
20000
30000
40000
NN Distance


mean2
Frequency
0
50
100
150
200
250
15000
20000
25000
30000
35000
40000
NN Distance

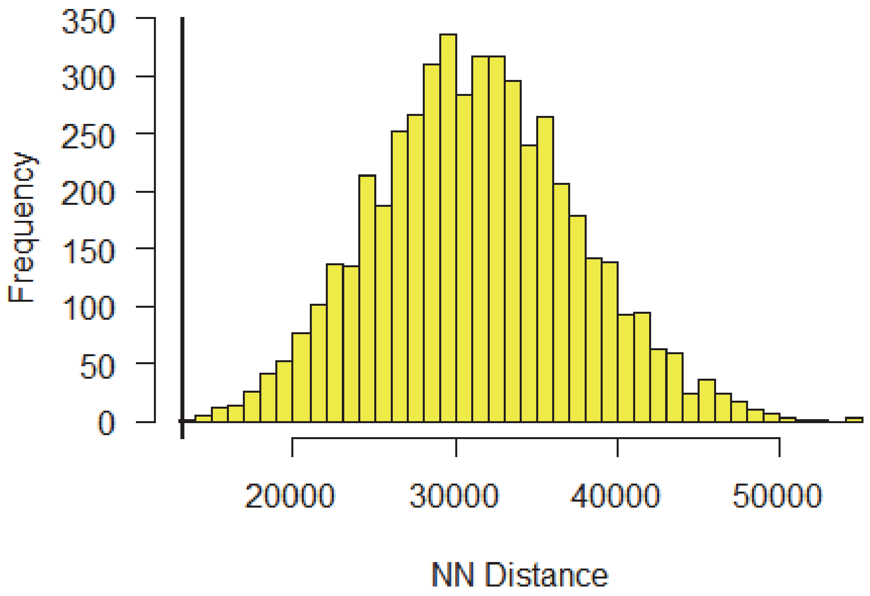

q32
Frequency
300
250
200
150
100
50
0
20000
30000
40000
50000
60000
70000
NN Distance


max2
Frequency
800
600
400
200
0
50000
100000
150000
200000
NN Distance

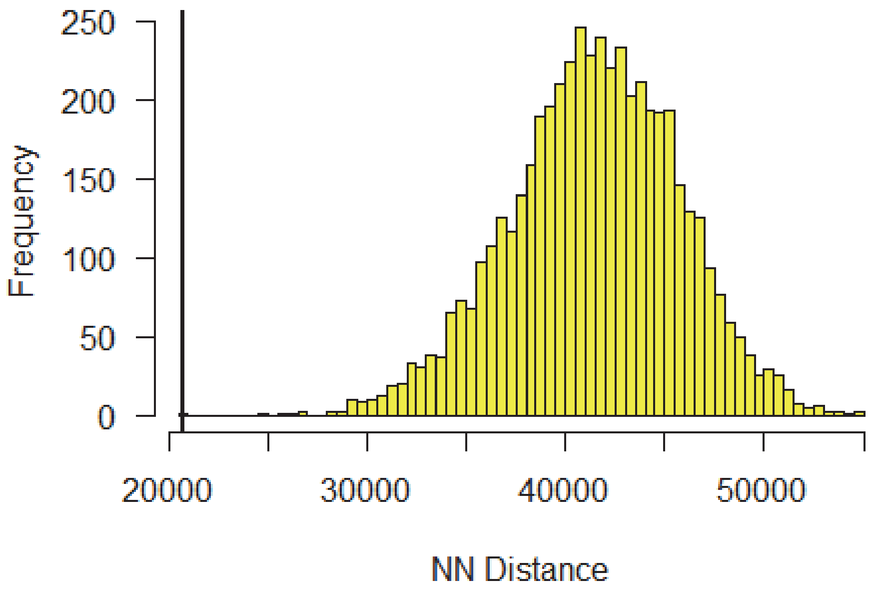

min3
Frequency
0
100
200
300
0
5000
10000
15000
20000
25000
NN Distance

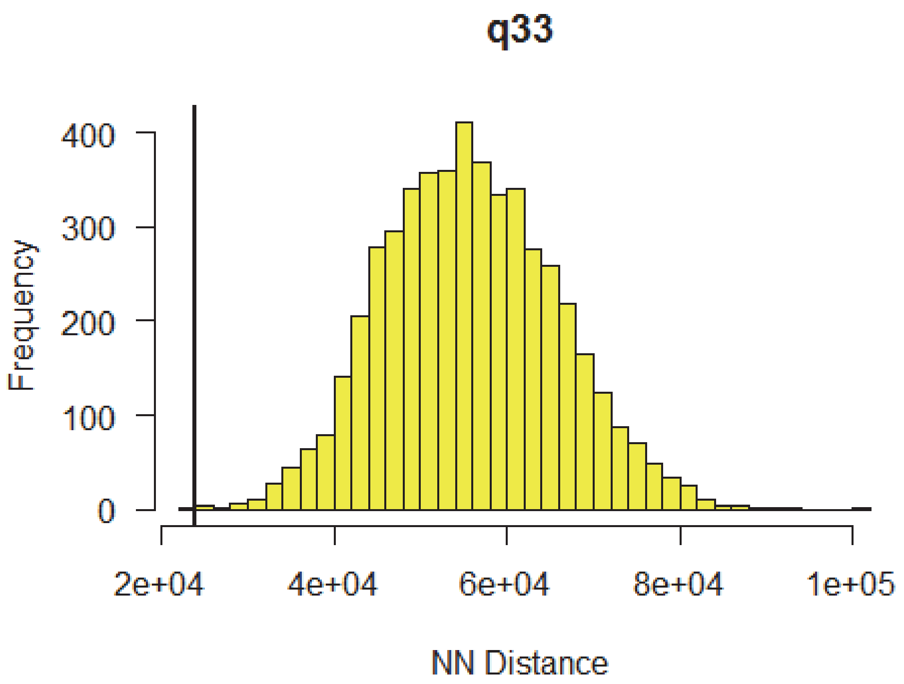

q13
Frequency
0
100
200
300
400
5000
15000
25000
35000
NN Distance

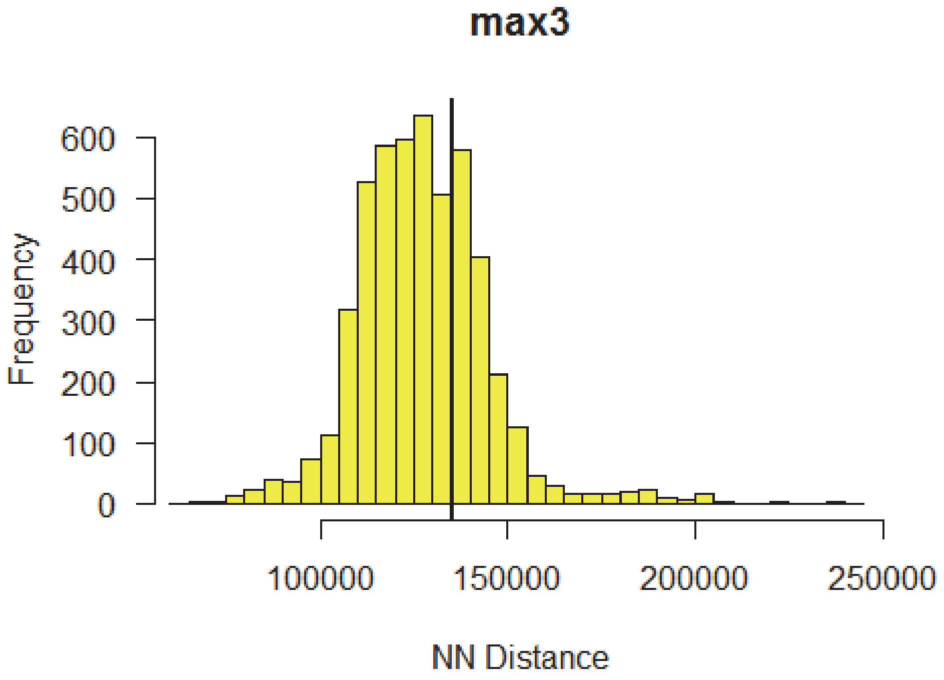
med3

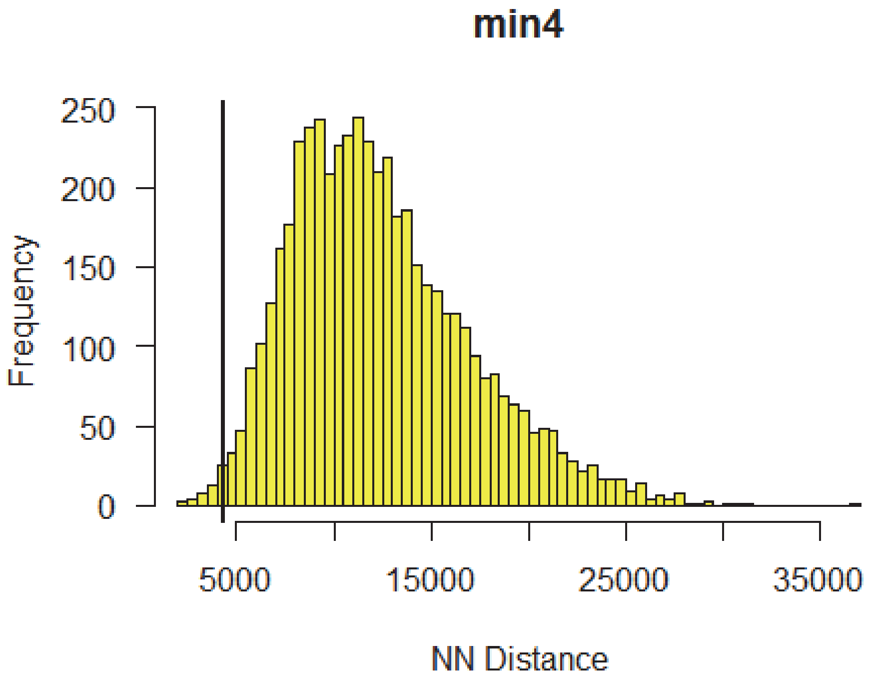

350
300
250
200
150
100
50
0
Frequency
20000
30000
40000
50000
NN Distance

mean3

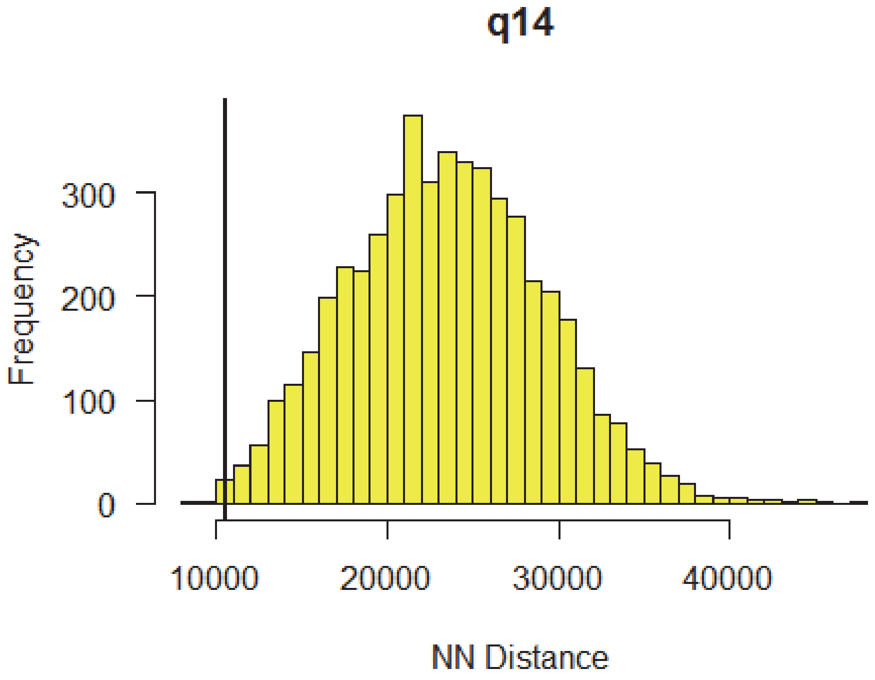

250
200
150
100
50
0
Frequency
20000
30000
40000
50000
NN Distance


q33
Frequency
0
100
200
300
400
2e+04
4e+04
6e+04
8e+04
1e+05
NN Distance

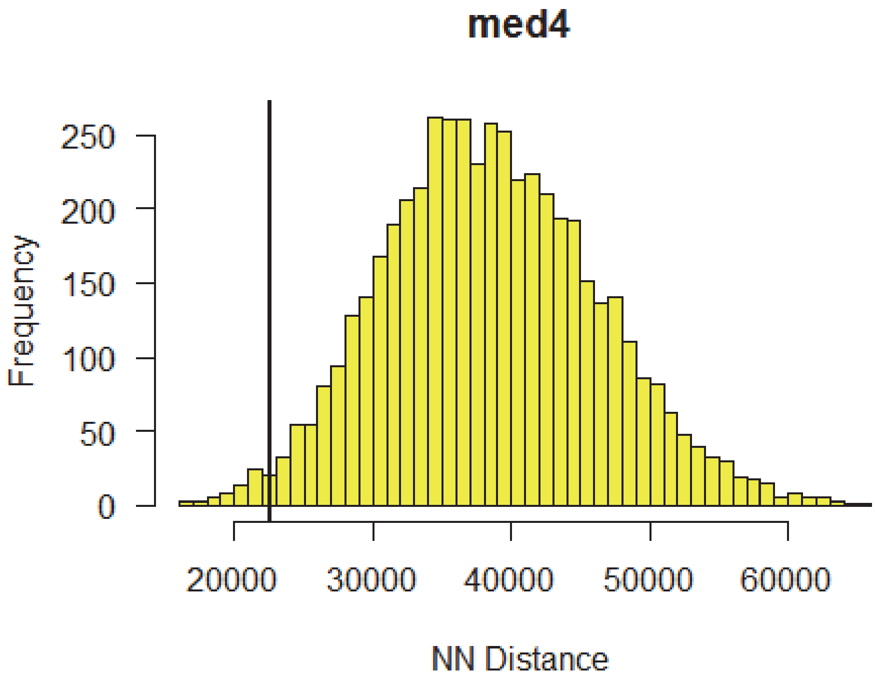

max3
Frequency
0
100
200
300
400
500
600
100000
150000
200000
250000
NN Distance


min4

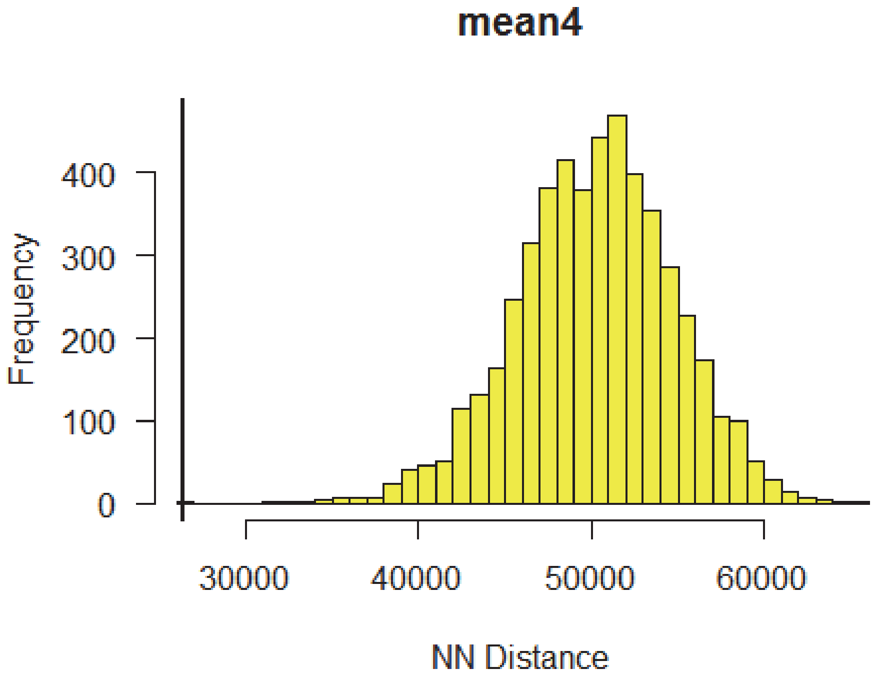
Frequency
250
200
150
100
50
0
5000
15000
25000
35000
NN Distance


q14

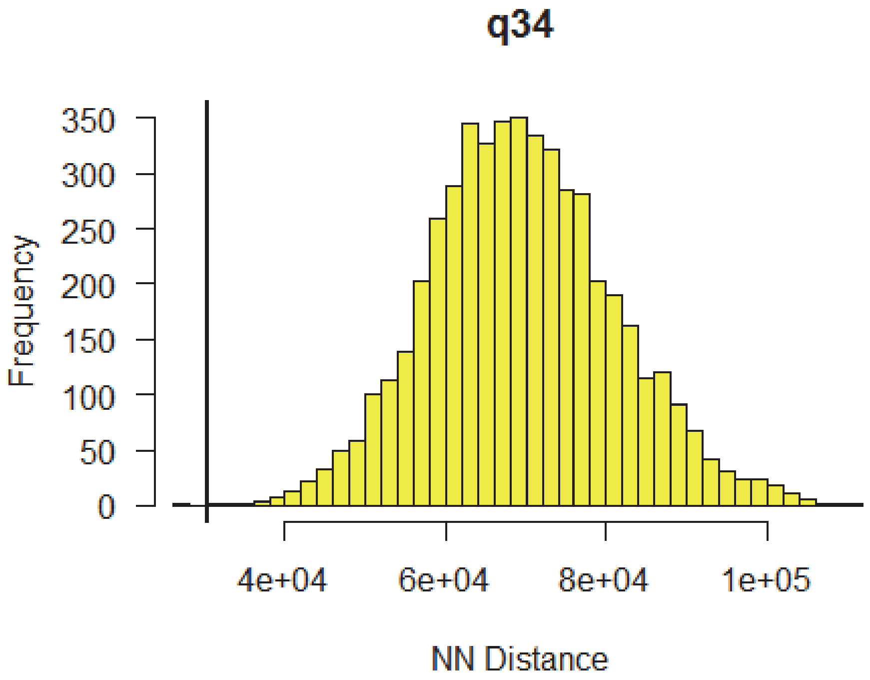
Frequency
300
200
100
0
10000
20000
30000
40000
NN Distance

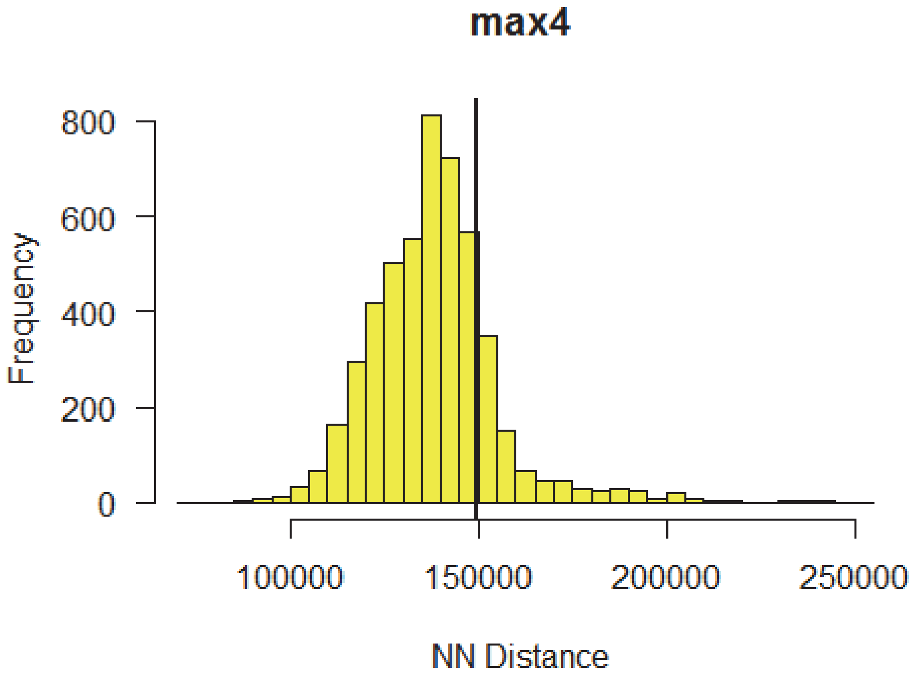

med4

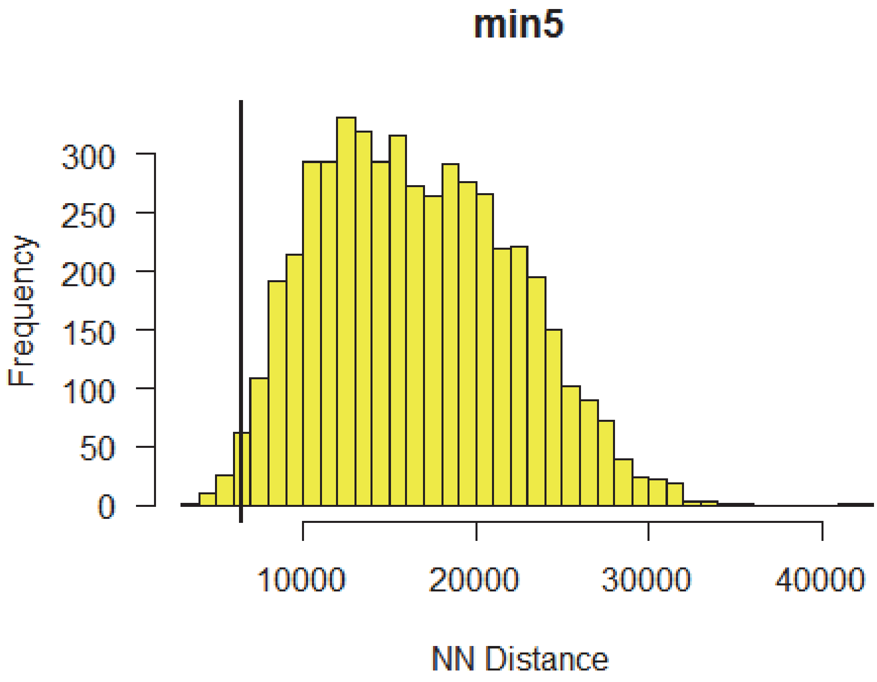
Frequency
0
50
100
150
200
250
20000
30000
40000
50000
60000
NN Distance

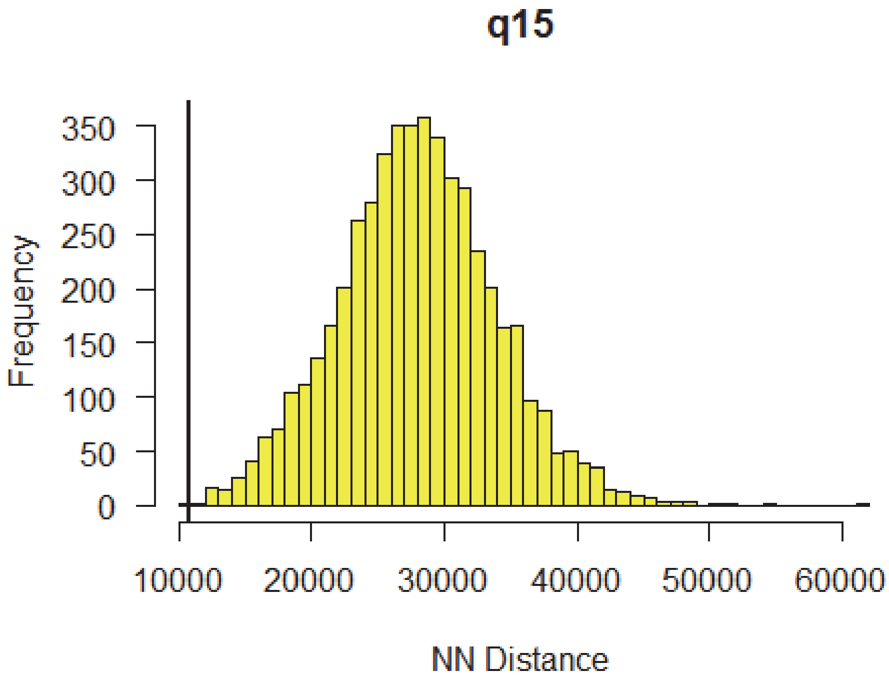

mean4

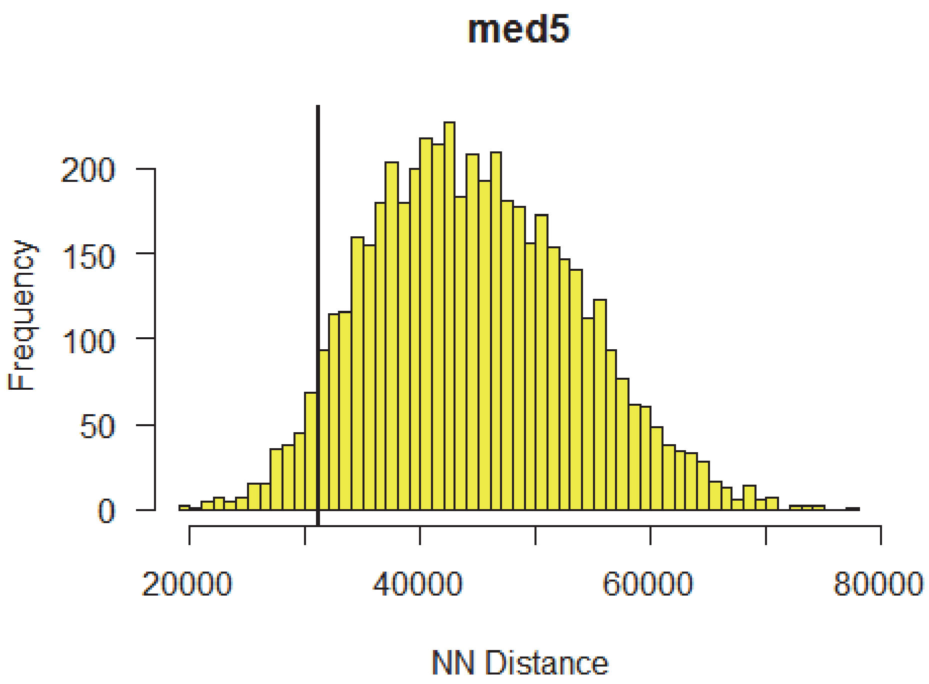
Frequency
0
100
200
300
400
30000
40000
50000
60000
NN Distance

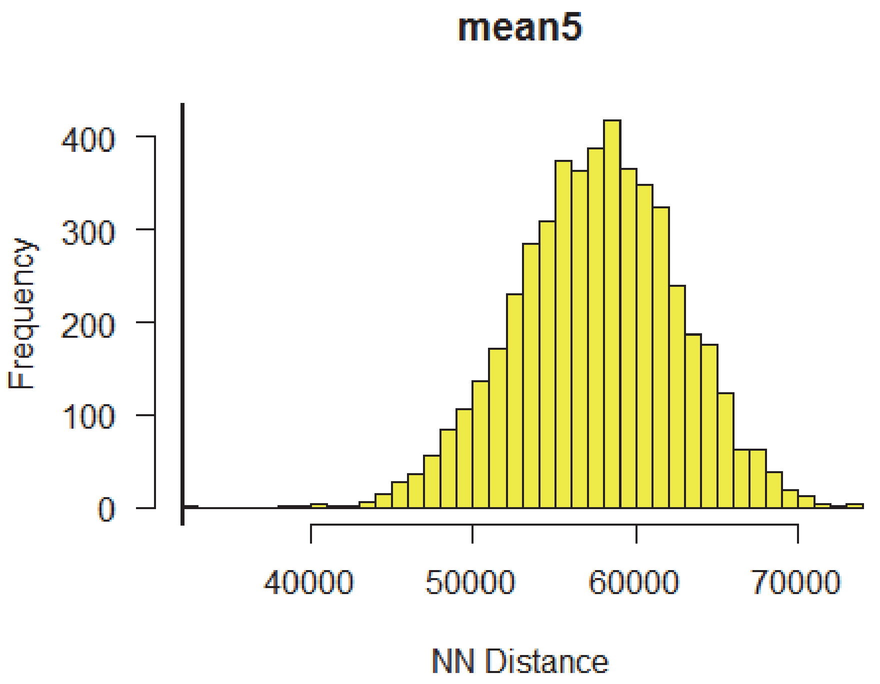

q34
Frequency
350
300
250
200
150
100
50
0
4e+04
6e+04
8e+04
1e+05
NN Distance

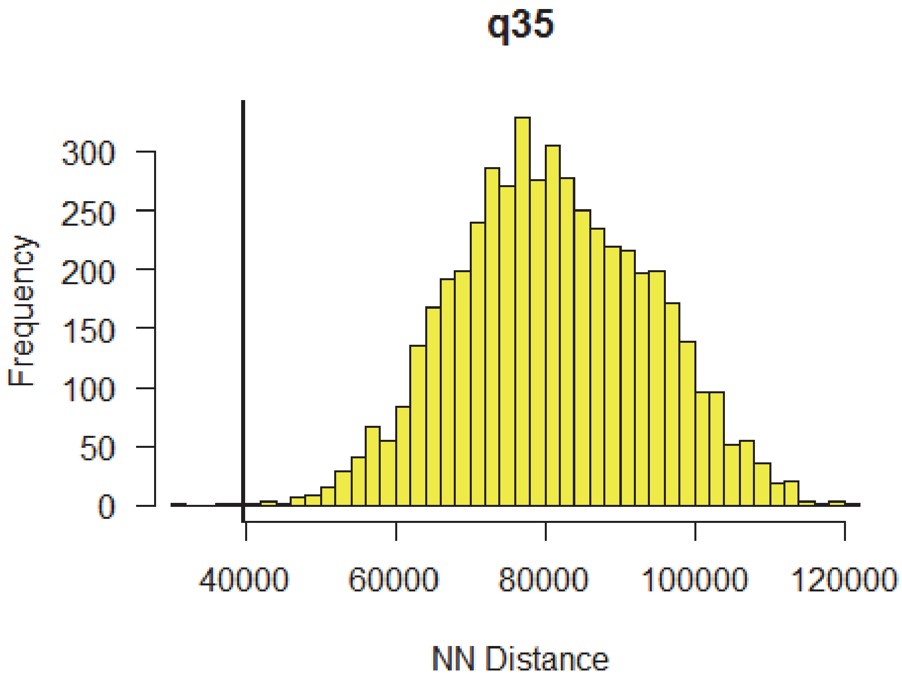

max4
Frequency
800
600
400
200
0
100000
150000
200000
250000
NN Distance


min5
Frequency
0
50
100
150
200
250
300
10000
20000
30000
40000
NN Distance


q15
Frequency
0
50
100
150
200
250
300
350
10000
20000
30000
40000
50000
60000
NN Distance

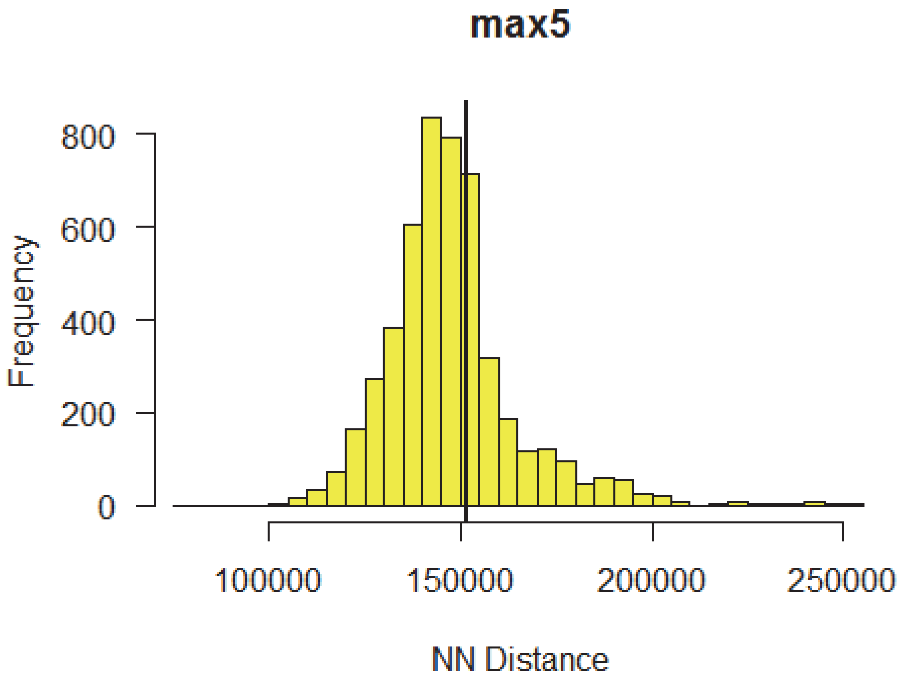

med5
Frequency
0
50
100
150
200
20000
40000
60000
80000
NN Distance


mean5
Frequency
0
100
200
300
400
40000
50000
60000
70000
NN Distance



q35

Frequency
0
50
100
150
200
250
300
40000
60000
80000
100000
120000
NN Distance



max5

Frequency
0
200
400
600
800
100000
150000
200000
250000
NN Distance

ANNEX 2.3. Satellite tag nearest neighbour sampling all tags excluding 80NS & 105GPS with no undetected tag failures

05/02/2017

R Libraries

```
library(knitr)
library(foreign)
library(plyr)
library(FNN)
library(qdapRegex)
```

Background

See Annex 2.1

```
xylocs<-read.csv("xydata_nodups_Feb17.csv", as.is = FALSE)
```

Tag metadata

The metadata about the tags are loaded and used to create subsets for subsequent sampling. The data have a snmlf field in which 1 indicates a last fix from a tag with a stopped-no malfunction status, other values are 0. The number of snmlfs is retained as qsus. There is a filtering to exclude the 105GPS tags.

```
tagmeta<-read.csv("tagmetadatajan17.csv", as.is = FALSE)
attach(tagmeta)
tagmeta<-tagmeta[which(tagmeta$Tagtype!="105GPS" ),]
qsus<-sum(tagmeta$snmlf)
```

Sampling effort

See Annex 2.1

```
daysum<-sum(tagmeta$Days)
tagmeta$dayprop<-tagmeta$Days/daysum
```

Preparing sampling

See Annex 2.1

```
attach(xylocs)

## The following object is masked from tagmeta:
##     Days

iterations<-5000
rows<-iterations
nndists <- data.frame(min1=numeric(rows), q11=numeric(rows), med1=numeric(rows),
mean1=numeric(rows), q31=numeric(rows), max1=numeric(rows),min2=numeric(rows),
q12= numeric(rows), med2=numeric(rows), mean2=numeric(rows), q32=numeric(rows),
max2=numeric(rows), min3=numeric(rows),q13=numeric(rows), med3=numeric(rows),
mean3=numeric(rows), q33=numeric(rows), max3=numeric(rows),
min4=numeric(rows),q14=numeric(rows), med4=numeric(rows), mean4=numeric(rows),
q34=numeric(rows), max4=numeric(rows), min5=numeric(rows),q15=numeric(rows),
med5=numeric(rows), mean5=numeric(rows), q35=numeric(rows), max5=numeric(rows))
IDlist<-data.frame(matrix(ncol = qsus, nrow = rows))
set.seed(12345)
```

Random sampling

See Annex 2.1

```
for (i in 2:iterations) {
    qsample <- tagmeta[sample(1:nrow(tagmeta),qsus,replace=FALSE,tagmeta$dayprop),]
    lst<-qsample$TagID
    IDlist[i-1,]<-lst[order(lst)]
    xylocsample<-xylocs[xylocs$ID%in% lst,]
    lstlen<-length(lst)
    s2<-data.frame(X=numeric(lstlen), Y=numeric(lstlen))
    for (a in 1:lstlen) {
        s <- xylocsample[ which(xylocsample$ID==lst[a]), ]
        samp_idx <- sample(seq_len(nrow(s)), 1, prob=s$samp_p)
        s2[a,] <- s[samp_idx,c("X","Y") ]
    }
    nnd<-knn.dist(s2,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
    nndo<-summary(nnd)
    nndo<-gsub("[:]",": ",nndo)
    tmp2<-as_numeric2(ex_number(nndo))
    for (j in 1:30) nndists[i,j]<- tmp2[j]
}
```

Real nearest neighbours

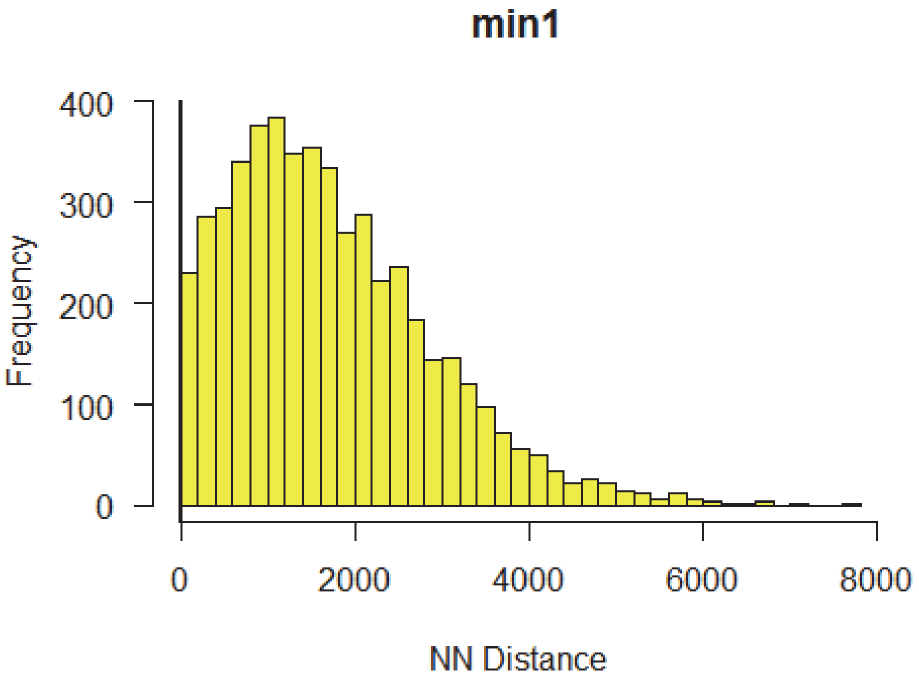
See Annex 2.1

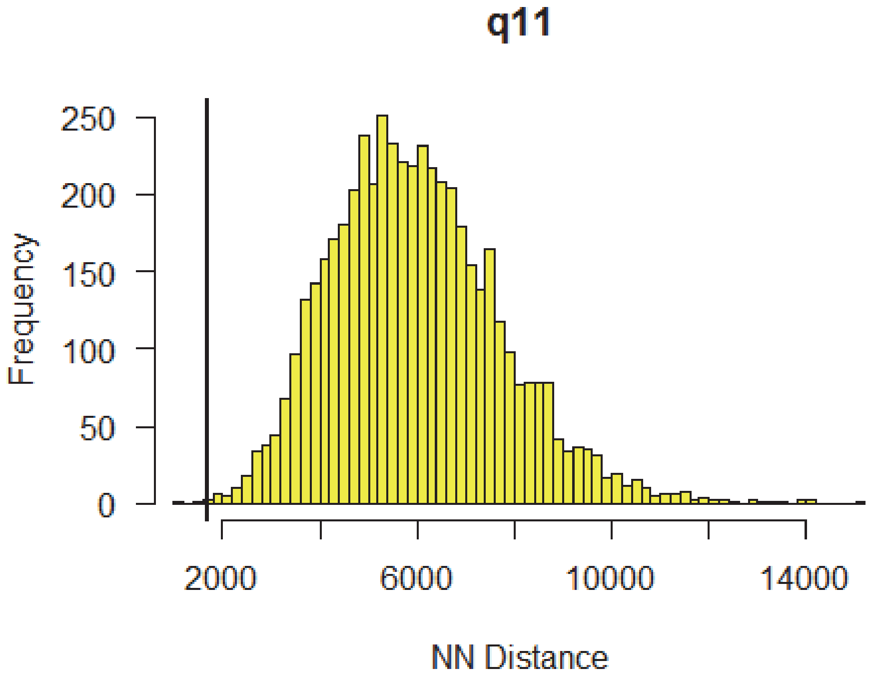
```
sx<-tagmeta[which(tagmeta$snmlf>0),c("FinX","FinY")]
nndx<-knn.dist(sx, k=5, algorithm=c("kd_tree","cover_tree","CR","brute"))
nndo<-summary(nndx)
nndo<-gsub("[:]",": ",nndo)
tmp2<-as_numeric2(ex_number(nndo))
for (j in 1:30) nndists[1,j]<- tmp2[j]
write.table(nndists,file="nndists5_7095tags.txt",sep="\t")
IDcount<-stack(IDlist)
IDcount<-as.matrix(table(IDcount$values))
write.table(IDcount,file="nndists5_7095tags_n.txt",sep="\t")
```

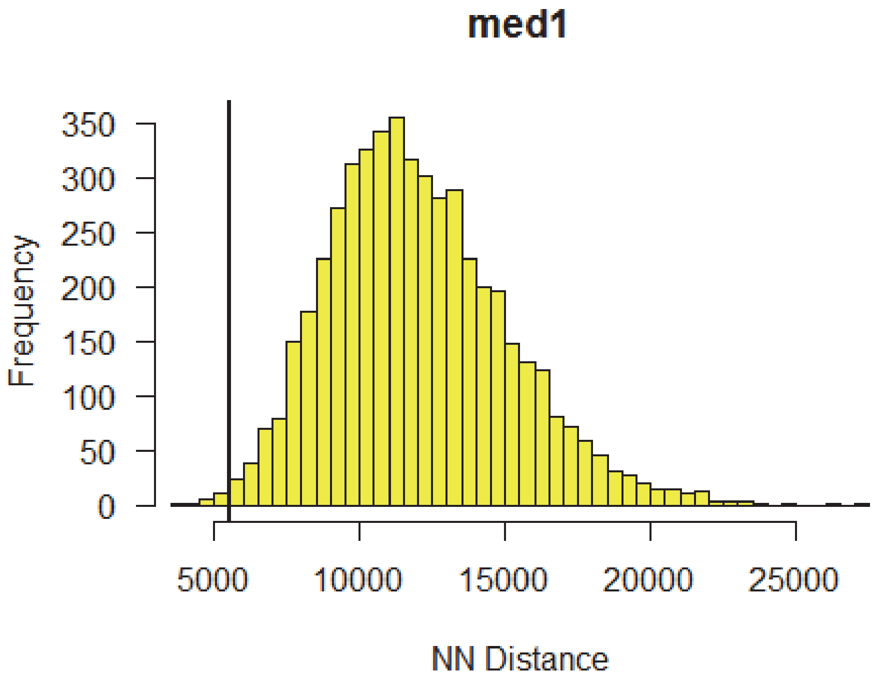
Plot the results

See Annex 2.1

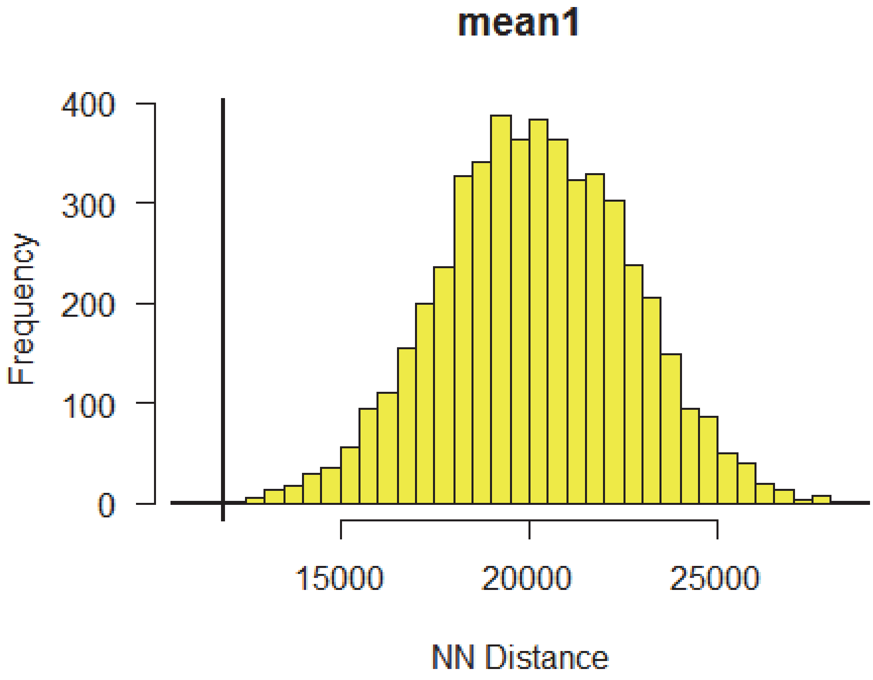
```
cnames<-names(nndists)
bins<-50
for (i in 1:length(cnames)) {
    title<-cnames[i]
    range<-round(range(nndists[,i]), digits=0)
    hist(nndists[,i], main=title, xlab="NN Distance", border="black", col="yellow",
xlim=c(range[1],range[2]), las=1, breaks=bins, prob = FALSE)
    abline(v=nndists[1,i],lty=1,lwd=2,col="black")
}
```


min1
Frequency
400
300
200
100
0
0
2000
4000
6000
8000
NN Distance

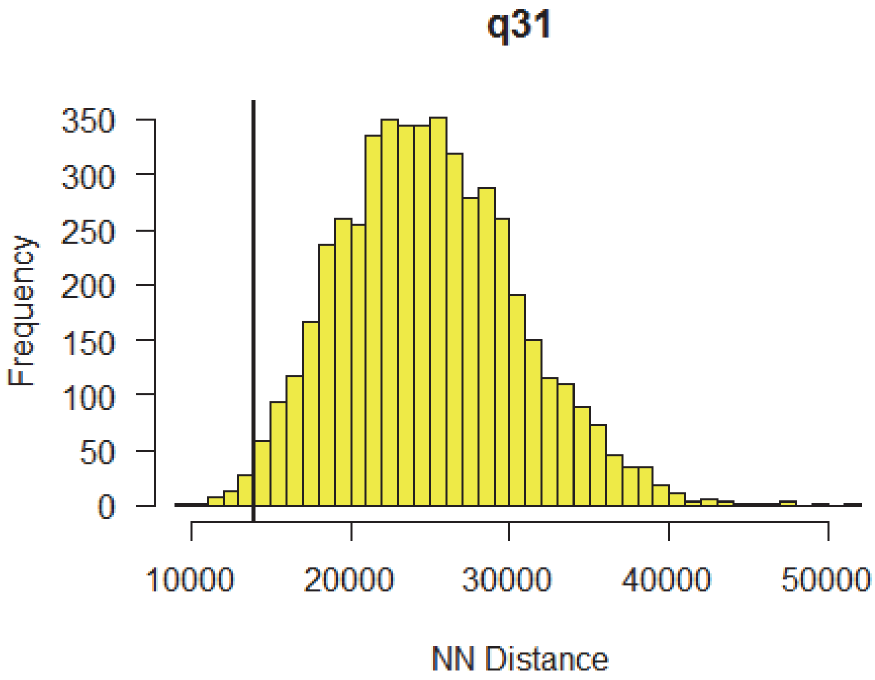

q11
Frequency
250
200
150
100
50
0
2000
6000
10000
14000
NN Distance

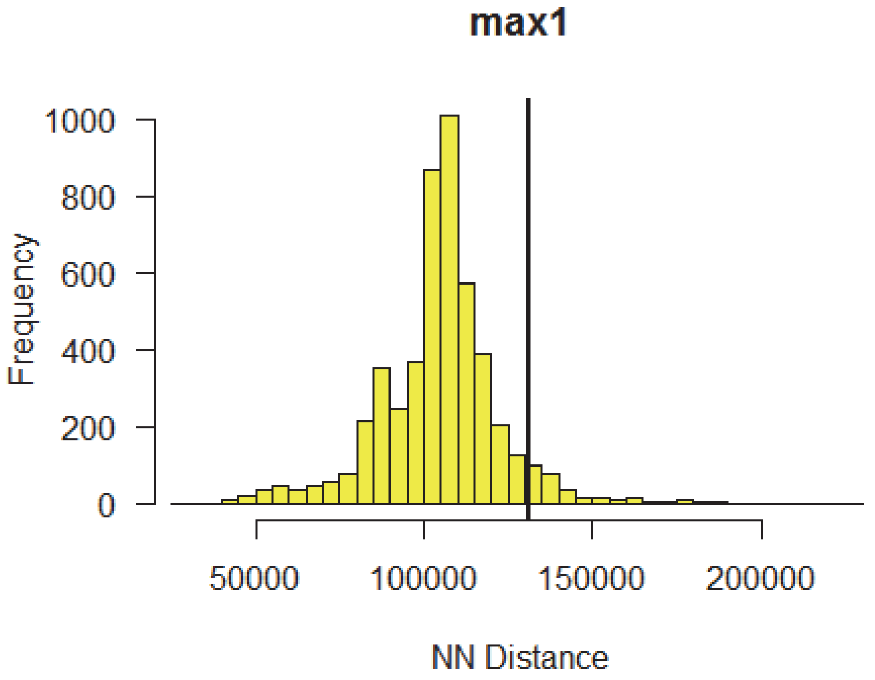

med1

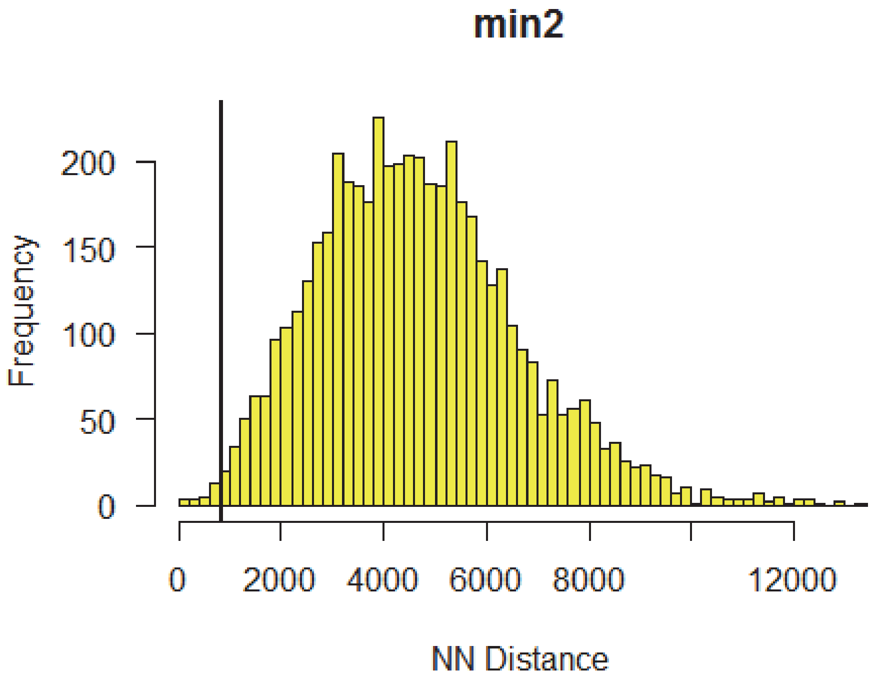
Frequency
350
300
250
200
150
100
50
0
5000
10000
15000
20000
25000
NN Distance

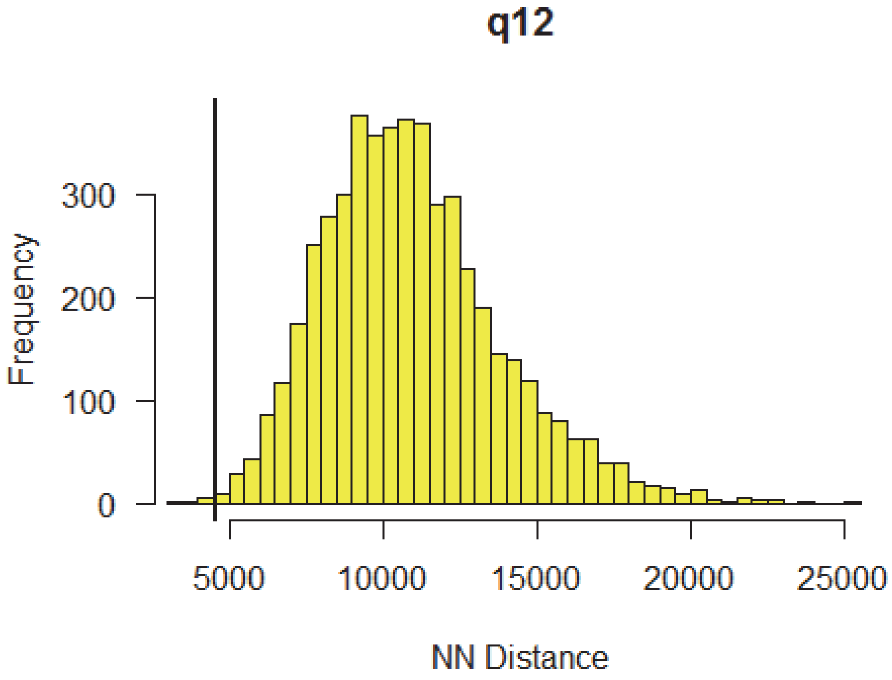

mean1

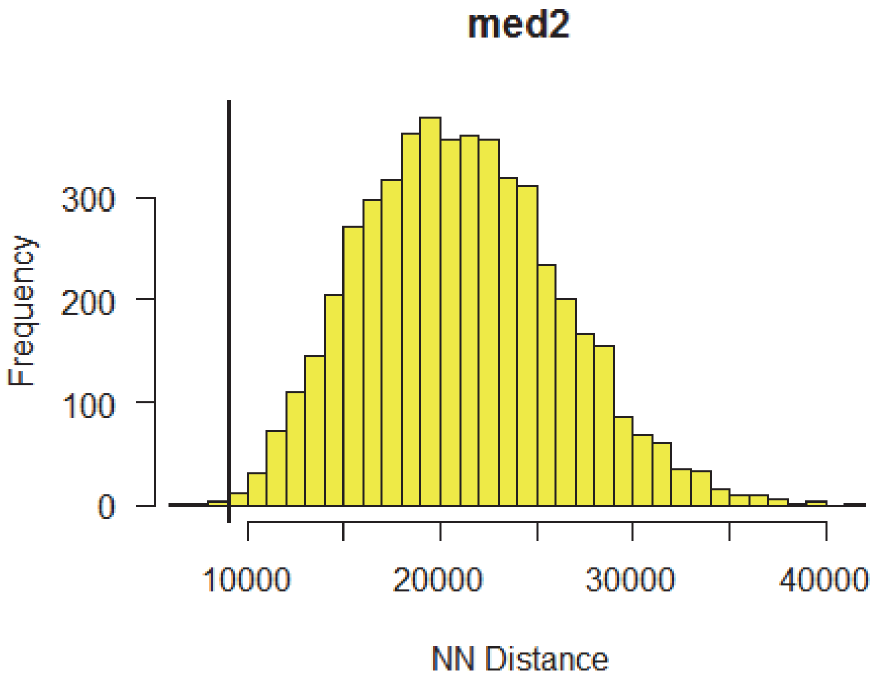
Frequency
400
300
200
100
0
15000
20000
25000
NN Distance

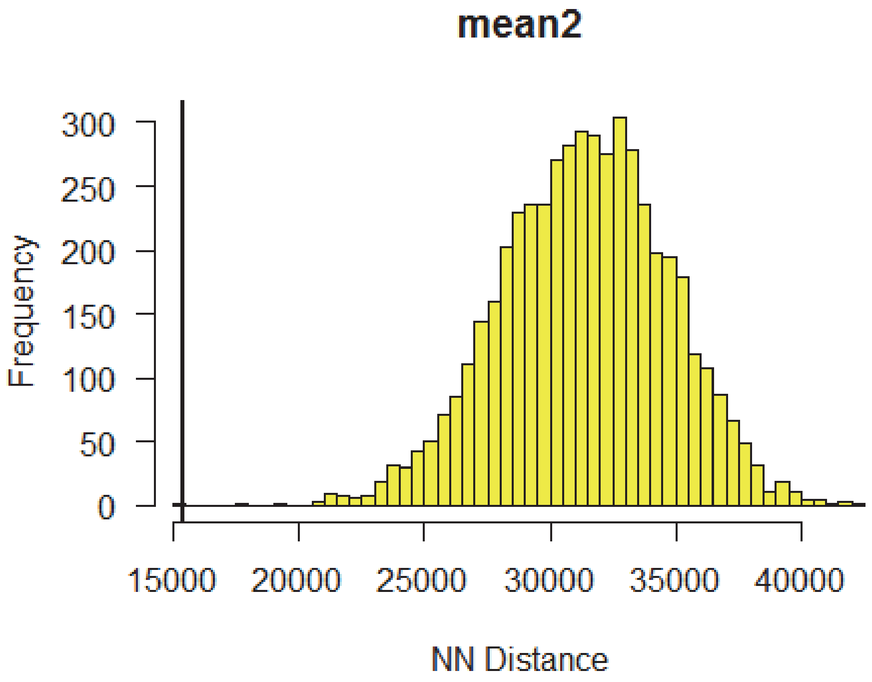

q31
Frequency
350
300
250
200
150
100
50
0
10000
20000
30000
40000
50000
NN Distance

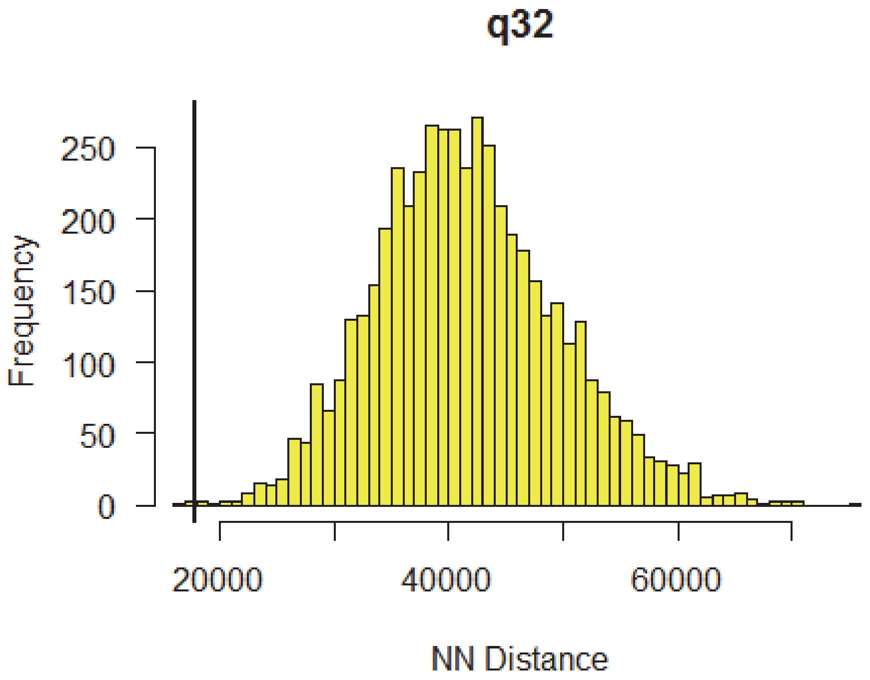

max1
Frequency
1000
800
600
400
200
0
50000
100000
150000
200000
NN Distance


min2
Frequency
200
150
100
50
0
0
2000
4000
6000
8000
12000
NN Distance


q12
Frequency
300
200
100
0
5000
10000
15000
20000
25000
NN Distance

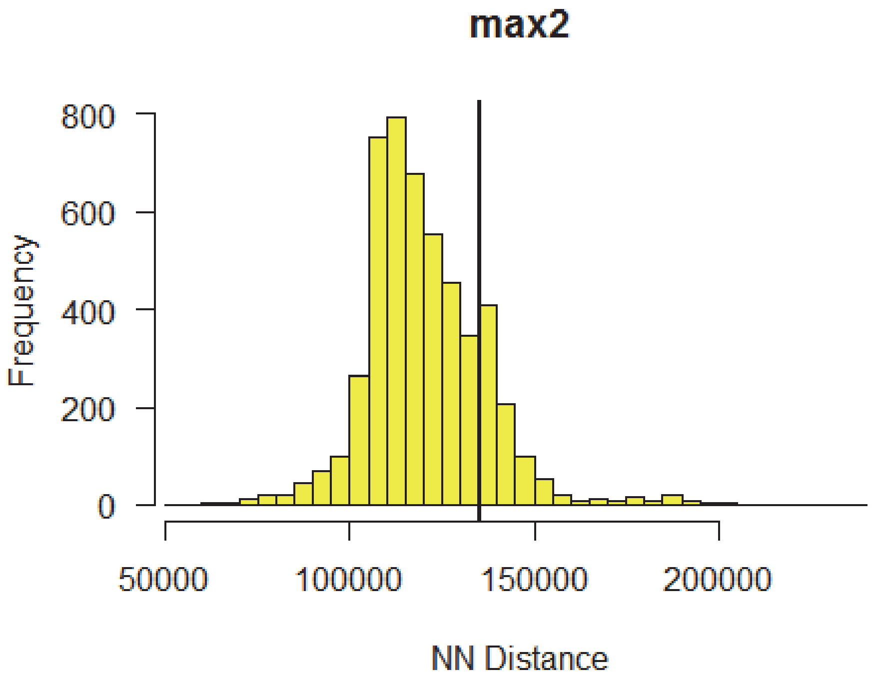

med2
Frequency
300
200
100
0
10000
20000
30000
40000
NN Distance


mean2
Frequency
300
250
200
150
100
50
0
15000
20000
25000
30000
35000
40000
NN Distance



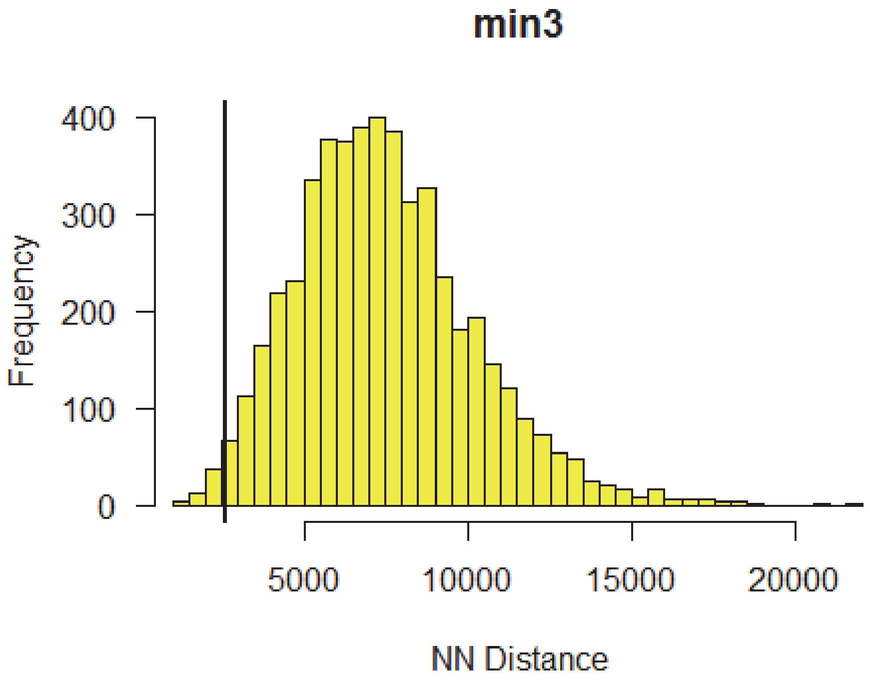
q32

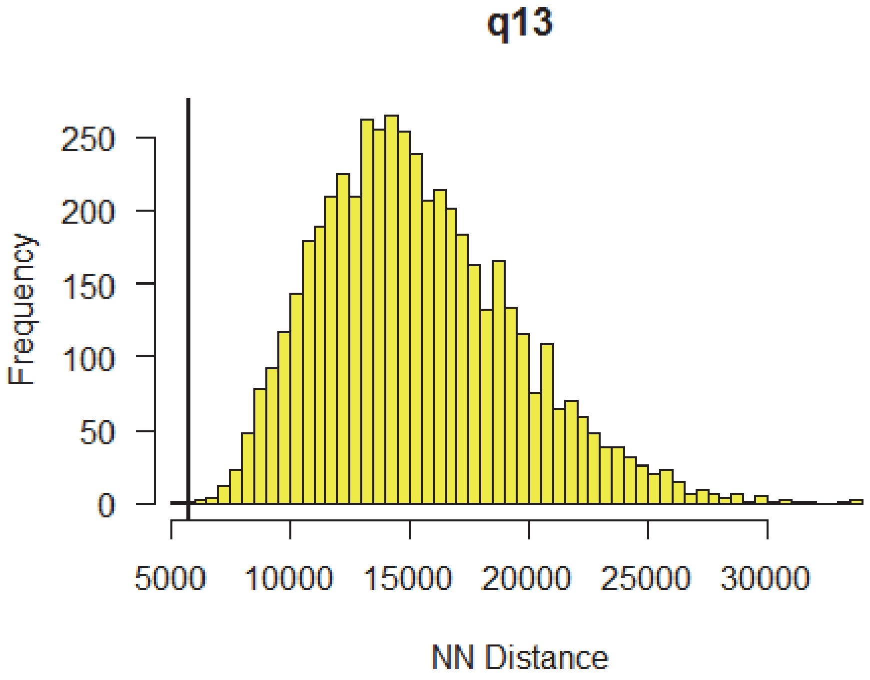
Frequency
0
50
100
150
200
250
20000
40000
60000
NN Distance

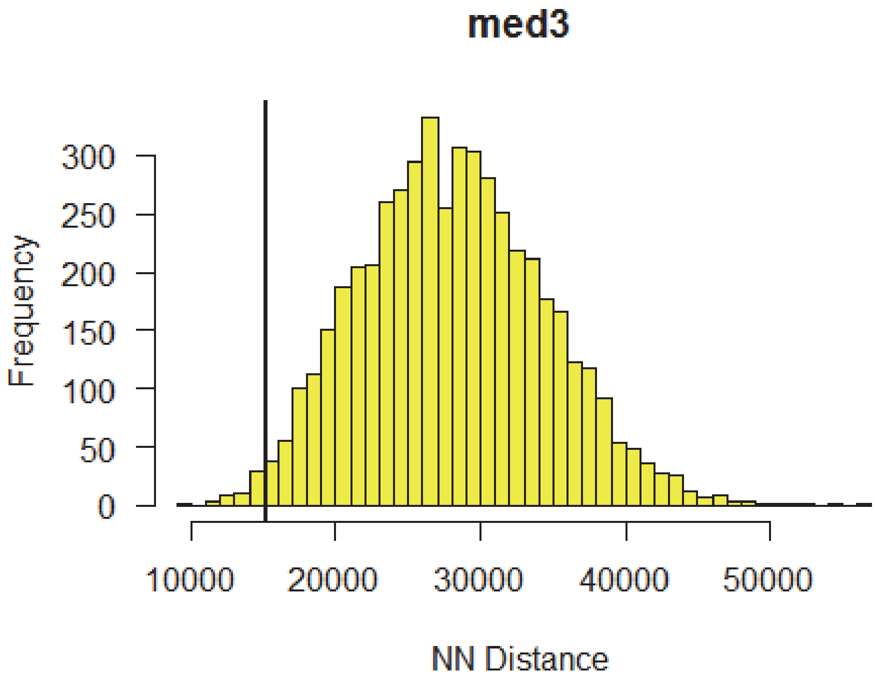


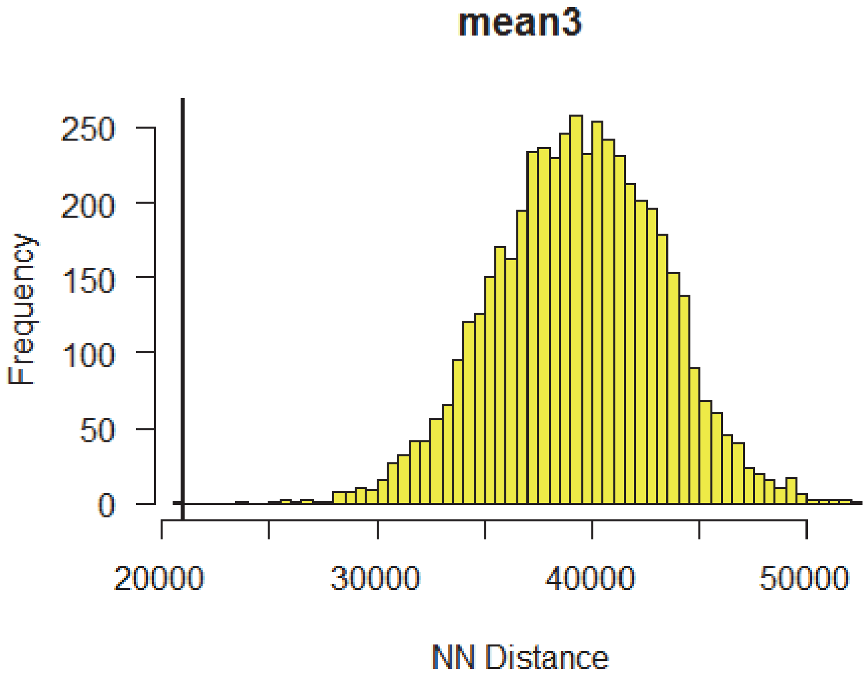
max2

Frequency
0
200
400
600
800
50000
100000
150000
200000
NN Distance

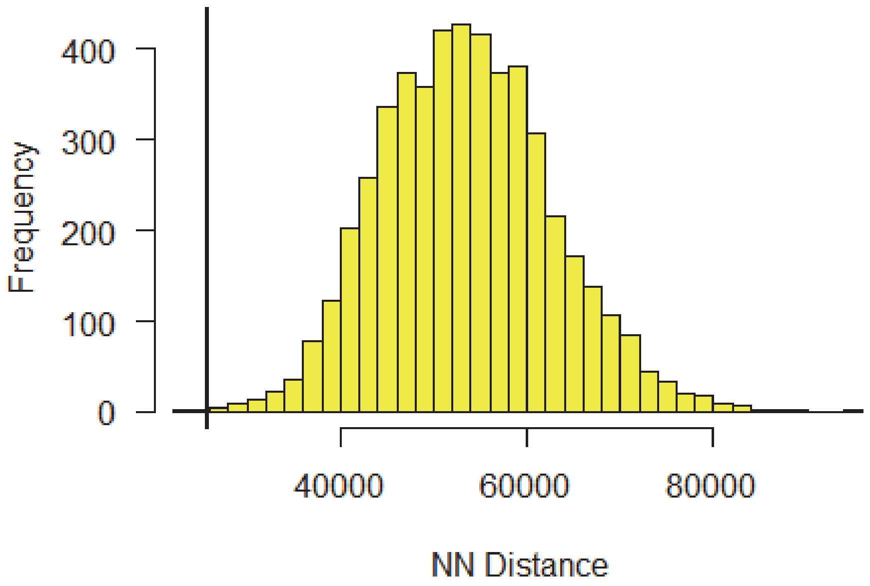

min3
400
300
200
100
0
Frequency
5000
10000
15000
20000
NN Distance


q13
250
200
150
100
50
0
Frequency
5000
10000
15000
20000
25000
30000
NN Distance


med3
Frequency
0
50
100
150
200
250
300
10000
20000
30000
40000
50000
NN Distance

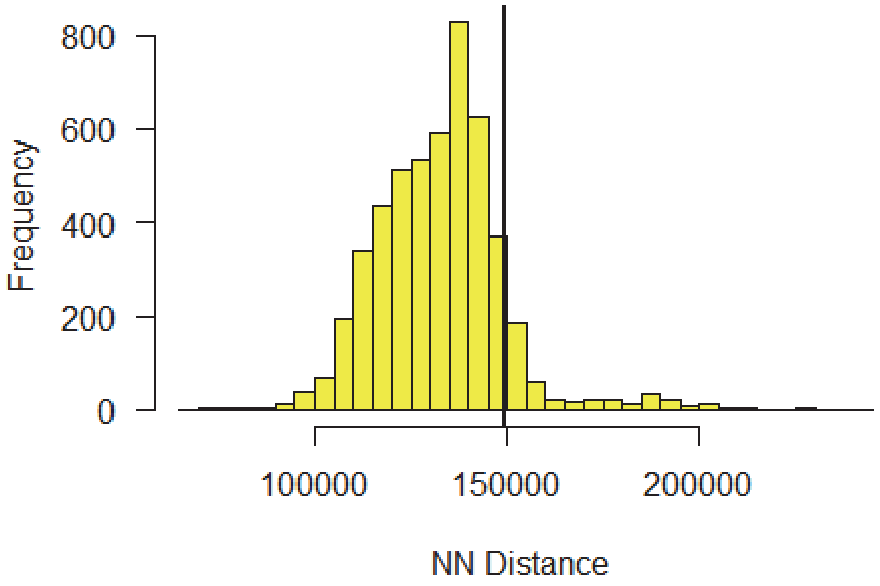

mean3
Frequency
0
50
100
150
200
250
20000
30000
40000
50000
NN Distance

q33

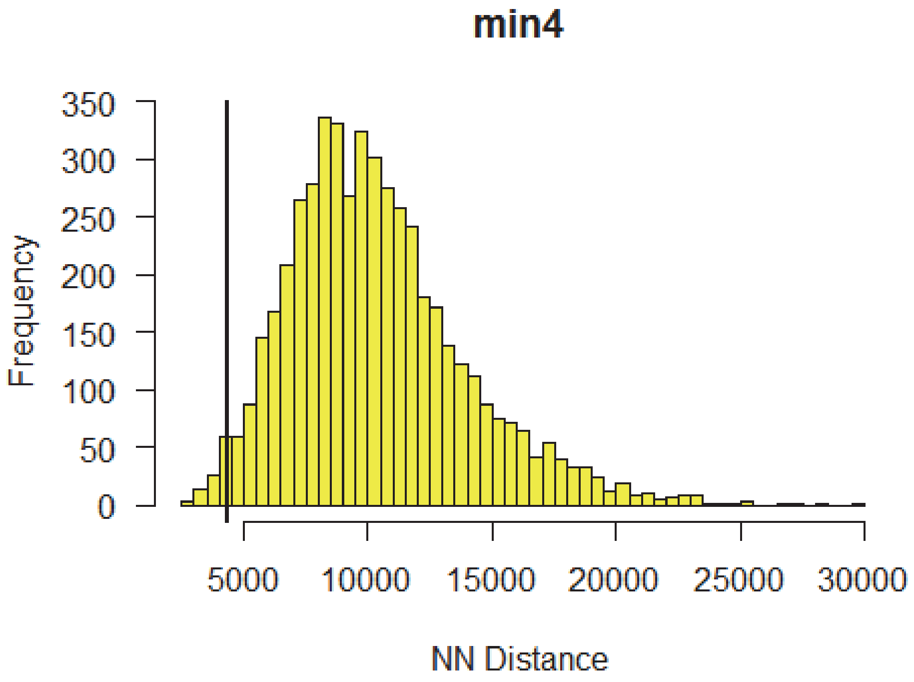


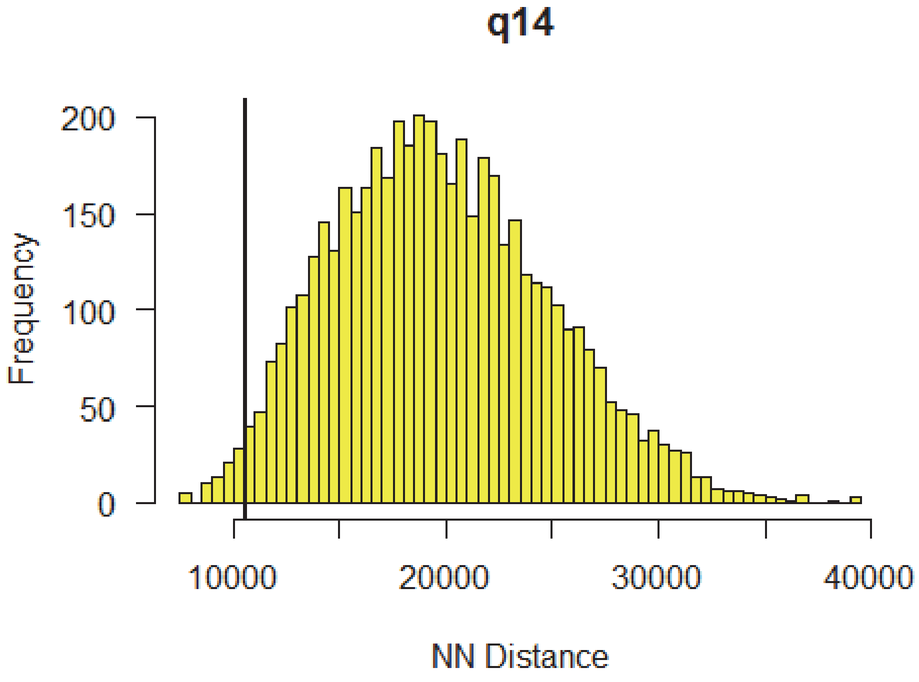
Frequency
0
100
200
300
400
40000
60000
80000
NN Distance

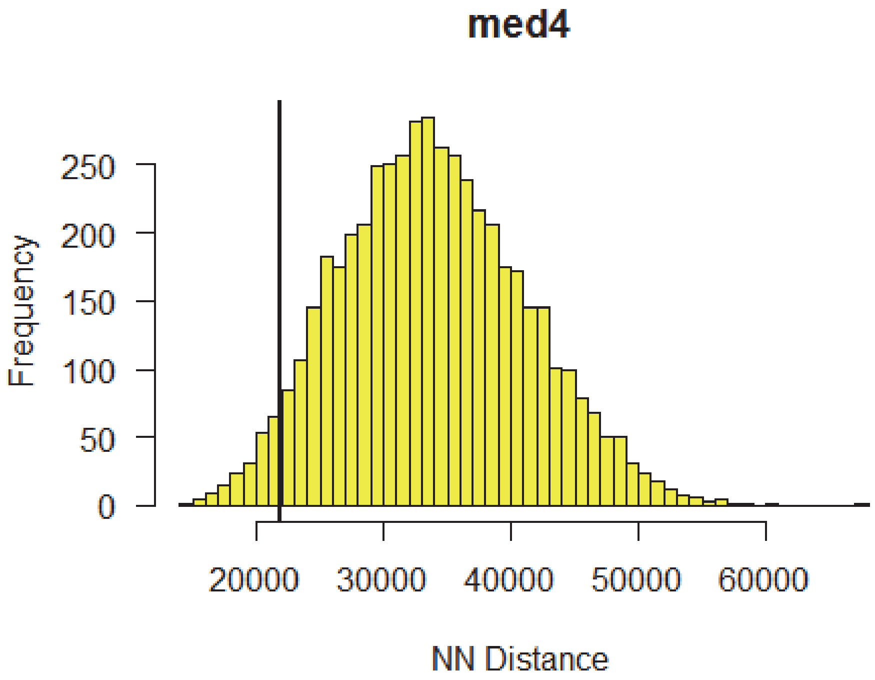
max3



Frequency
0
200
400
600
800
100000
150000
200000
NN Distance

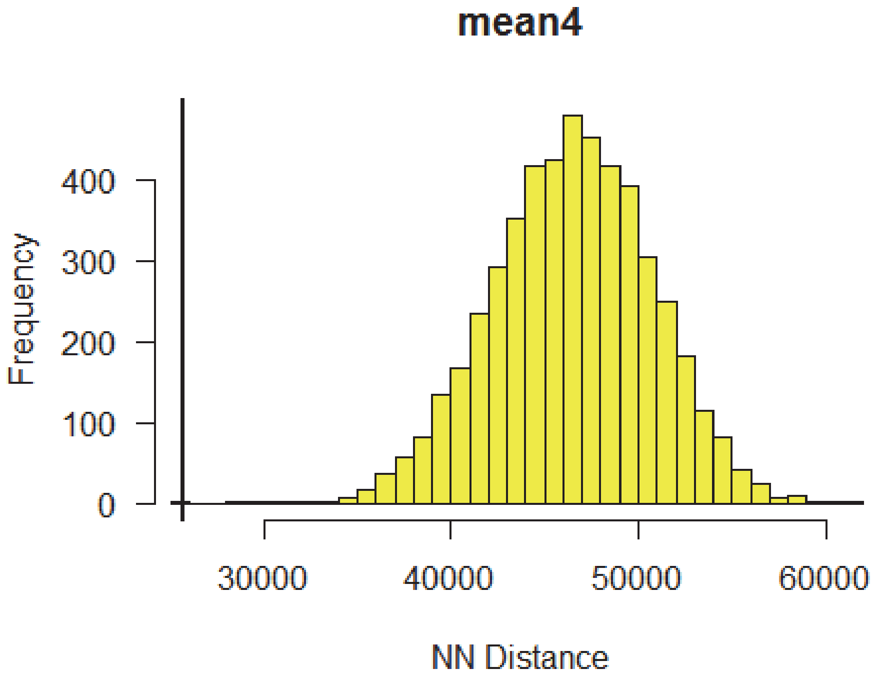

min4
Frequency
0
50
100
150
200
250
300
350
5000
10000
15000
20000
25000
30000
NN Distance


q14
Frequency
0
50
100
150
200
10000
20000
30000
40000
NN Distance



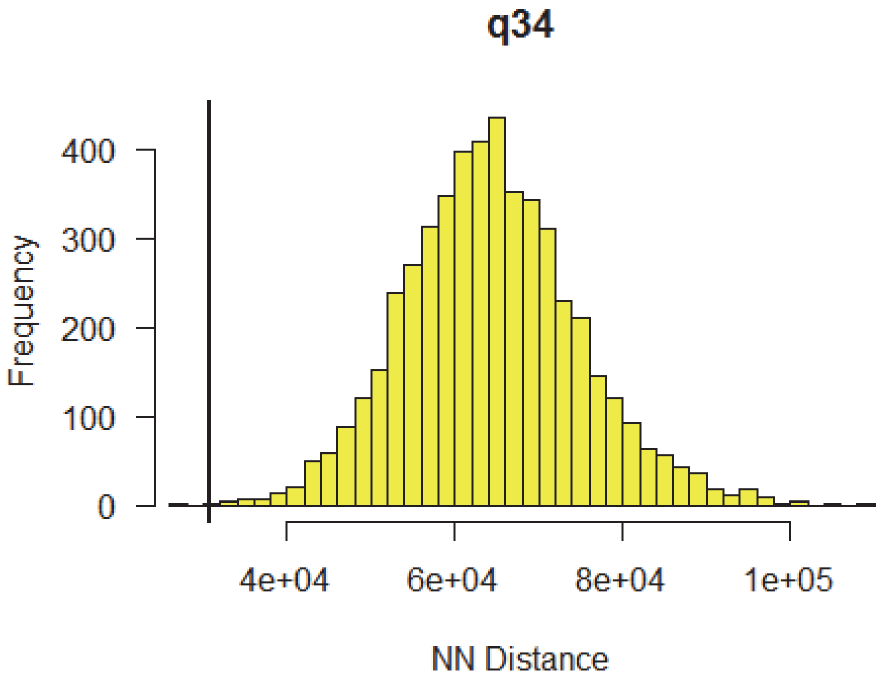
med4

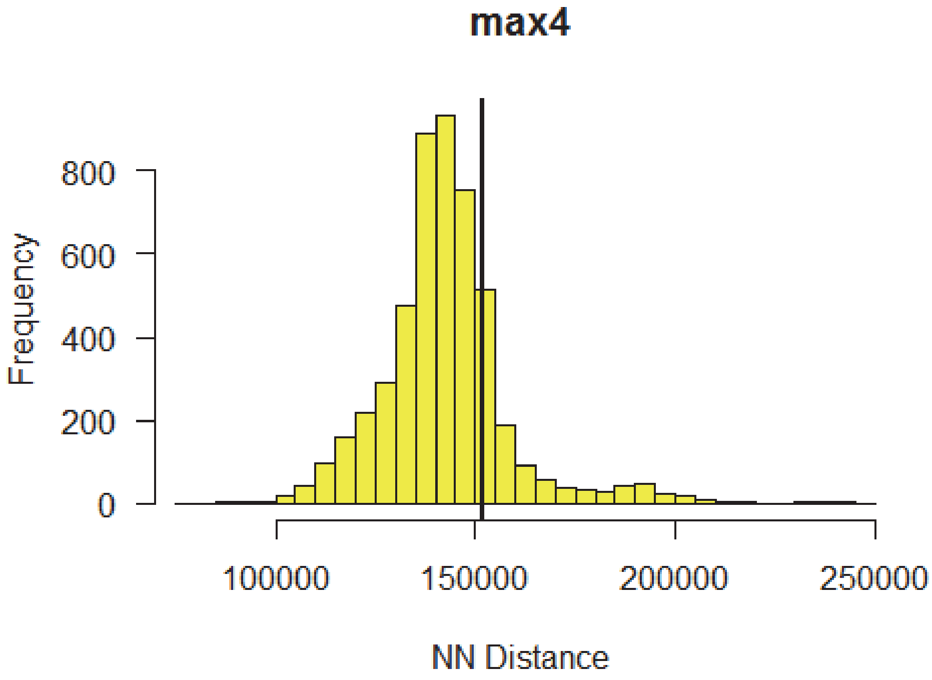
Frequency
0
50
100
150
200
250
20000
30000
40000
50000
60000
NN Distance

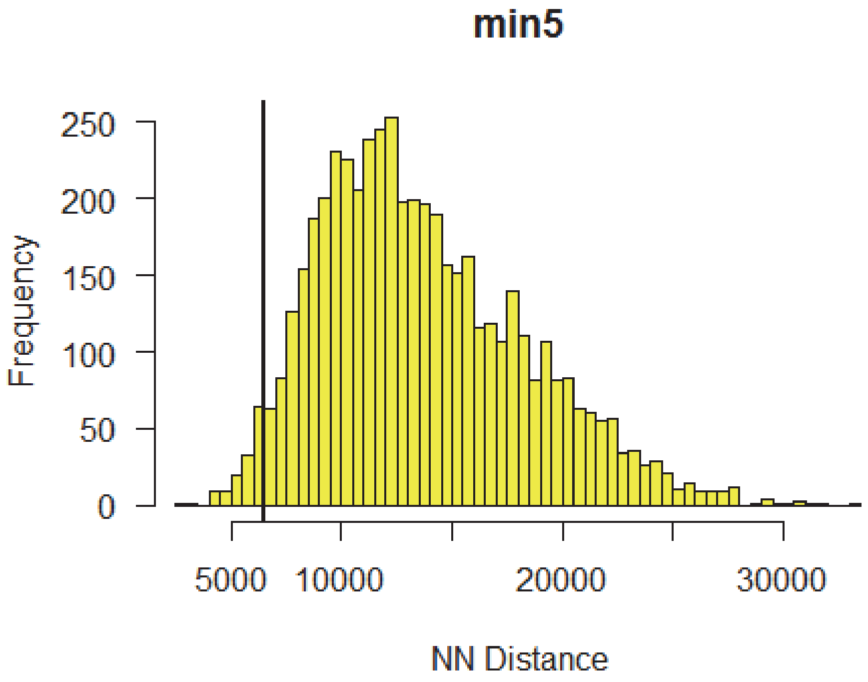


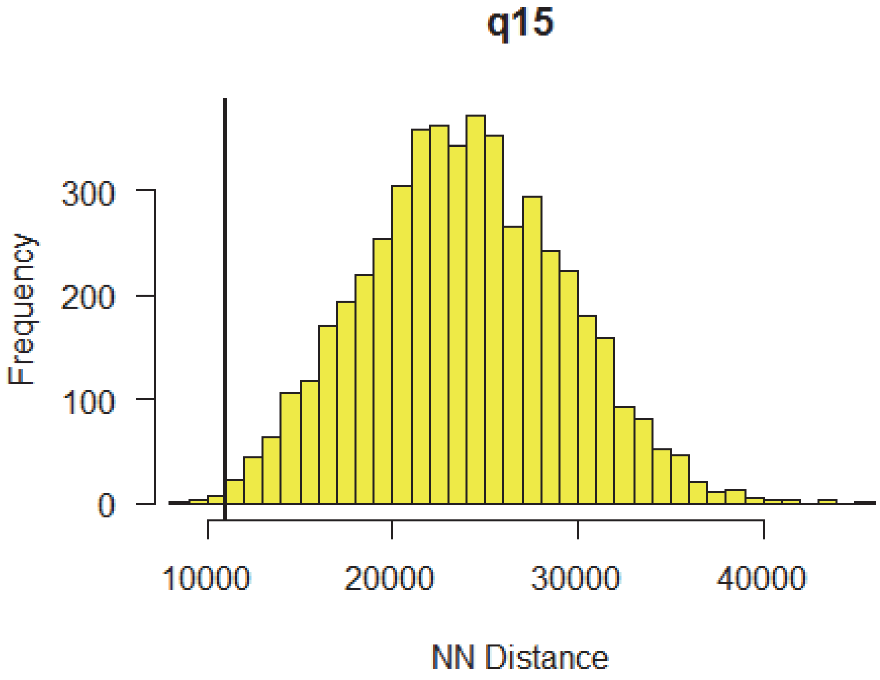
mean4

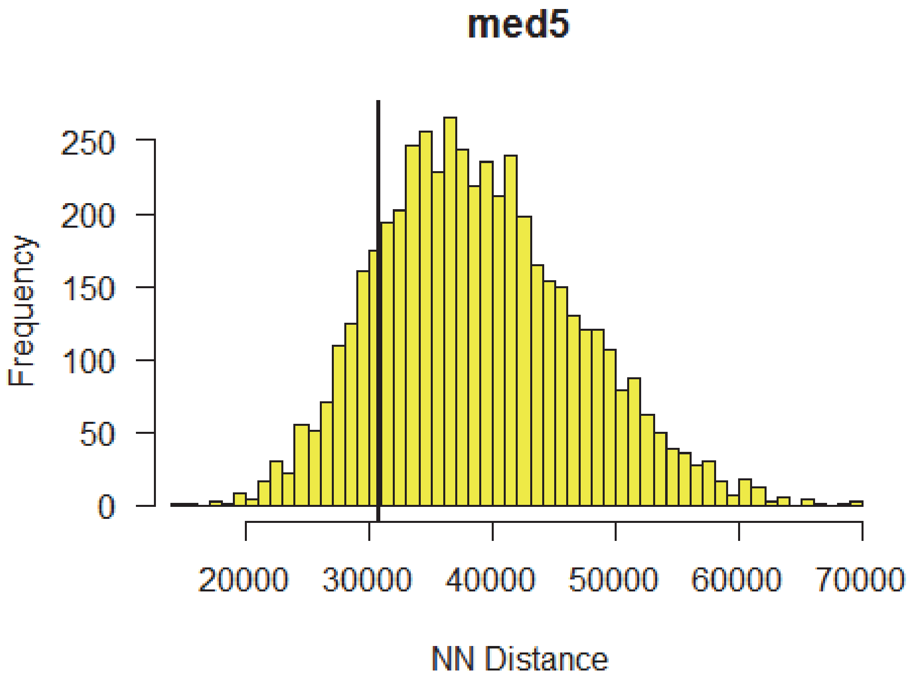
Frequency
0
100
200
300
400
30000
40000
50000
60000
NN Distance

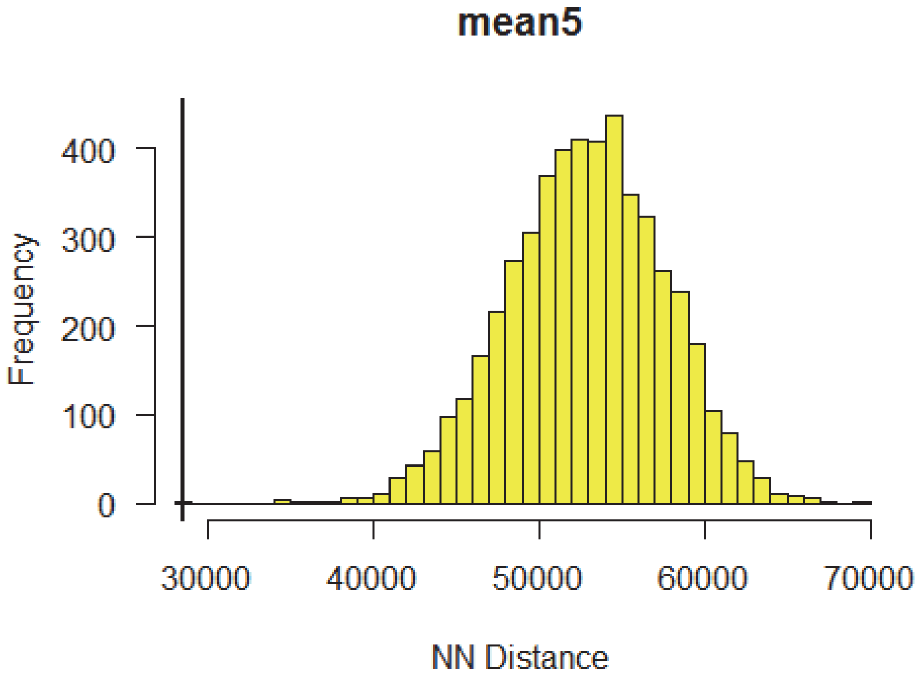

q34
Frequency
0
100
200
300
400
4e+04
6e+04
8e+04
1e+05
NN Distance

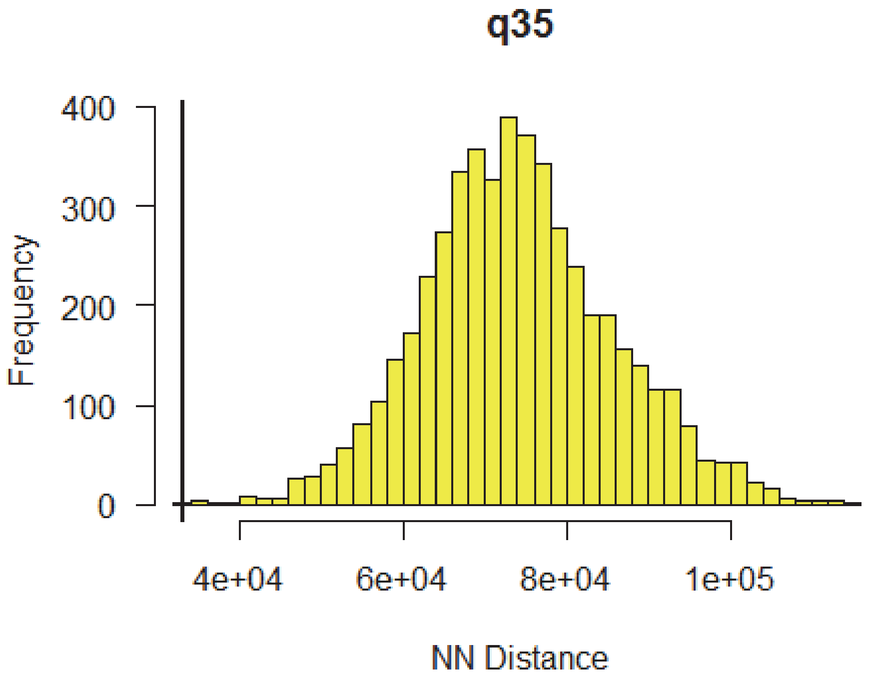

max4
Frequency
0
200
400
600
800
100000
150000
200000
250000
NN Distance

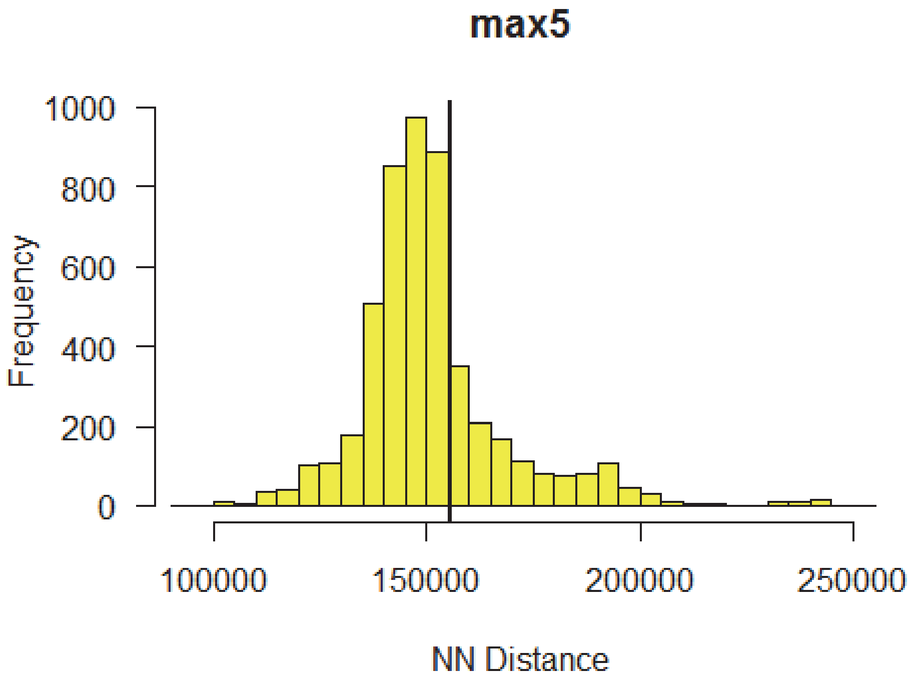

min5
Frequency
0
50
100
150
200
250
5000
10000
20000
30000
NN Distance


q15
Frequency
0
100
200
300
10000
20000
30000
40000
NN Distance


med5
Frequency
0
50
100
150
200
250
20000
30000
40000
50000
60000
70000
NN Distance


mean5
Frequency
0
100
200
300
400
30000
40000
50000
60000
70000
NN Distance


q35
Frequency
0
100
200
300
400
4e+04
6e+04
8e+04
1e+05
NN Distance


max5
Frequency
0
200
400
600
800
1000
100000
150000
200000
250000
NN Distance

ANNEX 2.4. Satellite tag nearest neighbour sampling all tags excluding 105GPS tags and killed birds with no undetected tag failures

05/02/2017

R Libraries

```
library(knitr)
library(foreign)
library(plyr)
library(FNN)
library(qdapRegex)
```

Background

See Annex 2.1

```
xylocs<-read.csv("xydata_nodups_Feb17.csv", as.is = FALSE)
```

Tag metadata

The metadata about the tags, excluding those related to tags fitted to birds known to have been killed and the 105GPS tags, are loaded and used to create subsets for subsequent sampling. The data have a snmlf field in which 1 indicates a snmlf, other values are 0. The number of snmlfs is retained as qsus.

```
tagmeta<-read.csv("tagmetadatajan17nokilled.csv", as.is = FALSE)
attach(tagmeta)
tagmeta<-tagmeta[which(tagmeta$Tagtype!="105GPS"),]
qsus<-sum(tagmeta$snmlf)
```

Sampling effort

See Annex 2.1

```
daysum<-sum(tagmeta$Days)
tagmeta$dayprop<-tagmeta$Days/daysum
```

Preparing sampling

See Annex 2.1

```
attach(xylocs)

## The following object is masked from tagmeta:
##     Days

iterations<-5000
rows<-iterations
nndists <- data.frame(min1=numeric(rows), q11=numeric(rows), med1=numeric(rows),
mean1=numeric(rows), q31=numeric(rows), max1=numeric(rows),min2=numeric(rows),
q12= numeric(rows), med2=numeric(rows), mean2=numeric(rows), q32=numeric(rows),
max2=numeric(rows), min3=numeric(rows),q13=numeric(rows), med3=numeric(rows),
mean3=numeric(rows), q33=numeric(rows), max3=numeric(rows),
min4=numeric(rows),q14=numeric(rows), med4=numeric(rows), mean4=numeric(rows),
q34=numeric(rows), max4=numeric(rows), min5=numeric(rows),q15=numeric(rows),
med5=numeric(rows), mean5=numeric(rows), q35=numeric(rows), max5=numeric(rows))
IDlist<-data.frame(matrix(ncol = qsus, nrow = rows))
set.seed(12345)
```

Random sampling

See Annex 2.1

```
for (i in 2:iterations) {
    qsample <- tagmeta[sample(1:nrow(tagmeta),qsus,replace=FALSE,tagmeta$dayprop),]
    lst<-qsample$TagID
    IDlist[i-1,]<-lst[order(lst)]
    xylocsample<-xylocs[xylocs$ID%in% lst,]
    lstlen<-length(lst)
    s2<-data.frame(X=numeric(lstlen), Y=numeric(lstlen))
    for (a in 1:lstlen) {
        s <- xylocsample[ which(xylocsample$ID==lst[a]), ]
        samp_idx <- sample(seq_len(nrow(s)), 1, prob=s$samp_p)
        s2[a,] <- s[samp_idx,c("X","Y") ]
    }
    nnd<-knn.dist(s2,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
    nndo<-summary(nnd)
    nndo<-gsub("[:]",": ",nndo)
    tmp2<-as_numeric2(ex_number(nndo))
    for (j in 1:30) nndists[i,j]<- tmp2[j]
}
```

Real nearest neighbours

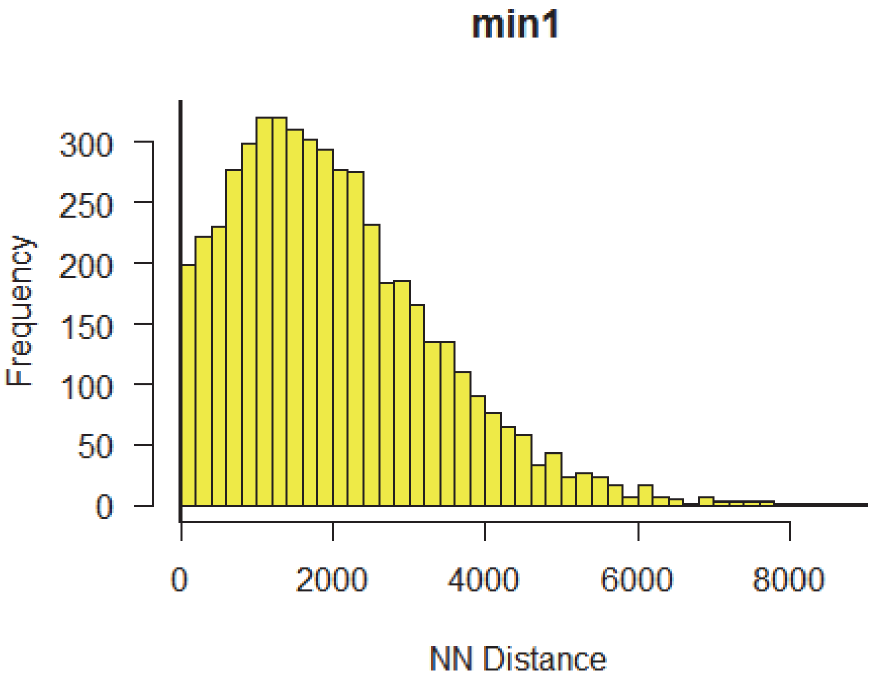
See Annex 2.1

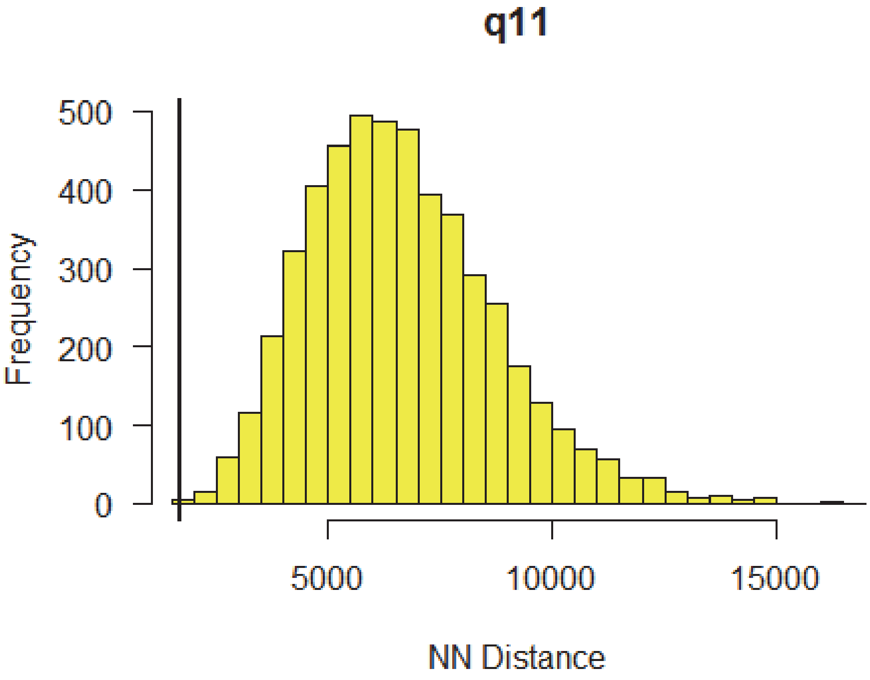
```
sx<-tagmeta[which(tagmeta$snmlf>0),c("FinX","FinY")]
nndx<-knn.dist(sx, k=5, algorithm=c("kd_tree","cover_tree","CR","brute"))
nndo<-summary(nndx)
nndo<-gsub("[:]",": ",nndo)
tmp2<-as_numeric2(ex_number(nndo))
for (j in 1:30) nndists[1,j]<- tmp2[j]
write.table(nndists,file="nndists5_70tagnokills.txt",sep="\t")
IDcount<-stack(IDlist)
IDcount<-as.matrix(table(IDcount$values))
write.table(IDcount,file="nndists5_70tagnokills_n.txt",sep="\t")
```

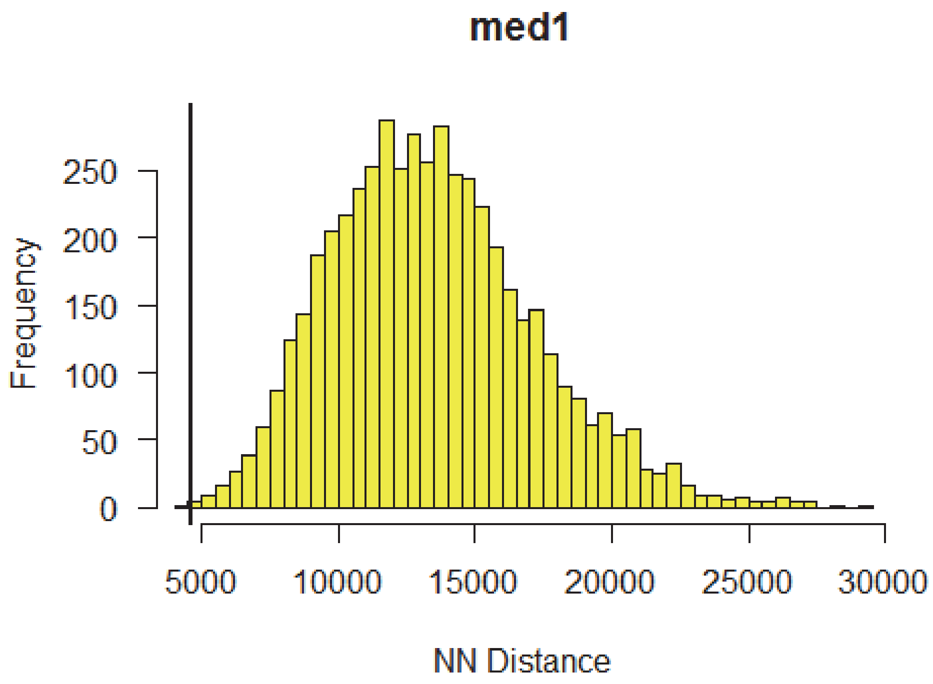
Plot the results

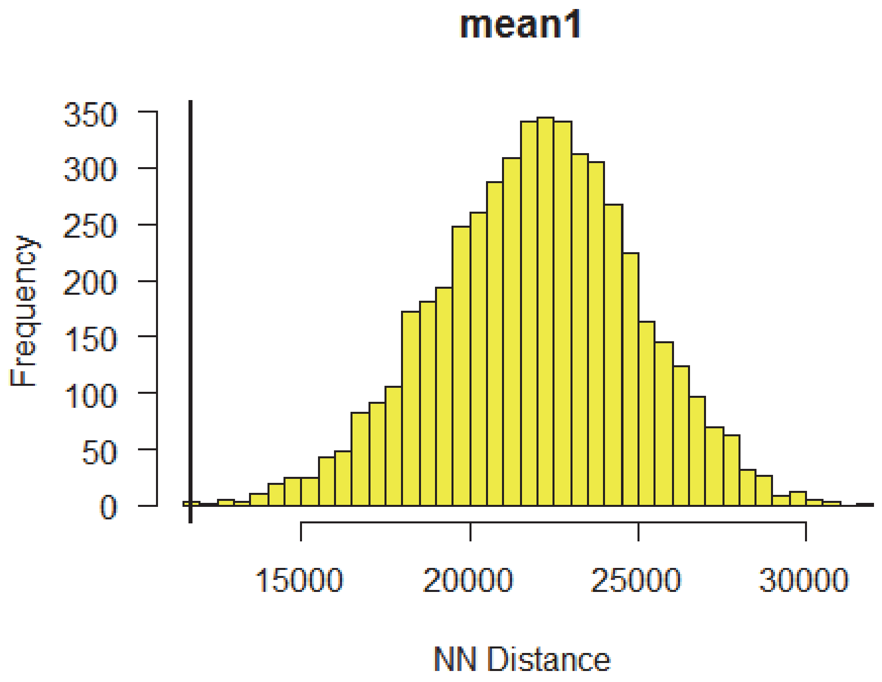
A frequency distribution is plotted for each nearest neighbour's sampling distribution and the real value is shown as a vertical black line.

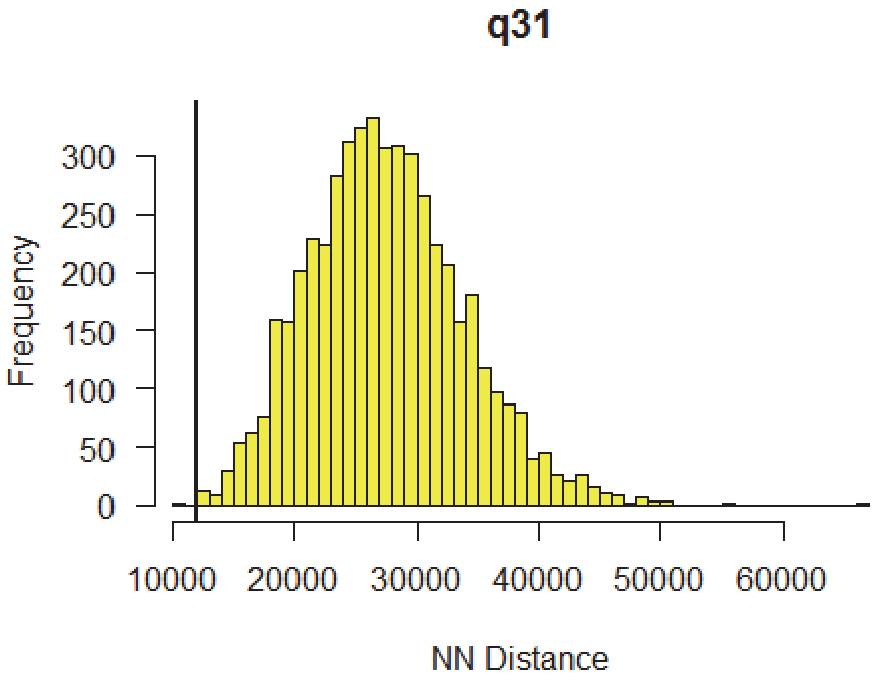
```
cnames<-names(nndists)
bins<-50
for (i in 1:length(cnames)) {
    title<-cnames[i]
    range<-round(range(nndists[,i]), digits=0)
    hist(nndists[,i], main=title, xlab="NN Distance", border="black", col="yellow",
xlim=c(range[1],range[2]), las=1, breaks=bins, prob = FALSE)
    abline(v=nndists[1,i],lty=1,lwd=2,col="black")
}
```

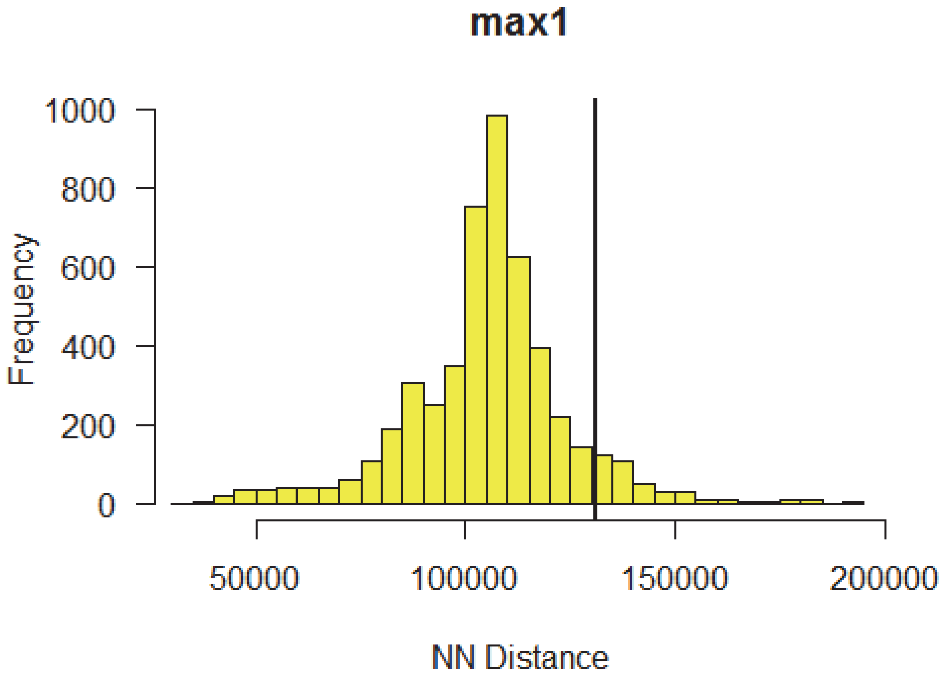

min1
Frequency
300
250
200
150
100
50
0
0
2000
4000
6000
8000
NN Distance

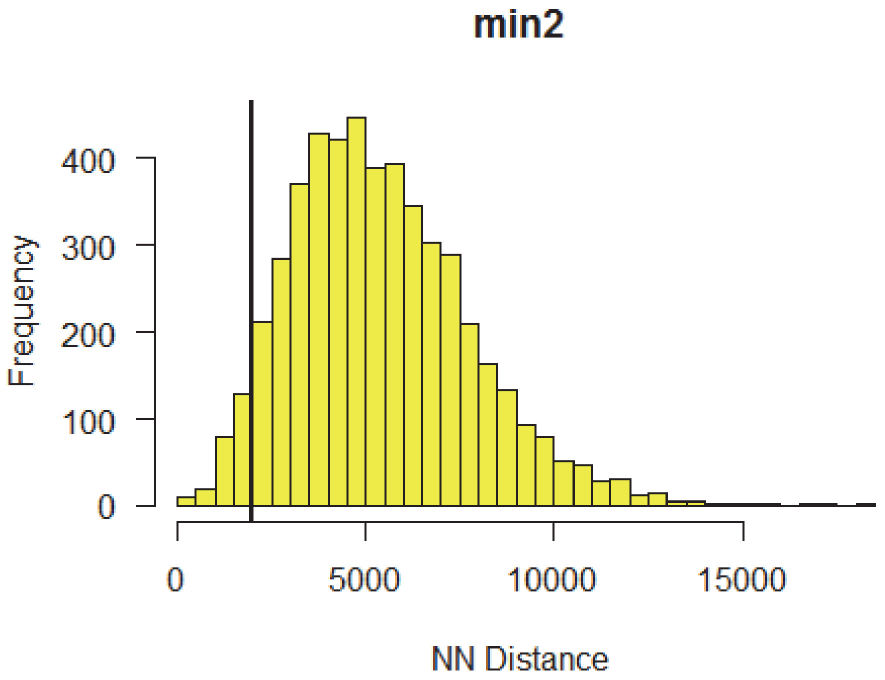

q11
Frequency
500
400
300
200
100
0
5000
10000
15000
NN Distance

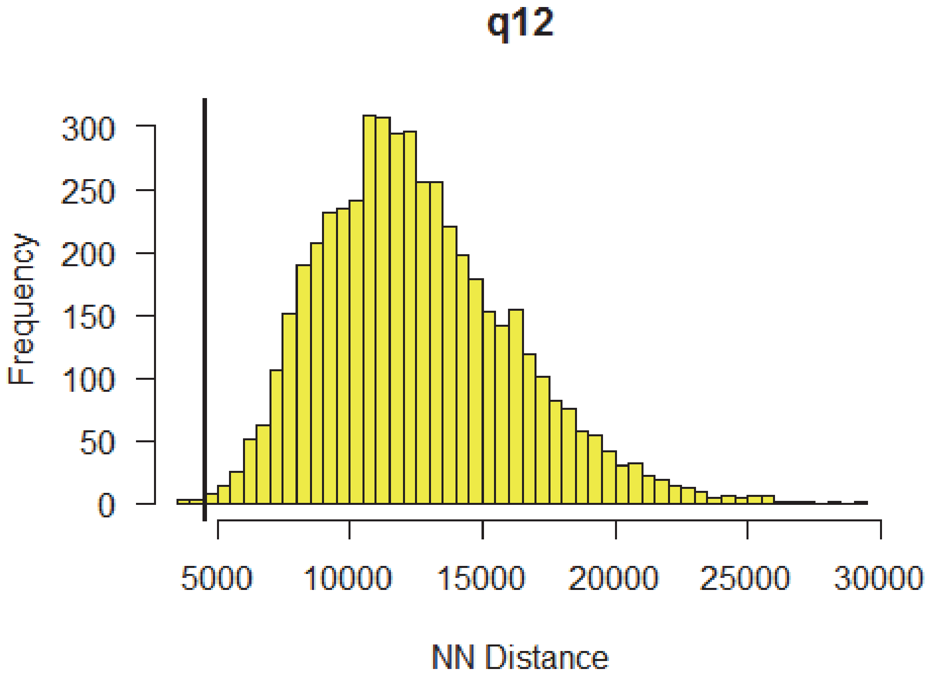

med1
Frequency
0
50
100
150
200
250
5000
10000
15000
20000
25000
30000
NN Distance

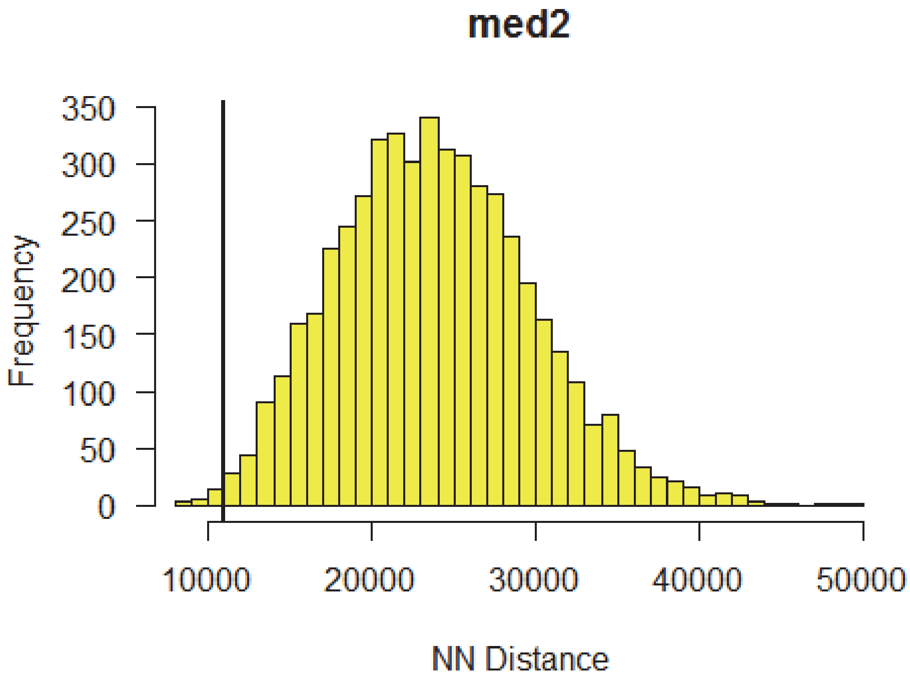

mean1
Frequency
0
50
100
150
200
250
300
350
15000
20000
25000
30000
NN Distance

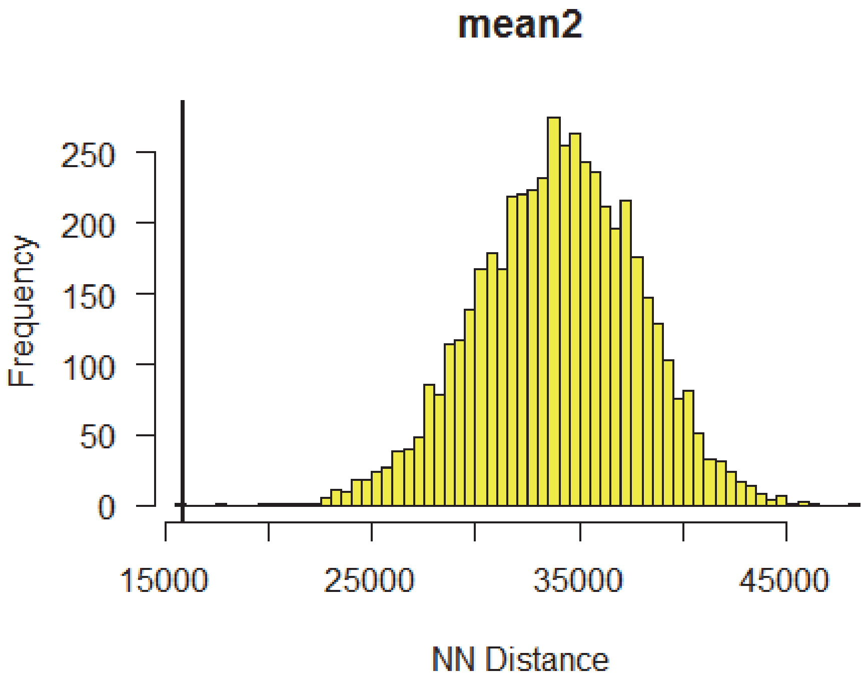

q31
Frequency
0
50
100
150
200
250
300
10000
20000
30000
40000
50000
60000
NN Distance

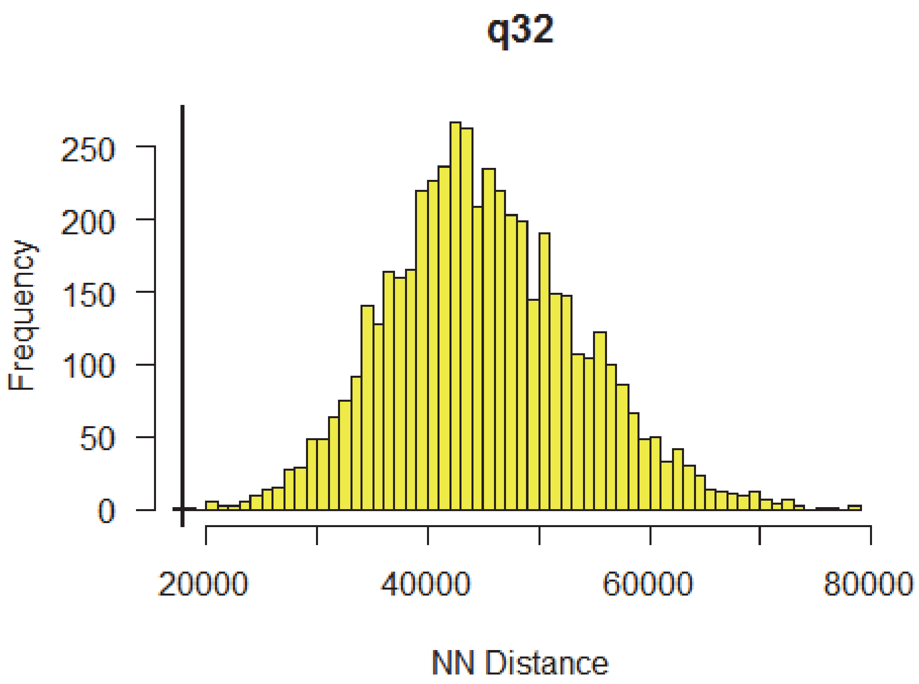

max1
Frequency
0
200
400
600
800
1000
50000
100000
150000
200000
NN Distance

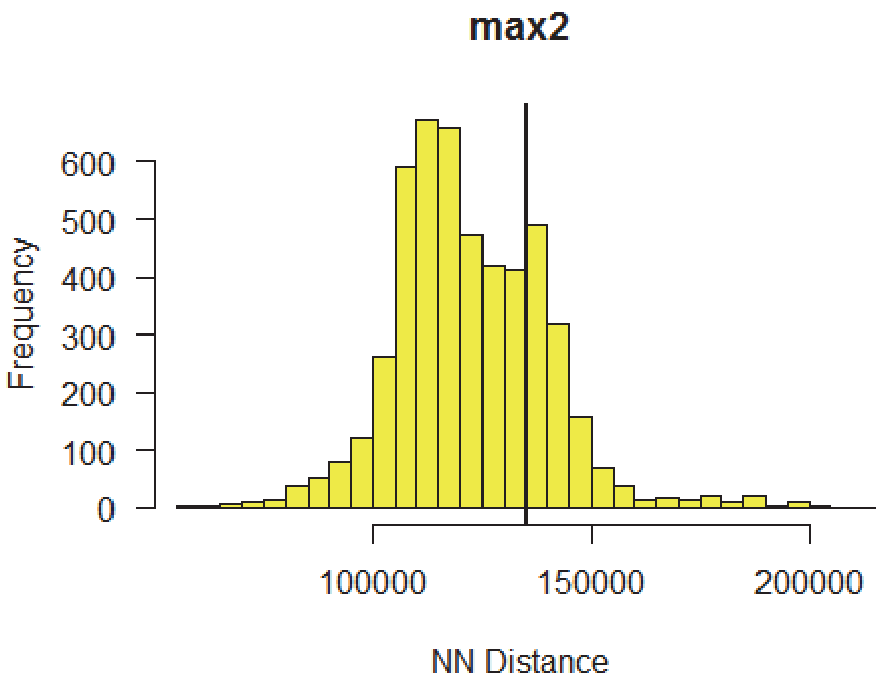

min2
Frequency
0
100
200
300
400
0
5000
10000
15000
NN Distance

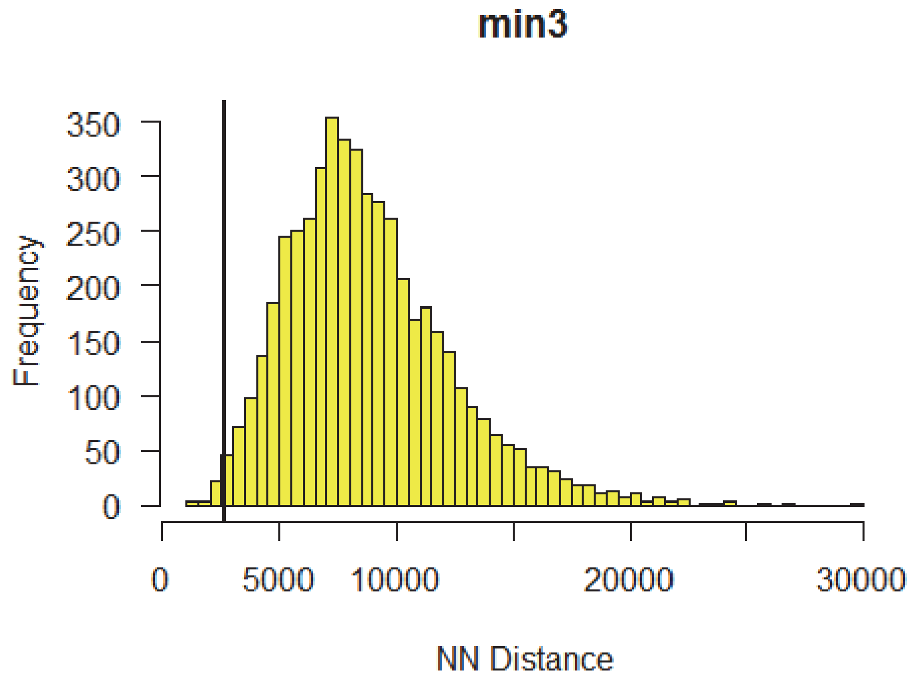

q12
Frequency
0
50
100
150
200
250
300
5000
10000
15000
20000
25000
30000
NN Distance

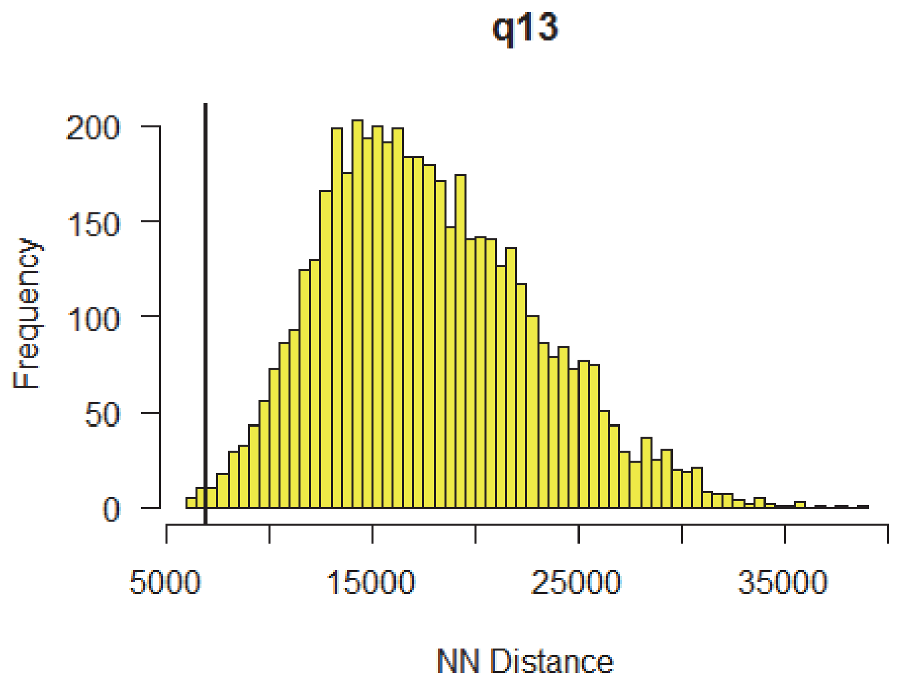

med2
Frequency
350
300
250
200
150
100
50
0
10000
20000
30000
40000
50000
NN Distance

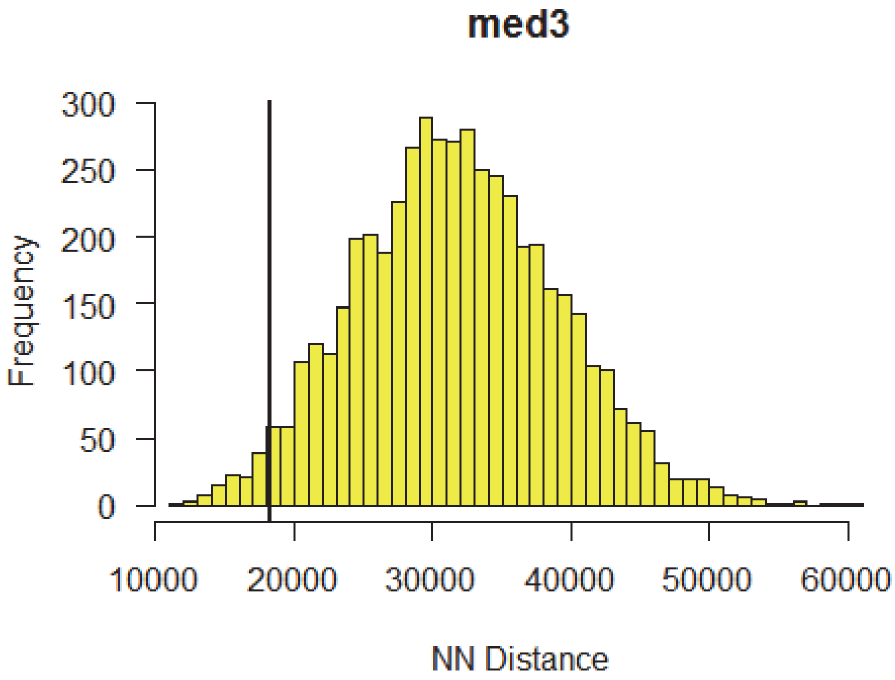

mean2
Frequency
250
200
150
100
50
0
15000
25000
35000
45000
NN Distance

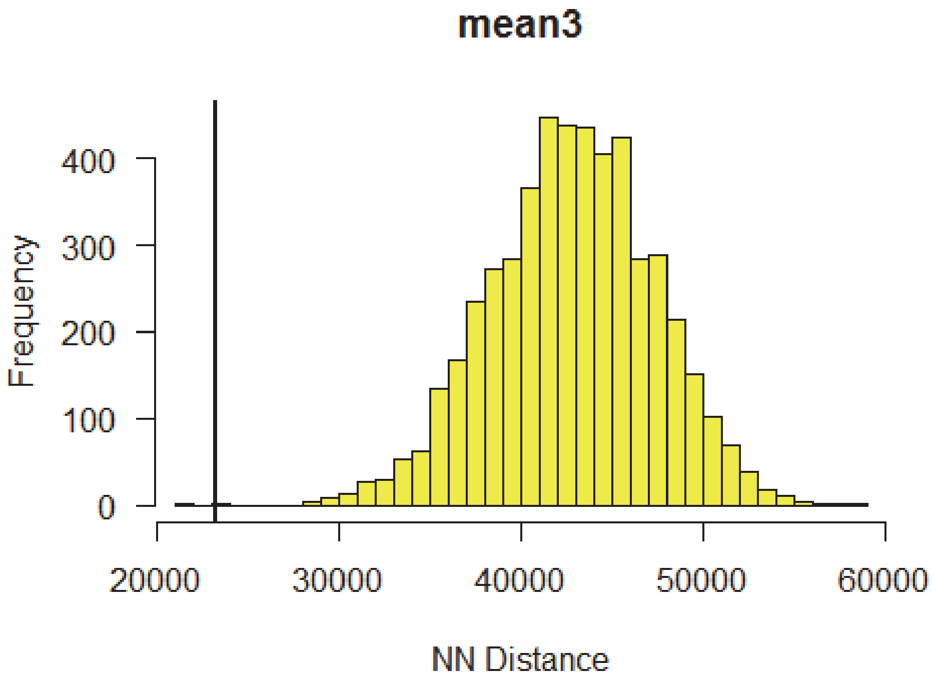

q32
Frequency
0
50
100
150
200
250
20000
40000
60000
80000
NN Distance

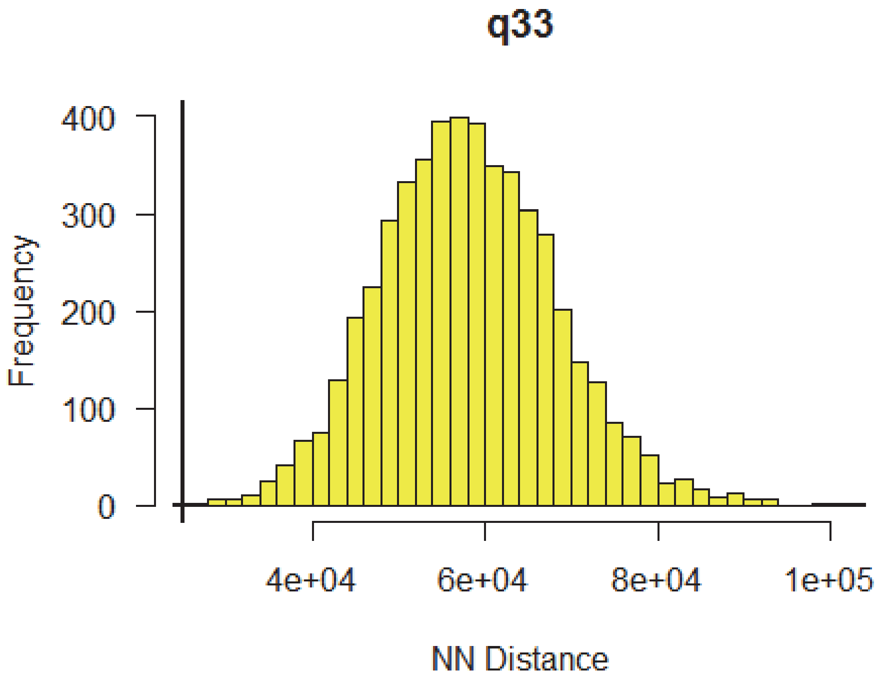

max2
Frequency
0
100
200
300
400
500
600
100000
150000
200000
NN Distance

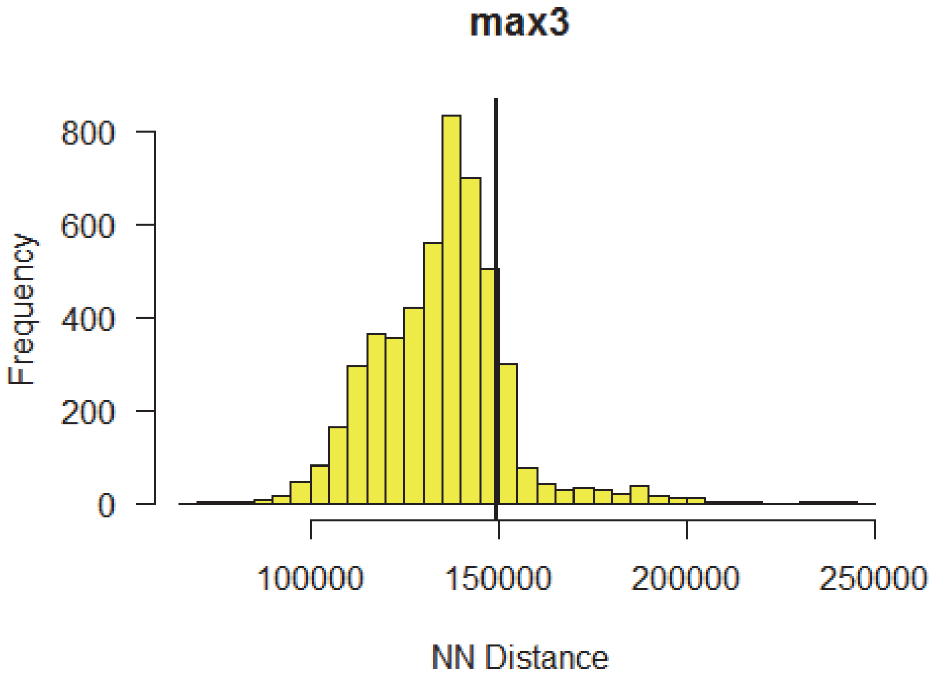

min3
Frequency
350
300
250
200
150
100
50
0
0
5000
10000
20000
30000
NN Distance

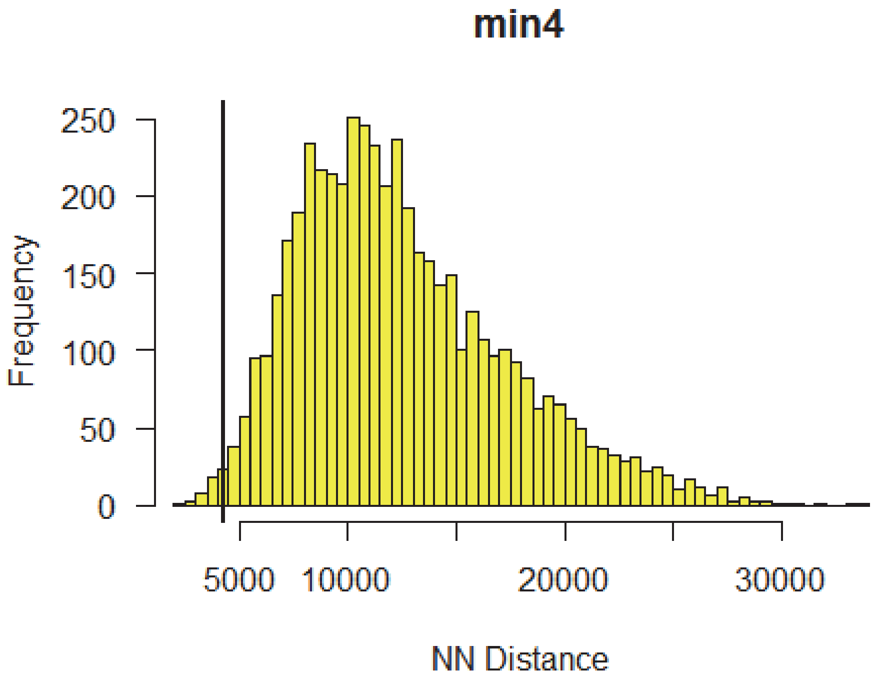

q13
Frequency
200
150
100
50
0
5000
15000
25000
35000
NN Distance


med3
Frequency
300
250
200
150
100
50
0
10000
20000
30000
40000
50000
60000
NN Distance

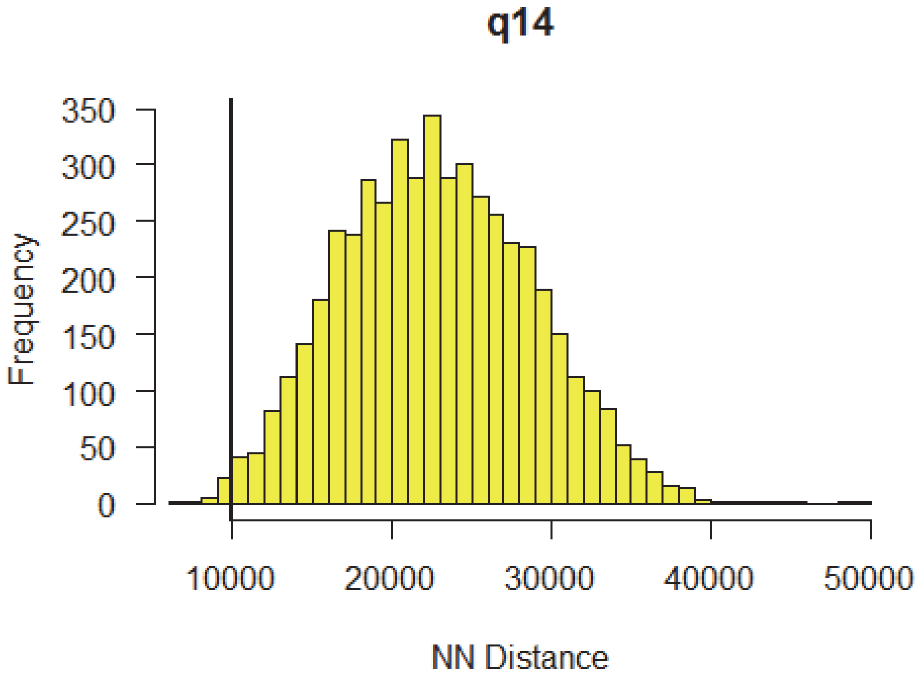

mean3
Frequency
400
300
200
100
0
20000
30000
40000
50000
60000
NN Distance


q33
Frequency
400
300
200
100
0
4e+04
6e+04
8e+04
1e+05
NN Distance

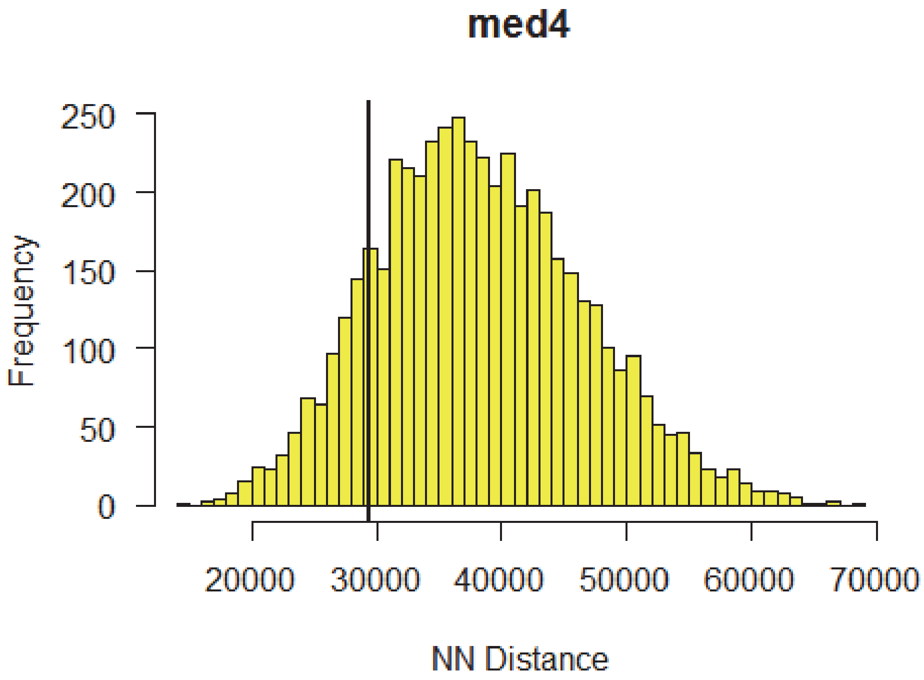

max3
Frequency
800
600
400
200
0
100000
150000
200000
250000
NN Distance

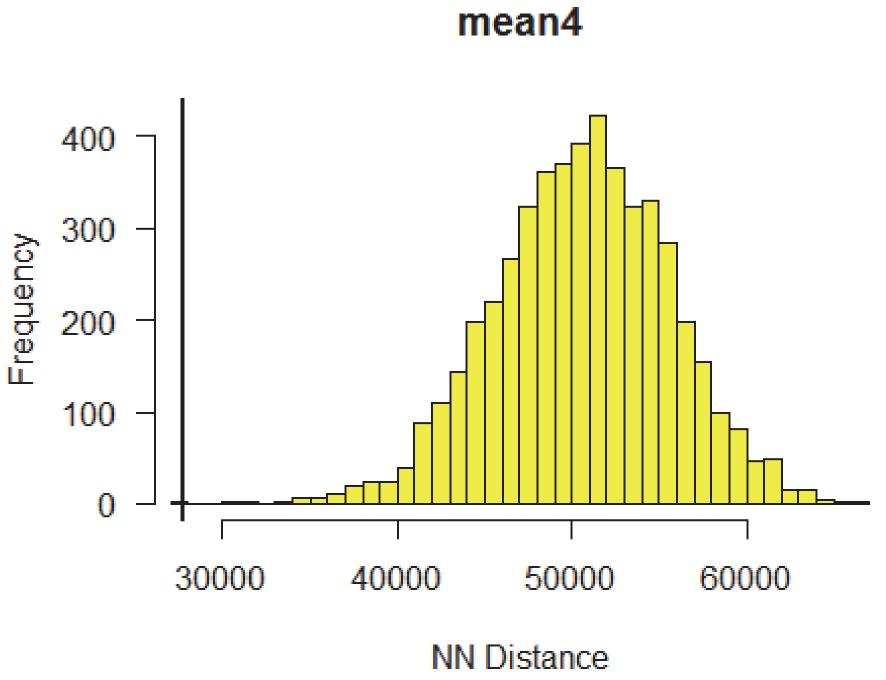

min4

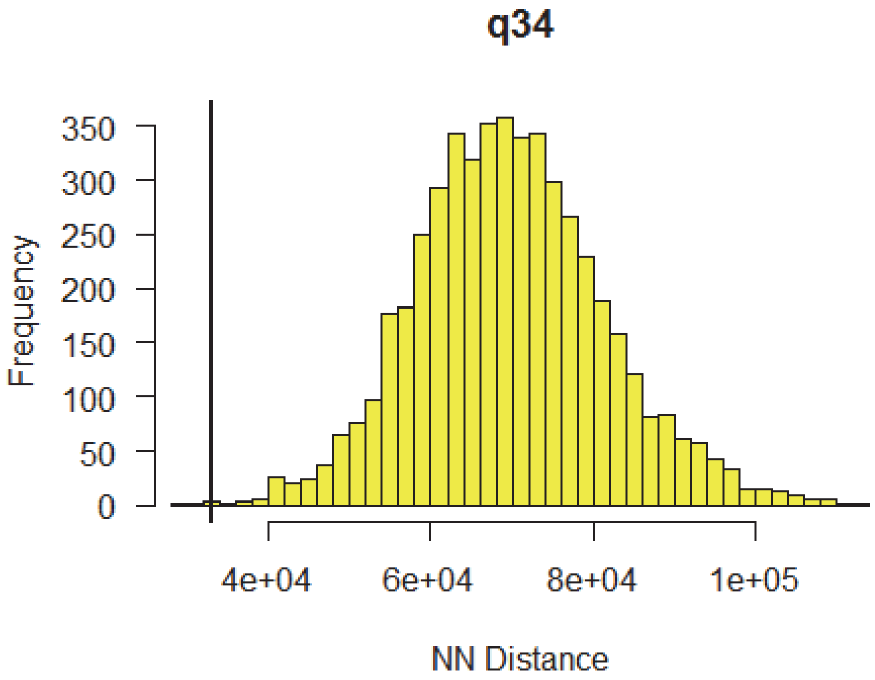
Frequency
0
50
100
150
200
250
5000
10000
20000
30000
NN Distance

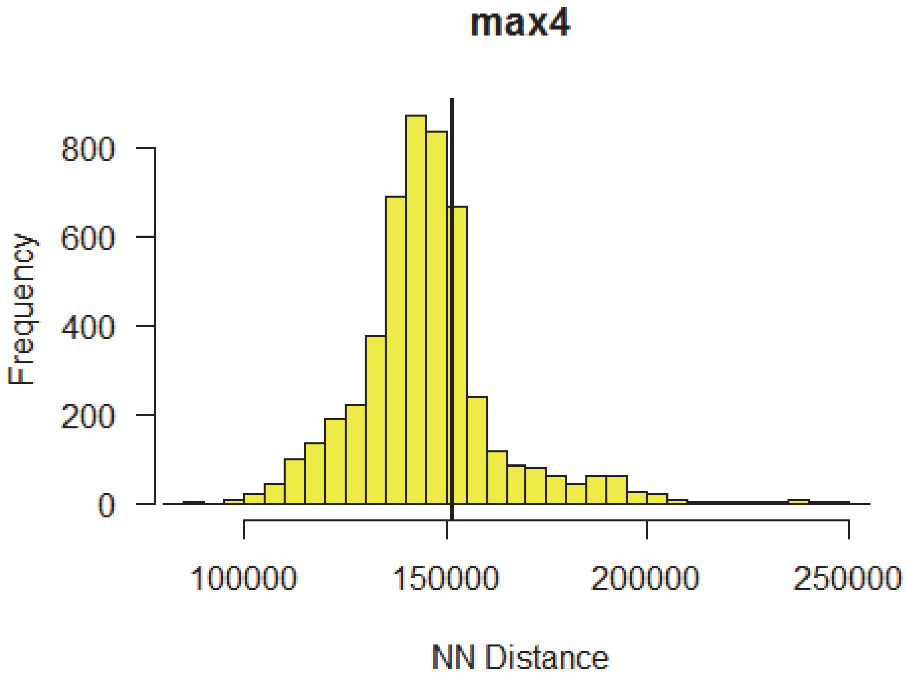

q14

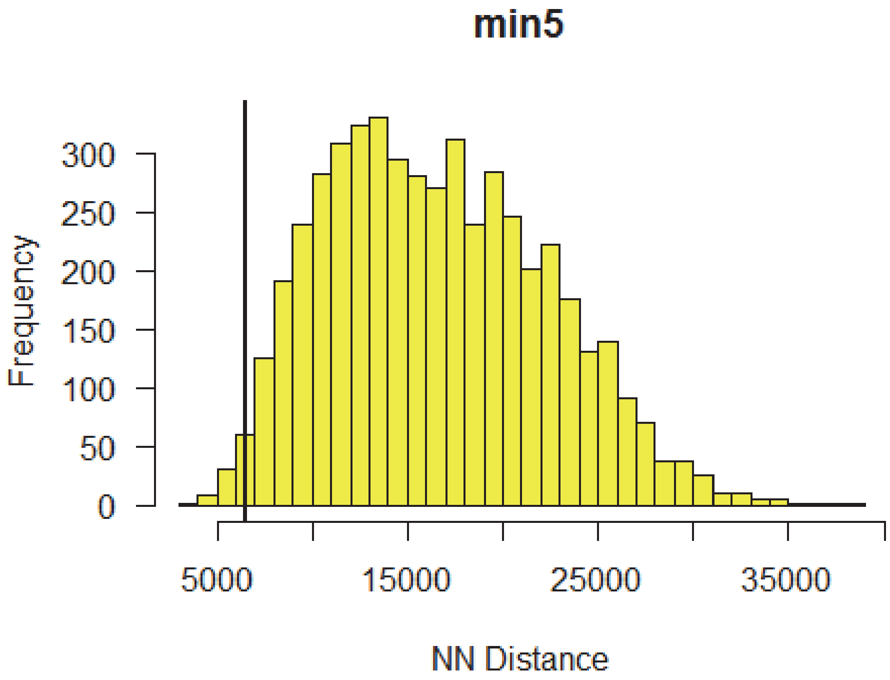
Frequency
0
50
100
150
200
250
300
350
10000
20000
30000
40000
50000
NN Distance

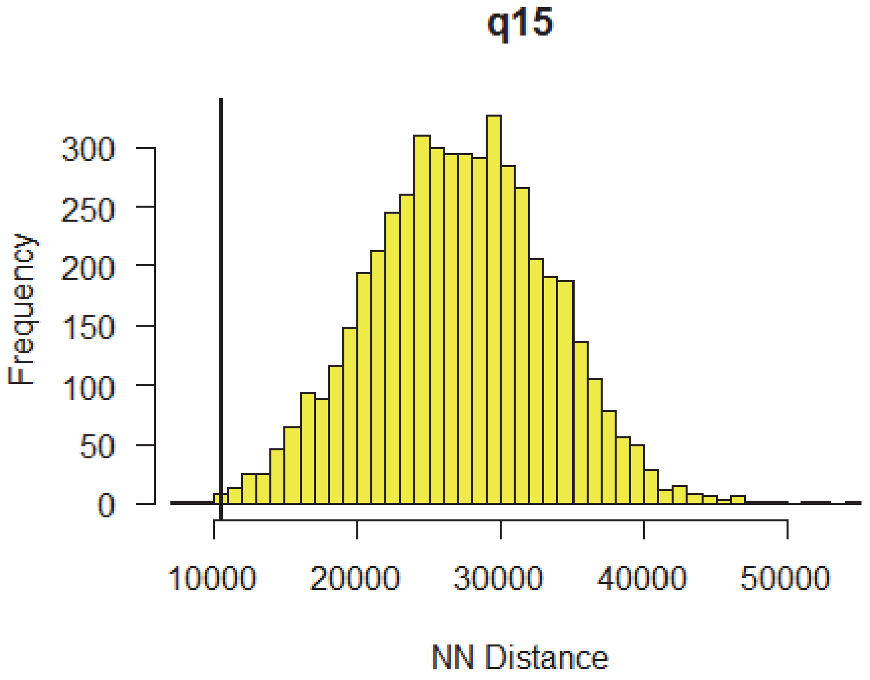

med4
Frequency
250
200
150
100
50
0
20000
30000
40000
50000
60000
70000
NN Distance

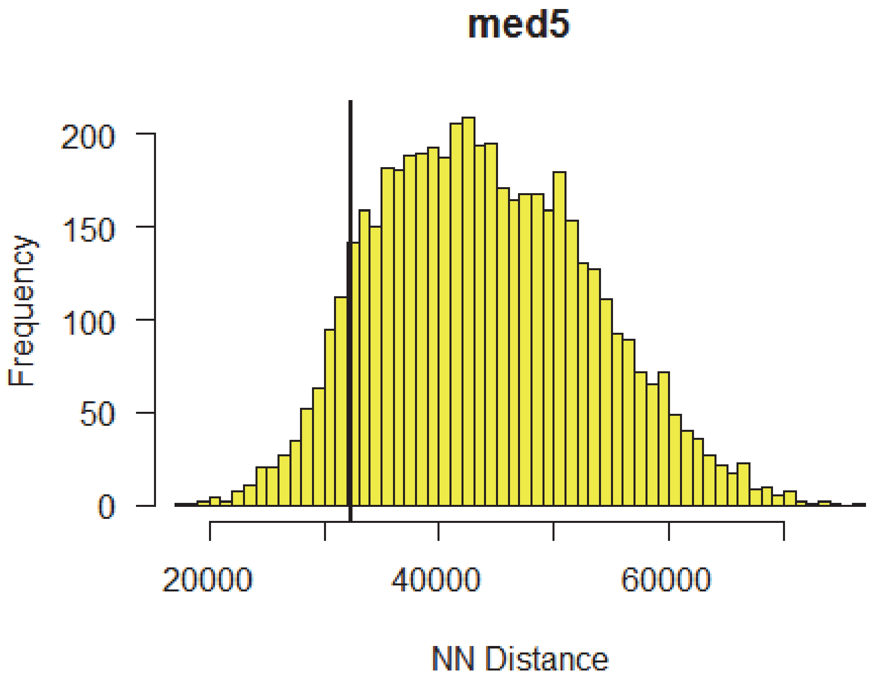

mean4
Frequency
400
300
200
100
0
30000
40000
50000
60000
NN Distance

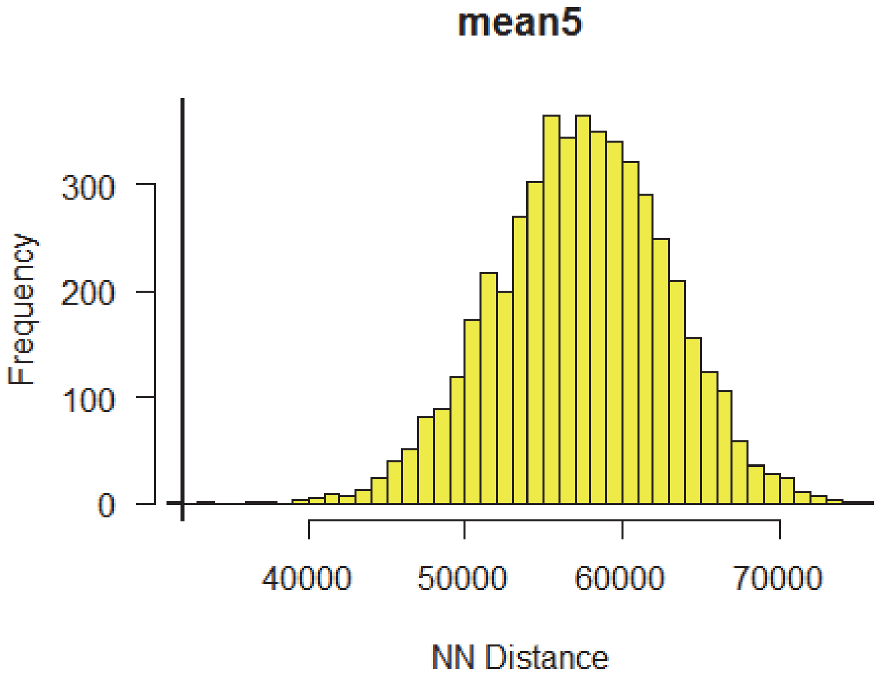

q34
Frequency
350
300
250
200
150
100
50
0
4e+04
6e+04
8e+04
1e+05
NN Distance

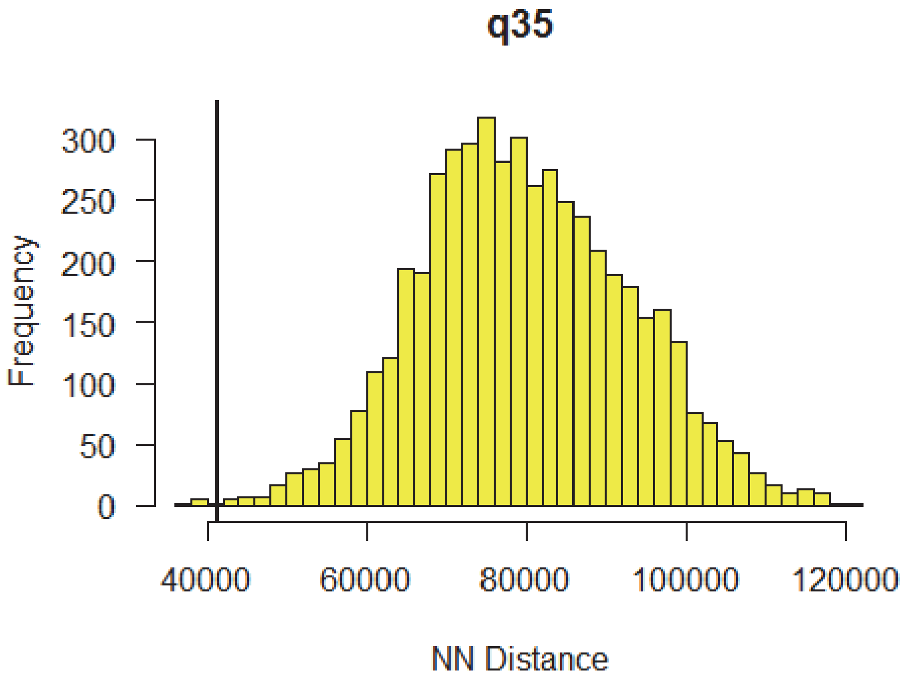

max4
Frequency
800
600
400
200
0
100000
150000
200000
250000
NN Distance

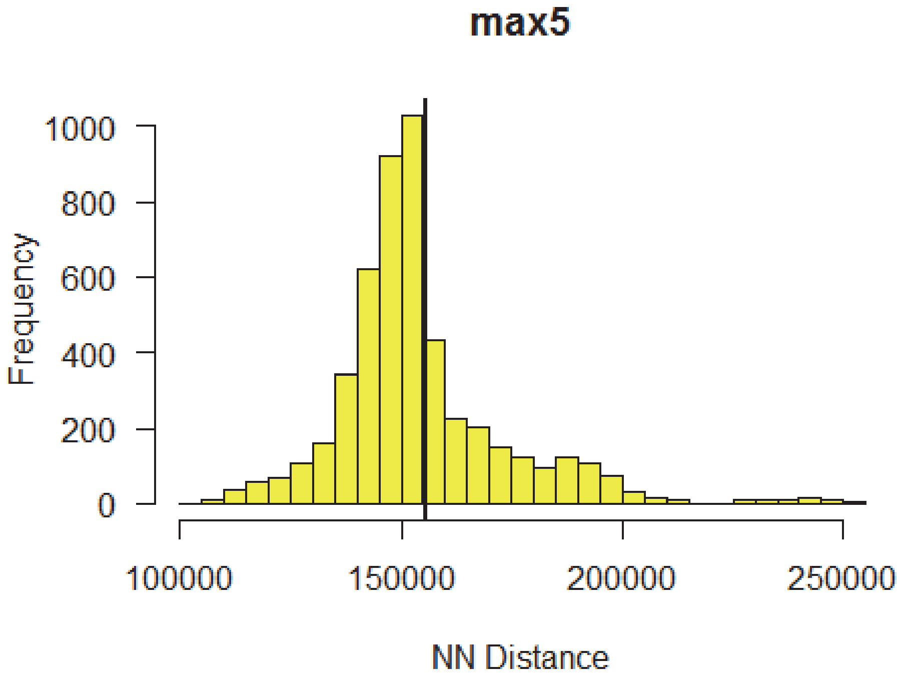

min5
Frequency
0
50
100
150
200
250
300
5000
15000
25000
35000
NN Distance


q15
Frequency
0
50
100
150
200
250
300
10000
20000
30000
40000
50000
NN Distance


med5
Frequency
200
150
100
50
0
20000
40000
60000
NN Distance


mean5
Frequency
300
200
100
0
40000
50000
60000
70000
NN Distance


q35
Frequency
0
50
100
150
200
250
300
40000
60000
80000
100000
120000
NN Distance


max5
Frequency
0
200
400
600
800
1000
100000
150000
200000
250000
NN Distance

Annex 2.5. Undetected tag failures with all tags including all birds

07/02/2017

Background

This analysis uses random sampling algorithms to determine the probability of observing the spatial pattern of last known fixes (lkf) from satellite tags fitted to golden eagles that appeared to be functioning correctly prior to their final location. The measure of spatial pattern is the nearest neighbour distance (NND), i.e. the distance to the nearest other lkf. The median NNDs from sampled and real lkfs are compared using a Mann Whitney statistical test. This version assumes that between one of twenty of the snmlfs is due to an undetected technical problem.

R Libraries

```
library(knitr)
library(foreign)
library(plyr)
library(FNN)
library(qdapRegex)
```

Functions

Two functions are defined. 1). sample_sim samples the complete location data set and returns the NNDs for the sampled simulated lkfs. The random sampling is designed to preferentially select tags in the relation to the number of days of records, i.e. weighted random sampling. In order to allow this the number of days between and a tag's last and first records is recorded in a new variable called Days. daysum is sum of days over all tags. Therefore, days/daysum is the proportion of tracked days allocated to a particular tag. The sample size (number of tags) is equal to the number of snmlfs minus the number of assumed technical failures. 2). sample_real samples the real lkfs and finds their NNDs.

```
sample_sim <- function(y,fails) {
   qsample <- tagmeta[sample(1:nrow(tagmeta),qsus-
fails,replace=FALSE,tagmeta$dayprop),]
   lst<-qsample$TagID
   xylocsample<-y[y$ID %in% lst,]
   lstlen<-length(lst)
   s2<-data.frame(X=numeric(lstlen), Y=numeric(lstlen))
   for (a in 1:lstlen) {
      s <- xylocsample[ which(xylocsample$ID==lst[a]), ]
      samp_idx <- sample(seq_len(nrow(s)), 1, prob=s$samp_p)
      s2[a,] <- s[samp_idx,c("X","Y") ]
   }
   nny<-knn.dist(s2,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
   return(nny)
}

sample_real <- function(x, fails) {
  qsx<-x[sample(1:nrow(x),qsus-fails,replace=FALSE),]
  nnx<-nn.dist(qsx,k=nns,algorithm=c("kd_tree","cover_tree","CR","brute"))
  nnx[nnx==0]<-NA
  return(nnx)
}
```

Preparing sampling and setting simulation conditions

The number of random sampling iterations is set, in this example to 86. Also fixed in this section are the number of NNDs to calculate (nns) and the number of tags with undetected failures. The nndists and nndists2 data frames are created to store the results of the median NNDs from each sampling iteration. mannw stores the p-values from the Mann Whitney tests used to compare the median NNDs and medians stores the median NNDs for the real and sampled lkfs. Finally the random number seed is set to ensure reproducibility of the results.

```
samples<-86
nns<-5
failed<-20
rows<-samples
rows2<-failed+1
set.seed(12345)
nndists <- data.frame(nn1=numeric(rows), nn2=numeric(rows), nn3=numeric(rows),
nn4=numeric(rows), nn5=numeric(rows))
nndists2 <- data.frame(med1=numeric(rows), med2=numeric(rows),
med3=numeric(rows), med4=numeric(rows), med5=numeric(rows))
mannw<-data.frame(failed=numeric(failed+1), nn1=numeric(failed+1),
nn2=numeric(failed+1), nn3=numeric(failed+1), nn4=numeric(failed+1),
nn5=numeric(failed+1))
medians <- data.frame(failed=numeric(rows2), med1=numeric(rows2),
med2=numeric(rows2), med3=numeric(rows2), med4=numeric(rows2),
med5=numeric(rows2),  med1r=numeric(rows2), med2r=numeric(rows2),
med3r=numeric(rows2), med4r=numeric(rows2), med5r=numeric(rows2))
row<-1
```

Reading in data

This begins by reading in a previously edited CSV file of location data. Data columns are tag ID, Date, Time and X & Y locations. Duplicate records have been removed, for example multiple locations from a roost site. Note that the same location, from one tag, will be retained on different days because the unique function examines the entire record and not just the location. The next stage reads in metadata about the tags and uses this to create subsets for subsequent sampling. All tags, excluding 80NS, are included. The data, as read in, contain a snmlf field in which 1 indicates a snmlf, other values are 0. The number of snmlfs is retained as qsus.

```
xylocs<-read.csv("xydata_nodups_Feb17.csv", as.is = FALSE)
tagmeta<-read.csv("tagmetadatajan17.csv", as.is = FALSE)
attach(tagmeta)
qsus<-sum(tagmeta$snmlf)
IDlist<-data.frame(matrix(ncol = qsus, nrow = rows))
sx<-tagmeta[which(tagmeta$snmlf>0),c("FinX","FinY")]
```

Sampling effort

The random sampling of the location data is designed to preferentially select tags in relation to the number of days of records, i.e. weighted random sampling. daysum is sum of days over all tags. Therefore, days/daysum is the proportion of all tracked days allocated to a particular tag.

```
daysum<-sum(tagmeta$Days)
tagmeta$dayprop<-tagmeta$Days/daysum
```

Random sampling

The sampling iterations are contained within a set of nested loops and make use of two functions. The outer loop cycles through the number of undetected failures, starting at zero and ending at maximum number of undetected tag failures (failed). Within this loop there is the main random sampling loop which uses the sample_sim function to draw the random samples and calculate the nearest neighbour distance statistics. The five nearest neighbours for the actual lkfs of tags that ceased to function with no prior indication of a fault with the tag are found in a similar way except that the tag metadata file is the source of the final X & Y fixes. If there is one or more assumed undetected failures these actual final X & Y fixes are sampled. Median NNDs are stored in the two nndists data frames. Once all of the random samples for one failed loop are available Mann Whitney tests are used to compare the median NNDs and the resulting p values are stored as percentages in the mannw data frame.

```
for (f in 0:failed) {
  for (i in 1:samples) {
      nnd<-sample_sim(xylocs, f)
      nndr<-sample_real(sx, f)
      for (nn in 1:nns) {
         nndists[i,nn]<-median(nnd[nn],na.rm = TRUE)
         nndists2[i,nn]<-median(nndr[nn],na.rm = TRUE)
      }
  }
  mannw[f+1,1]<-f
  medians[f+1,1]<-f
  for (nn in 1:nns) {
   tst<-wilcox.test(nndists[,nn],nndists2[,nn])
   mannw[f+1,nn+1]<-tst$p.value*100
   medians[f+1,nn+1]<-round(median(nndists[,nn],na.rm=TRUE),digits=0)
   medians[f+1,nn+nns+1]<-round(median(nndists2[,nn],na.rm=TRUE),digits=0)
  }
}
```

Results

The p values from the Mann Whitney tests are displayed and stored. Also displayed and stored are the median NNDs from the sampled NNDs.

```
mannw

   failed         nn1          nn2          nn3          nn4          nn5
1       0 0.8550817378 4.301887e-04 3.327718e-01 5.271525e-04 1.524764e-04
2       1 0.0001460219 6.808253e-01 4.245654e-01 4.289290e-01 3.450462e-02
3       2 0.0062868735 8.170179e-01 6.263966e-01 1.218406e-02 3.328498e-01
4       3 2.6286007197 6.578123e-04 4.478720e-03 1.423054e-01 5.234151e+00
5       4 0.0038746137 1.586017e-07 3.873147e-06 4.421296e-03 1.875722e-02
6       5 0.1812262930 2.699596e-01 3.873024e-03 9.561148e-02 8.710233e-01
7       6 0.0633766996 6.211738e-04 6.938995e-02 3.772133e-03 1.600932e-02
8       7 0.0060565012 5.895826e-03 3.837005e-05 3.836370e-04 1.049110e-02
9       8 0.0656191239 4.085881e-03 8.631455e-01 3.366952e+00 8.951547e-02
10      9 0.0004313537 3.529383e-03 4.468507e+00 2.159069e-01 6.150468e-01
11     10 0.2839842409 9.489575e-05 1.057052e-04 1.868539e-04 7.212725e-06
12     11 0.0073488962 1.314532e-02 1.642416e-05 1.101419e-01 5.550694e-01
13     12 0.0047906584 2.028806e-03 1.509034e+00 5.609579e-04 3.970301e-01
14     13 0.1321412952 1.335493e-04 1.543559e-02 9.610637e-03 4.786917e-03
```

```
15     14 0.8634951410 1.054445e-03 9.489241e-03 1.702354e-02 2.587745e+00
16     15 0.2701180063 1.501541e-01 5.605668e-02 1.377495e-03 4.512186e-02
17     16 0.0085703609 8.955380e-02 1.013835e+00 7.394597e-05 4.534662e+00
18     17 0.0064631232 4.447800e-07 1.533580e-01 6.945863e-05 1.960357e-06
19     18 0.0005535119 3.200854e-01 1.116762e+00 1.175569e-02 7.176363e-04
20     19 0.1089878663 2.894785e-04 1.905821e+00 2.593511e-03 1.207976e+00
21     20 0.0915805439 3.487341e-03 1.010234e-01 8.408887e-04 5.118728e-02

medians

   failed  med1  med2  med3  med4  med5 med1r med2r med3r med4r med5r
1       0  8715 10400 11439 19136 10996  5519  5519  6017  6017  4602
2       1 12297 10848 11617 10472 13004  4602  6103  5519  6190  6017
3       2 13199 13365 13693 12934 11503  5568  6017  6393  6190  6292
4       3 13112 13754 10873 10035 10321  6848  5798  5519  5855  6017
5       4 13045 16970 12855 15721 11497  6017  5519  5519  6190  6017
6       5 11524 11183 10167 12808 12314  5941  7908  6017  7136  8543
7       6  9356 14708 14868 13605 14942  5519  7303  6292  6190  6393
8       7 15292 12623 11955 19571 14475  6017  4602  5519  6190  7939
9       8 12410 14614 15230 10265 13199  6393  6017 10988  6124  6292
10      9 16989 16176 12708 10922 13291  7908  7064  7939  5768  7939
11     10 12925 11606 14590 19925 16632  7908  4599  6017  7908  5741
12     11 15348 14769 13801 14206 13943  6103  6292  5519  7908  8499
13     12 19288 16807 12720 21508 12384  7939  6393  9060  7591  6017
14     13 12470 12524 16758 15100 14064  6393  5874  6848  7581  6103
15     14 12462 18117 13500 19716 13763 11077  6701  6557  7982  9839
16     15 14632 18843 17366 18901 16055 10988  6965  8499  6190 10293
17     16 18450 17139 12610 19253 15344  7878  8025  9676  6393 11077
18     17 18453 21909 16698 15522 20493  7878  6103  8499  6991  6190
19     18 17499 16539 13226 18742 14846  7012  7303  7982 10803  6103
20     19 15808 15009 17956 15251 16762  7716  6017 11534  9266 12603
21     20 19086 19079 15743 21379 20859 11276  7908 10823  8543 11276

write.table(mannw,file="mannwhit_alltagsfailuresRepF.txt",sep="\t",row.names=FALSE)
write.table(medians,file="medians_alltagsfailuresRefF.txt",sep="\t",row.names=FALSE)
```

ANNEX 2.6 Undetected tag failures with all tags excluding birds that were killed

07/02/2017

Background

See Annex2.5. This version excludes tags fitted to birds that are known to have been killed.

R Libraries

```r
library(knitr)
library(foreign)
library(plyr)
library(FNN)
library(qdapRegex)
```

Functions

See Annex2.5.

```r
sample_sim <- function(y,fails) {
    qsample <- tagmeta[sample(1:nrow(tagmeta),qsus-fails,replace=FALSE,tagmeta$dayprop),]
    lst<-qsample$TagID
    xylocsample<-y[y$ID %in% lst,]
    lstlen<-length(lst)
    s2<-data.frame(X=numeric(lstlen), Y=numeric(lstlen))
    for (a in 1:lstlen) {
        s <- xylocsample[ which(xylocsample$ID==lst[a]), ]
        samp_idx <- sample(seq_len(nrow(s)), 1, prob=s$samp_p)
        s2[a,] <- s[samp_idx,c("X","Y") ]
    }
    nny<-knn.dist(s2,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
    return(nny)
}

sample_real <- function(x, fails) {
  qsx<-x[sample(1:nrow(x),qsus-fails,replace=FALSE),]
  nnx<-nn.dist(qsx,k=nns,algorithm=c("kd_tree","cover_tree","CR","brute"))
  nnx[nnx==0]<-NA
  return(nnx)
}
```

Preparing sampling and setting simulation conditions

See Annex2.5.

```r
samples<-86
nns<-5
failed<-20
rows<-samples
rows2<-failed+1
set.seed(12345)
nndists <- data.frame(nn1=numeric(rows), nn2=numeric(rows), nn3=numeric(rows), nn4=numeric(rows), nn5=numeric(rows))
nndists2 <- data.frame(med1=numeric(rows), med2=numeric(rows), med3=numeric(rows), med4=numeric(rows), med5=numeric(rows))
```

```
mannw<-data.frame(failed=numeric(failed+1), nn1=numeric(failed+1),
nn2=numeric(failed+1), nn3=numeric(failed+1), nn4=numeric(failed+1),
nn5=numeric(failed+1))
medians <- data.frame(failed=numeric(rows2), med1=numeric(rows2),
med2=numeric(rows2), med3=numeric(rows2), med4=numeric(rows2),
med5=numeric(rows2),  med1r=numeric(rows2), med2r=numeric(rows2),
med3r=numeric(rows2), med4r=numeric(rows2), med5r=numeric(rows2))
row<-1
```

Reading in data

See Annex2.5. This analysis excludes tags from five birds known to have been killed (57139, 89254, 89272, 286611 and 841261).

```
xylocs<-read.csv("xydata_nodups_Feb17.csv", as.is = FALSE)
tagmeta<-read.csv("tagmetadatajan17nokilled.csv", as.is = FALSE)
attach(tagmeta)
qsus<-sum(tagmeta$snmlf)
IDlist<-data.frame(matrix(ncol = qsus, nrow = rows))
sx<-tagmeta[which(tagmeta$snmlf>0),c("FinX","FinY")]
```

Sampling effort

See Annex2.5.

```
daysum<-sum(tagmeta$Days)
tagmeta$dayprop<-tagmeta$Days/daysum
```

Random sampling

See Annex2.5.

```
for (f in 0:failed) {
  for (i in 1:samples) {
      nnd<-sample_sim(xylocs, f)
      nndr<-sample_real(sx, f)
      for (nn in 1:nns) {
         nndists[i,nn]<-median(nnd[nn],na.rm = TRUE)
         nndists2[i,nn]<-median(nndr[nn],na.rm = TRUE)
      }
  }
  mannw[f+1,1]<-f
  medians[f+1,1]<-f
  for (nn in 1:nns) {
   tst<-wilcox.test(nndists[,nn],nndists2[,nn])
   mannw[f+1,nn+1]<-tst$p.value*100
   medians[f+1,nn+1]<-round(median(nndists[,nn],na.rm=TRUE),digits=0)
   medians[f+1,nn+nns+1]<-round(median(nndists2[,nn],na.rm=TRUE),digits=0)
  }
}
```

Results

The p values from the Mann Whitney tests are displayed and stored. Also displayed and stored are the median NNDs from the sampled NNDs.

```
mannw
```

```
   failed          nn1          nn2          nn3          nn4          nn5
1       0 2.305127e-04 2.730822e-05 2.465398e-05 2.494974e-08 5.911633e-02
2       1 1.318377e-03 3.871476e-03 5.173406e-03 7.805005e-04 1.716047e-03
3       2 8.750801e-05 1.395833e-02 1.176855e-04 2.016559e+00 1.741388e-03
4       3 7.705833e-06 7.149298e-05 4.248855e-03 3.019227e-04 7.844806e-05
5       4 2.202374e-04 1.234919e-07 3.616376e-06 2.341532e-04 6.472408e-04
6       5 2.331276e-06 1.346411e-02 1.968169e-03 6.181141e-07 5.897366e-03
7       6 2.360501e-09 1.946095e-02 1.842466e-07 7.444229e-06 3.366851e-06
8       7 8.530205e-06 3.777024e-05 2.169330e-04 6.202500e-05 3.456097e-04
9       8 8.842804e-06 1.389177e-07 1.888133e-06 9.776817e-05 2.845812e-07
10      9 3.070600e-04 3.627482e-03 8.520873e-04 1.581312e-06 1.825609e-08
11     10 6.328803e-08 1.283218e-03 6.613843e-05 1.616044e-05 4.252828e-04
12     11 5.130483e-05 3.392157e-03 5.218762e-04 2.378845e-04 1.234468e-02
13     12 2.044694e-02 6.303557e-04 1.487606e-02 1.783266e-05 2.170469e+00
14     13 1.462389e-05 3.531971e-03 4.100968e-05 1.398625e-02 1.706439e-04
15     14 3.217733e-02 4.063730e-02 2.071461e-07 4.070112e-04 1.132126e-02
16     15 3.836979e-07 2.647667e-01 9.983015e-03 5.668491e-02 1.846881e-05
17     16 6.719567e-03 3.437799e-05 1.723298e-02 3.269888e-05 4.447500e-05
18     17 8.479216e-02 2.085438e-03 1.673610e-03 3.430435e-01 3.044748e-06
19     18 1.083898e-05 6.582407e-04 2.321014e-01 4.546984e-01 1.148444e-03
20     19 5.462660e-03 1.303484e-06 3.634341e-07 9.029920e-04 9.796960e-06
21     20 3.609772e-05 2.114978e-03 1.150353e-01 9.357712e-05 6.721097e-03

medians

   failed  med1  med2  med3  med4  med5 med1r med2r med3r med4r med5r
1       0 13369 12380 15245 13086 11839  5519  5519  5519  4602  6017
2       1 12858 14093 13139 11975 12561  5519  4602  6017  5060  5519
3       2 14434 14271 13237 14100 13892  5768  6205  5519  9159  5519
4       3 14736 14211 14536 14542 16843  5568  5741  7908  5768  6393
5       4 15575 14424 14898 11945 15272  5519  4602  5941  5060  6017
6       5 16078 11632 14746 14445 15444  5519  5519  5941  5519  7209
7       6 14818 17563 16585 12543 16663  4599  7982  4602  4252  5519
8       7 17292 14127 15687 12585 16492  5060  5519  5519  6017  6017
9       8 15009 13506 16021 17036 18405  5732  4599  5519  6848  6393
10      9 16854 15451 16877 16475 18400  7548  6393  7951  4602  5060
11     10 25852 20316 18059 17485 15718 10640  7939  6205  5865  5865
12     11 16263 14928 15839 14949 14384  6205  5798  6037  7136  6205
13     12 16325 17357 14734 18121 12406  7939  7908  7008 10293  6991
14     13 16014 16390 19545 22662 16554  5674  9159  6536 10988  5798
15     14 15254 14056 23920 17857 17923  9159  7279  7303  7300 10988
16     15 20819 21008 19499 14018 22865  6393 11132  7982  9116  7878
17     16 24317 23700 16973 17427 21487 10803  6225  7982  6017  9116
18     17 16533 18879 18110 19787 22706 10293  7939  8705 10988 10389
19     18 21806 18889 16048 19784 25105  8709 10213 10988 12195 11276
20     19 23752 24018 25896 24065 23040 11510  8459  8025 11573  7939
21     20 20844 21471 24021 28629 18952  7982 11276 11573 10823  8025
```

```
write.table(mannw,file=" mannwhit_alltagsfailuresNOKilled.txt",sep="\t",row.names=FALSE)
write.table(medians,file=" medians_alltagsfailuresNoKilled.txt",sep="\t",row.names=FALSE)
```

ANNEX 2.7 Undetected tag failures excluding 105GPS tags, including all birds

07/02/2017

Background

See Annex 2.5.

R Libraries

```
library(knitr)
library(foreign)
library(plyr)
library(FNN)
library(qdapRegex)
```

Functions

See Annex 2.5.

```
sample_sim <- function(y,fails) {
   qsample <- tagmeta[sample(1:nrow(tagmeta),qsus-
fails,replace=FALSE,tagmeta$dayprop),]
   lst<-qsample$TagID
   xylocsample<-y[y$ID %in% lst,]
   lstlen<-length(lst)
   s2<-data.frame(X=numeric(lstlen), Y=numeric(lstlen))
   for (a in 1:lstlen) {
      s <- xylocsample[ which(xylocsample$ID==lst[a]), ]
      samp_idx <- sample(seq_len(nrow(s)), 1, prob=s$samp_p)
      s2[a,] <- s[samp_idx,c("X","Y") ]
   }
   nny<-knn.dist(s2,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
   return(nny)
}

sample_real <- function(x, fails) {
  qsx<-x[sample(1:nrow(x),qsus-fails,replace=FALSE),]
  nnx<-nn.dist(qsx,k=nns,algorithm=c("kd_tree","cover_tree","CR","brute"))
  nnx[nnx==0]<-NA
  return(nnx)
}
```

Preparing sampling and setting simulation conditions

See Annex 2.5.

```
samples<-86
nns<-5
failed<-20
rows<-samples
rows2<-failed+1
set.seed(12345)
nndists <- data.frame(nn1=numeric(rows), nn2=numeric(rows), nn3=numeric(rows),
nn4=numeric(rows), nn5=numeric(rows))
nndists2 <- data.frame(med1=numeric(rows), med2=numeric(rows),
med3=numeric(rows), med4=numeric(rows), med5=numeric(rows))
```

```
mannw<-data.frame(failed=numeric(failed+1), nn1=numeric(failed+1),
nn2=numeric(failed+1), nn3=numeric(failed+1), nn4=numeric(failed+1),
nn5=numeric(failed+1))
medians <- data.frame(failed=numeric(rows2), med1=numeric(rows2),
med2=numeric(rows2), med3=numeric(rows2), med4=numeric(rows2),
med5=numeric(rows2),  med1r=numeric(rows2), med2r=numeric(rows2),
med3r=numeric(rows2), med4r=numeric(rows2), med5r=numeric(rows2))
row<-1
```

Reading in data

See Annex 2.5. In this case the filtering excludes the 105GPS tags.

```
xylocs<-read.csv("xydata_nodups_Feb17.csv", as.is = FALSE)
tagmeta<-read.csv("tagmetadatajan17.csv", as.is = FALSE)
attach(tagmeta)
tagmeta<-tagmeta[which(tagmeta$Tagtype!="105GPS"),]
qsus<-sum(tagmeta$snmlf)
IDlist<-data.frame(matrix(ncol = qsus, nrow = rows))
sx<-tagmeta[which(tagmeta$snmlf>0),c("FinX","FinY")]
```

Sampling effort

See Annex 2.5.

```
daysum<-sum(tagmeta$Days)
tagmeta$dayprop<-tagmeta$Days/daysum
```

Random sampling

See Annex 2.5.

```
for (f in 0:failed) {
  for (i in 1:samples) {
    nnd<-sample_sim(xylocs, f)
    nndr<-sample_real(sx, f)
    for (nn in 1:nns) {
      nndists[i,nn]<-median(nnd[nn],na.rm = TRUE)
      nndists2[i,nn]<-median(nndr[nn],na.rm = TRUE)
    }
  }
  mannw[f+1,1]<-f
  medians[f+1,1]<-f
  for (nn in 1:nns) {
   tst<-wilcox.test(nndists[,nn],nndists2[,nn])
   mannw[f+1,nn+1]<-tst$p.value*100
   medians[f+1,nn+1]<-round(median(nndists[,nn],na.rm=TRUE),digits=0)
   medians[f+1,nn+nns+1]<-round(median(nndists2[,nn],na.rm=TRUE),digits=0)
  }
}
```

Results

The p values from the Mann Whitney tests are displayed and stored. Also displayed and stored are the median NNDs from the sampled NNDs.

```
mannw

   failed          nn1          nn2          nn3          nn4          nn5
1       0 2.247637e-02 1.279205e-02 2.894320e-01 1.407450e-01 4.934753e-02
2       1 2.450488e-03 1.087987e-02 1.541207e-02 2.585310e+00 2.079154e-03
3       2 7.258848e-04 5.760869e-06 1.857587e+00 5.347825e-02 4.206515e-01
4       3 5.348109e-02 4.565634e+00 1.057175e-04 1.264978e-03 1.352850e-04
5       4 1.538659e-03 6.389128e-04 3.122177e-03 5.596754e-01 4.075890e-03
6       5 6.504005e-06 4.194867e-07 5.143232e-01 6.211269e-04 3.434036e-05
7       6 1.821148e-06 2.074751e-04 8.829714e-06 1.841284e-05 2.378877e-04
8       7 9.768615e-02 3.253775e-02 9.678952e-04 3.206877e-04 2.399697e-07
9       8 6.202953e-02 4.537300e-06 1.040913e+00 2.643299e-04 4.965262e-05
10      9 2.590482e-07 7.347024e-03 3.815159e-06 1.640626e-02 1.284185e-03
11     10 4.915852e-03 1.444455e-07 1.642828e-05 8.777931e-05 4.789477e-03
12     11 8.377487e-05 9.561745e-02 4.614339e-02 1.435578e-03 4.001938e+00
13     12 3.214629e-03 1.159852e-02 2.467863e-06 1.036595e-02 1.702473e-01
14     13 1.178525e-04 6.418583e-02 4.068889e-04 5.046057e-03 1.532589e-04
15     14 1.180946e-03 1.217466e-04 1.947100e-03 1.364743e-01 1.063282e-08
16     15 2.605414e-05 1.754013e+00 1.198883e-04 1.843470e-03 1.149842e-01
17     16 1.456255e-03 2.139329e-04 2.019746e-02 2.104185e-06 4.540437e-06
18     17 1.561989e-03 2.744909e-07 2.490132e-03 6.513962e-05 3.779542e-04
19     18 6.301125e-03 4.604539e-03 6.633210e-03 3.660309e-02 3.034892e-02
20     19 1.398234e+00 1.253612e-01 1.181257e-04 8.531818e-04 3.882054e-02
21     20 3.550702e-05 2.726670e-04 1.013234e-05 3.821478e-06 2.821215e+00

medians

   failed  med1  med2  med3  med4  med5 med1r med2r med3r med4r med5r
1       0 12518 12231  9992 11053 11975  7878  6240  5519  5519  6190
2       1 11856  9356  9529 10676 12030  4602  5060  4602  7034  5060
3       2 12924 12528 10180 11168  9370  4602  5519  7939  5060  6190
4       3 10612 10563 12846 12563 13235  5519  7878  4602  5519  4602
5       4 13950 13695  9179  9823  9936  6747  5060  5519  5519  5519
6       5 16493 16900 13344 13531 17410  5798  5519  7908  5519  5060
7       6 19151 12878 12471 16485 20353  4602  5519  5519  6190  7034
8       7 13232 12031 15000 15447 19903  7279  5519  5865  5674  4602
9       8 12536 17382 14350 15193 18355  7303  5798  8499  5519  6028
10      9 15823 14488 14911 13434 13961  5060  7878  5519  7548  6124
11     10 13003 16235 14678 13544 17743  7591  6190  4599  5865  7982
12     11 19499 14133 14763 11468 11622  7550  7878  7939  4602 10803
13     12 13260 16655 20572 15025 16150  6190  7878  6028  7878 10024
14     13 18370 16203 16770 15744 12495  6190  9256  5692  6028  5519
15     14 20500 19613 20292 16251 20259  7939  5798  7939  7908  4602
16     15 17525 13458 21210 19701 15771  5568  7300  7908 11223 10988
17     16 14012 15022 12901 19420 18041  7878  5519  6991  5732  5961
18     17 20578 21695 17506 18645 17815  7908  5961  6949  6704  7878
19     18 19493 16698 17487 18177 20509 11276  7878  7908  7878 11276
20     19 16209 16471 20603 18141 17548 12813 10024  7878  7621 10552
21     20 24308 24001 27766 29296 23212 10045 11582 11132  7939 16007

write.table(mannw,file="mannwhit_7095failuresRepF.txt",sep="\t",row.names=FALSE)
write.table(medians,file="medians_7095failuresRepF.txt",sep="\t",row.names=FALSE)
```

ANNEX 2.8. Undetected tag failures excluding 105GPS tags, excluding all birds

07/02/2017

Background

See Annex 2.7. This version excludes tags fitted to birds that are known to have been killed.

R Libraries

```
library(knitr)
library(foreign)
library(plyr)
library(FNN)
library(qdapRegex)
```

Functions

See Annex 2.7.

```
sample_sim <- function(y,fails) {
   qsample <- tagmeta[sample(1:nrow(tagmeta),qsus-
fails,replace=FALSE,tagmeta$dayprop),]
   lst<-qsample$TagID
   xylocsample<-y[y$ID %in% lst,]
   lstlen<-length(lst)
   s2<-data.frame(X=numeric(lstlen), Y=numeric(lstlen))
   for (a in 1:lstlen) {
      s <- xylocsample[ which(xylocsample$ID==lst[a]), ]
      samp_idx <- sample(seq_len(nrow(s)), 1, prob=s$samp_p)
      s2[a,] <- s[samp_idx,c("X","Y") ]
   }
   nny<-knn.dist(s2,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
   return(nny)
}

sample_real <- function(x, fails) {
 qsx<-x[sample(1:nrow(x),qsus-fails,replace=FALSE),]
 nnx<-knn.dist(qsx,k=nns,algorithm=c("kd_tree","cover_tree","CR","brute"))
 nnx[nnx==0]<-NA
 return(nnx)
}
```

Preparing sampling and setting simulation conditions

See Annex 2.7.

```
samples<-86
nns<-5
failed<-20
rows<-samples
rows2<-failed+1
set.seed(12345)
nndists <- data.frame(nn1=numeric(rows), nn2=numeric(rows), nn3=numeric(rows),
nn4=numeric(rows), nn5=numeric(rows))
nndists2 <- data.frame(med1=numeric(rows), med2=numeric(rows),
med3=numeric(rows), med4=numeric(rows), med5=numeric(rows))
```

```
mannw<-data.frame(failed=numeric(failed+1), nn1=numeric(failed+1),
nn2=numeric(failed+1), nn3=numeric(failed+1), nn4=numeric(failed+1),
nn5=numeric(failed+1))
medians <- data.frame(failed=numeric(rows2), med1=numeric(rows2),
med2=numeric(rows2), med3=numeric(rows2), med4=numeric(rows2),
med5=numeric(rows2),  med1r=numeric(rows2), med2r=numeric(rows2),
med3r=numeric(rows2), med4r=numeric(rows2), med5r=numeric(rows2))
row<-1
```

Reading in data

See Annex 2.7. This analysis excludes tags from five birds known to have been killed (57139, 89254, 89272, 286611 and 841261).

```
xylocs<-read.csv("xydata_nodups_Feb17.csv", as.is = FALSE)
tagmeta<-read.csv("tagmetadatajan17nokilled.csv", as.is = FALSE)
attach(tagmeta)
tagmeta<-tagmeta[which(tagmeta$Tagtype!="105GPS"),]
qsus<-sum(tagmeta$snmlf)
IDlist<-data.frame(matrix(ncol = qsus, nrow = rows))
sx<-tagmeta[which(tagmeta$snmlf>0),c("FinX","FinY")]
```

Sampling effort

See Annex 2.7.

```
daysum<-sum(tagmeta$Days)
tagmeta$dayprop<-tagmeta$Days/daysum
```

Random sampling

See Annex 2.7.

```
for (f in 0:failed) {
  for (i in 1:samples) {
    nnd<-sample_sim(xylocs, f)
    nndr<-sample_real(sx, f)
    for (nn in 1:nns) {
      nndists[i,nn]<-median(nnd[nn],na.rm = TRUE)
      nndists2[i,nn]<-median(nndr[nn],na.rm = TRUE)
    }
  }
  mannw[f+1,1]<-f
  medians[f+1,1]<-f
  for (nn in 1:nns) {
   tst<-wilcox.test(nndists[,nn],nndists2[,nn])
   mannw[f+1,nn+1]<-tst$p.value*100
   medians[f+1,nn+1]<-round(median(nndists[,nn],na.rm=TRUE),digits=0)
   medians[f+1,nn+nns+1]<-round(median(nndists2[,nn],na.rm=TRUE),digits=0)
  }
}
```

Results

The p values from the Mann Whitney tests are displayed and stored. Also displayed and stored are the median NNDs from the sampled NNDs.

```
mannw

   failed          nn1          nn2          nn3          nn4          nn5
1       0 2.168156e-06 2.547578e-03 1.410405e-03 1.118569e-06 2.200710e-05
2       1 6.612256e-03 9.993076e-08 1.262908e-03 5.849076e-06 6.361425e-04
3       2 5.713017e-09 1.273327e-06 4.056998e-02 1.140664e-04 2.167228e-05
4       3 1.779506e-04 1.184218e-06 5.025833e-07 2.722001e-02 1.077415e-10
5       4 1.079415e-05 3.870941e-06 1.118259e-06 1.080047e-05 2.080321e-03
6       5 3.109763e-04 4.146052e-05 4.191961e-03 3.545110e-07 3.250571e-02
7       6 4.494818e-09 1.017347e-08 3.574756e-03 2.755597e-02 3.435263e-03
8       7 1.422637e-01 5.763140e-06 2.418399e-02 2.554407e-05 3.944649e-06
9       8 5.747726e-07 9.726482e-03 6.296037e-03 8.828637e-06 5.688467e-04
10      9 2.454211e-04 1.874124e-05 1.387174e-07 5.139343e-07 3.666651e-04
11     10 2.693776e-02 3.749522e-06 1.977113e-08 3.255340e-06 1.168229e-06
12     11 1.069074e-03 2.422932e-06 1.614178e-05 1.581839e-03 6.407859e-05
13     12 1.254399e-04 1.510959e-05 1.255862e-06 3.376974e-06 1.346393e-05
14     13 1.556275e-04 7.503208e-02 2.992014e-06 1.089822e-02 1.497367e-03
15     14 1.433359e-02 1.357330e-03 9.014011e-03 4.233755e-05 2.951779e-07
16     15 4.460066e-02 5.627420e-08 6.781747e-07 3.117380e-04 4.831914e-02
17     16 9.961445e-01 7.004785e-01 1.295220e-04 1.294032e-01 9.001493e-06
18     17 2.152167e-07 1.508371e-04 1.465568e-04 2.852980e-04 7.163806e-03
19     18 3.461595e-04 1.895532e-03 2.447800e+00 5.586530e-06 6.985751e-03
20     19 4.377511e-05 3.440940e-03 1.651483e-03 4.144870e-03 2.929746e-03
21     20 1.948464e-03 1.043767e-08 1.303459e-06 2.869506e-01 2.289422e-05

medians

   failed  med1  med2  med3  med4  med5 med1r med2r med3r med4r med5r
1       0 13718 14531 11245 14902 14221  4602  5519  4602  4602  5519
2       1 13483 18257 10841 12681 11944  5519  4602  4602  4602  5519
3       2 13097 15941 12549 13055 13111  4602  5519  5519  5519  4599
4       3 11225 14677 13164 13423 17763  5519  4600  5060  6698  4599
5       4 15013 13252 16685 14465 17584  5519  4602  5060  4602  7878
6       5 13499 15948 16926 16403 11544  4602  4602  7878  4602  7878
7       6 16109 17012 19683 12525 14963  4599  4602  7878  5519  5519
8       7 12744 19599 12413 15898 17750  5568  6747  5519  7878  6949
9       8 20325 16220 15858 19721 14300  5519  7878  7908  5519  7878
10      9 19778 16133 16079 16332 18061  7878  7303  4602  5519  7878
11     10 17890 23691 21802 19040 25061  9506  5732  5519  7591  7295
12     11 17925 26191 18034 19635 18456  9278  7279  7591 10988  6541
13     12 20726 17851 19254 21016 20248  7295  6584  7548  6916  7878
14     13 22312 15782 18584 17443 15252  7878  7908  6638  8025  6972
15     14 15011 17305 18102 18559 20248  8748  7982  7591  5519  5961
16     15 21513 19309 24270 18813 15808 12044  5519  5568  6680  9755
17     16 17974 17351 20252 20027 22524 12303 10803  7591 15098  7908
18     17 28930 23197 24489 20107 22812  7908  7548  8025  7982 10988
19     18 30627 33101 17666 31174 26304 12925 12263 11166 12813 11276
20     19 25115 22441 25735 23644 25237  8705 13955 11132 13574 10958
21     20 26724 35358 34194 26528 31679 15706 10805 10988 15096 12813

write.table(mannw,file="mannwhit_7095failuresNOKilledRepF.txt",sep="\t",row.names=FALSE)
write.table(medians,file="medians_7095failuresNoKilledRepF.txt",sep="\t",row.names=FALSE)
```

ANNEX 2.9. Satellite tag nearest neighbour sampling of all tags and all birds (tags with no stopped-no malfunction status)

11 February 2017

R Libraries

```
library(knitr)
library(foreign)
library(plyr)
library(FNN)
library(qdapRegex)
```

Background

This analysis uses a random sampling algorithm to determine the probability of observing a random sample of virtual last known fixes (lkf) from satellite tags fitted to golden eagles that appeared to be functioning correctly prior to their final location. The analysis begins by reading in a CSV file of location data. These data have been edited previously so that duplicate records have been removed, for example multiple locations from a roost site. Note that the same location, from one tag, will be retained on different days because the unique function examines the entire record and not just the location.

```
xylocs<-read.csv("xydata_nodups_Feb17.csv", as.is = FALSE)
```

Tag metadata

Metadata about the tags is loaded and used to create subsets for subsequent sampling. Data have a snmlf field in which 1 indicates a snmlf, other values are 0. The number of cases in each lkfs category are retained as cases0 and cases1.

```
tagmeta<-read.csv("tagmetadatajan17.csv", as.is = FALSE)
attach(tagmeta)
cases<-nrow(tagmeta)
cases1<-sum(tagmeta$snmlf)
sx<-na.omit(tagmeta[which(tagmeta$snmlf<1),c("FinX","FinY")])
cases0<-nrow(sx)
```

Sampling effort

The subsequent random sampling is designed to preferentially select tags in the relation to the number of days of records, i.e. stratified random sampling. The Days field is the number of days between and a tag's last and first records. daysum is sum of days over all tags. Therefore, Days/daysum is the proportion of all tracked days allocated to a particular tag.

```
daysum<-sum(tagmeta$Days)
tagmeta$dayprop<-tagmeta$Days/daysum
```

Preparing sampling

The number of iterations is set, in this example, to 5,000. The nndists data frame is created to store the results of the summary statistics of the NNDs. Another data frame, IDlist, is created to keep a record of which tags are sampled as a check that the stratified sampling is working correctly. Finally the random number seed is set to ensure reproducibility.

```
attach(xylocs)
```

```
## The following object is masked from tagmeta:
##     Days
```

```
iterations<-5000
rows<-iterations
nndists <- data.frame(min1=numeric(rows), q11=numeric(rows), med1=numeric(rows),
mean1=numeric(rows), q31=numeric(rows), max1=numeric(rows),min2=numeric(rows),
q12= numeric(rows), med2=numeric(rows), mean2=numeric(rows), q32=numeric(rows),
max2=numeric(rows), min3=numeric(rows),q13=numeric(rows), med3=numeric(rows),
mean3=numeric(rows), q33=numeric(rows), max3=numeric(rows),
min4=numeric(rows),q14=numeric(rows), med4=numeric(rows), mean4=numeric(rows),
q34=numeric(rows), max4=numeric(rows), min5=numeric(rows),q15=numeric(rows),
med5=numeric(rows), mean5=numeric(rows), q35=numeric(rows), max5=numeric(rows))
IDlist<-data.frame(matrix(ncol = cases0, nrow = rows))
set.seed(12345)
```

Random sampling

The sampling iterations are contained within a loop. The loop begins at 2 to leave space in row 1 of the nndist data frame for the 'real' data. A random sample of tag IDs, qsample, is drawn without replacement from the tag metadata. The number of tags sampled is set to the number of tags that had a slkf of 1. Tags are sampled in proportion to their relative number of days (dayprop). lst is a list of the sampled tag IDs. The list is sorted and stored in the IDlist data frame. The IDlist can be used at the end of the analysis to verify that tags were sampled appropriately. XY locations for those tags in the sample are extracted from the full xylocs data frame into a smaller xylocsample data.frame (xylocs$ID %in% lst). A single location is selected, at random, from each of the sampled tag's locations. This sampling is weighted to decrease the probability of sampling an early record. The samp_p field is calculated as dayno/(dayno + Days/4). The extracted record is stored in s2. Only the X & Y columns are retained in s2 which are a single location from each tag in sample list lst. NNDs are found for the locations in s2. In this analysis the first five nearest neighbours are identified. At this point each sampled tag has a list of its five NNDs. The five sets of NNDs are summarised (min, 1st quartile (q1), median, mean, 3rd quartile (q3) and max) and stored in nndo. nndo contains text which needs to be removed using the as_numeric2 function from the qdapRegex package. However, this function requires a space before a digit so the colon separator is first replaced by: followed by a space using the gsub function. Finally, the 30 nearest neighbour summary statistics (six for each of the five distances) is retained in the nndists data frame.

```
for (i in 2:iterations) {
   qsample<-tagmeta[sample(1:nrow(tagmeta),cases0,replace=FALSE,tagmeta$dayprop),]
   lst<-qsample$TagID
   IDlist[i-1,]<-lst[order(lst)]
   xylocsample<-xylocs[xylocs$ID%in% lst,]
   lstlen<-length(lst)
   s2<-data.frame(X=numeric(lstlen), Y=numeric(lstlen))
   for (a in 1:lstlen) {
      s <- xylocsample[ which(xylocsample$ID==lst[a]), ]
      samp_idx <- sample(seq_len(nrow(s)), 1, prob=s$samp_p)
      s2[a,] <- s[samp_idx,c("X","Y") ]
   }
   nnd<-knn.dist(s2,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
   nndo<-summary(nnd)
   nndo<-gsub("[:]",": ",nndo)
   tmp2<-as_numeric2(ex_number(nndo))
```

```
   for (j in 1:30) nndists[i,j]<- tmp2[j]
}
```

Real nearest neighbours

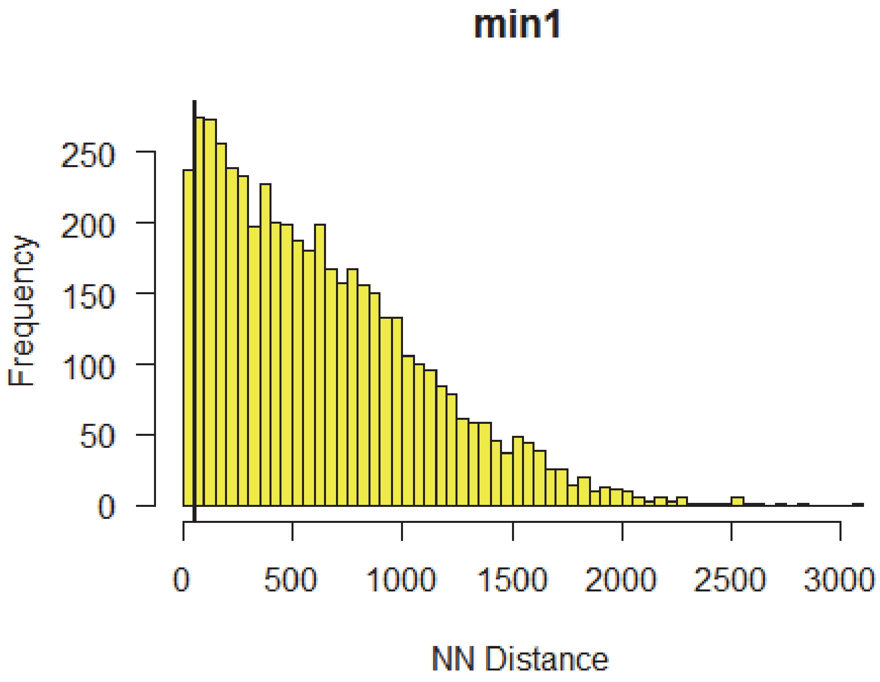
The final section finds the five NNDs for the virtual lkfs of tags that did not have a stopped-no malfunction status. The process is the same as in the sampling iterations except that the tag metadata file is the source of the final X & Y fixes (for tags that were still functioning these are the last fix in the data set). Summary statistics are stored in the first row of the nndists data frame. The final step is storing the results in text files.

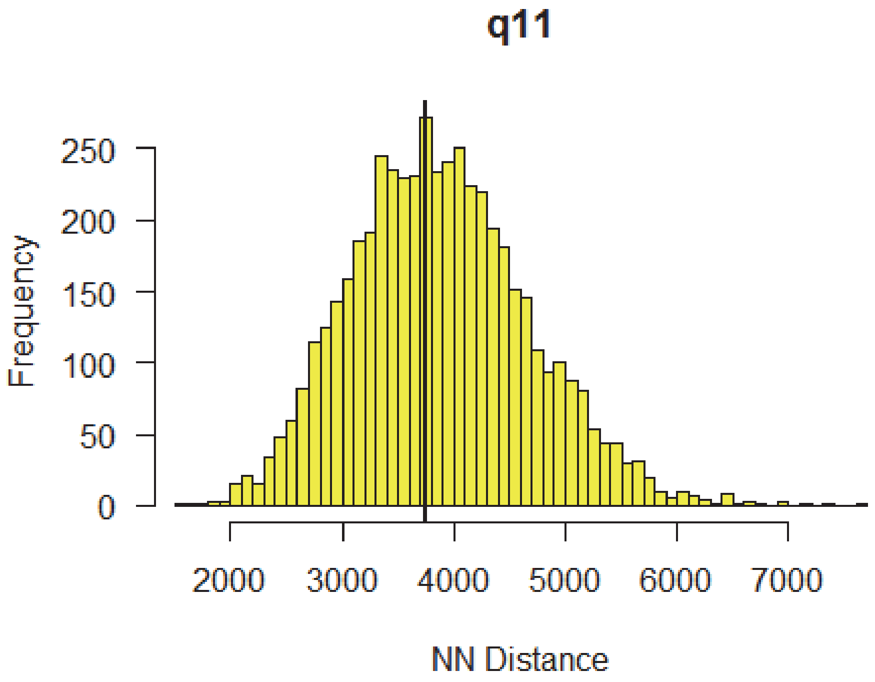
```
sx<-na.omit(tagmeta[which(tagmeta$snmlf<1),c("FinX","FinY")])
nndx<-knn.dist(sx,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
nndo<-summary(nndx)
nndo<-gsub("[:]",": ",nndo)
tmp2<-as_numeric2(ex_number(nndo))
for (j in 1:30) nndists[1,j]<- tmp2[j]
write.table(nndists,file="nndists5_Alltags_NonSuspect.txt",sep="\t")
IDcount<-stack(IDlist)
IDcount<-as.matrix(table(IDcount$values))
```

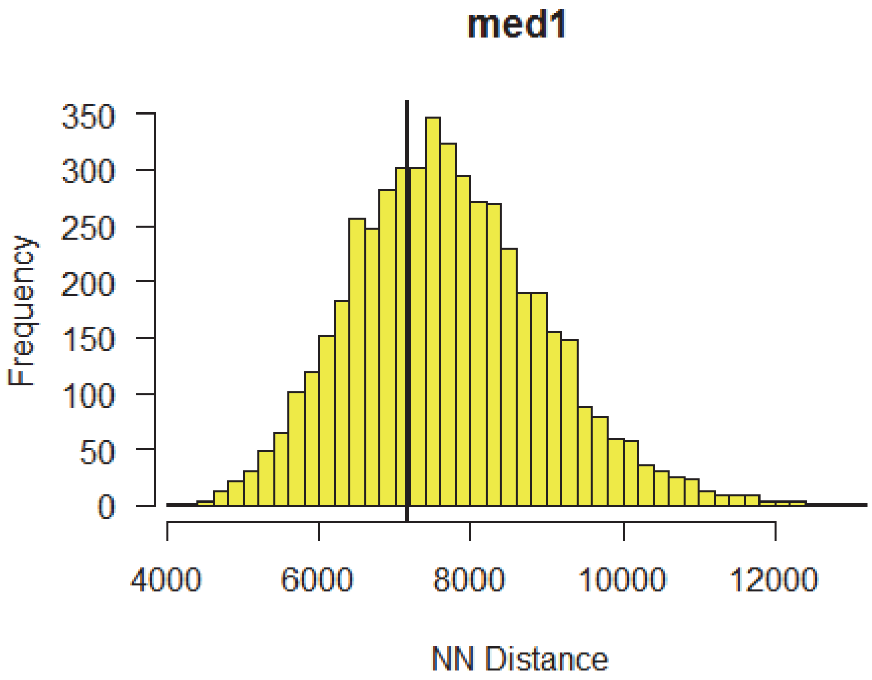
Plot the results

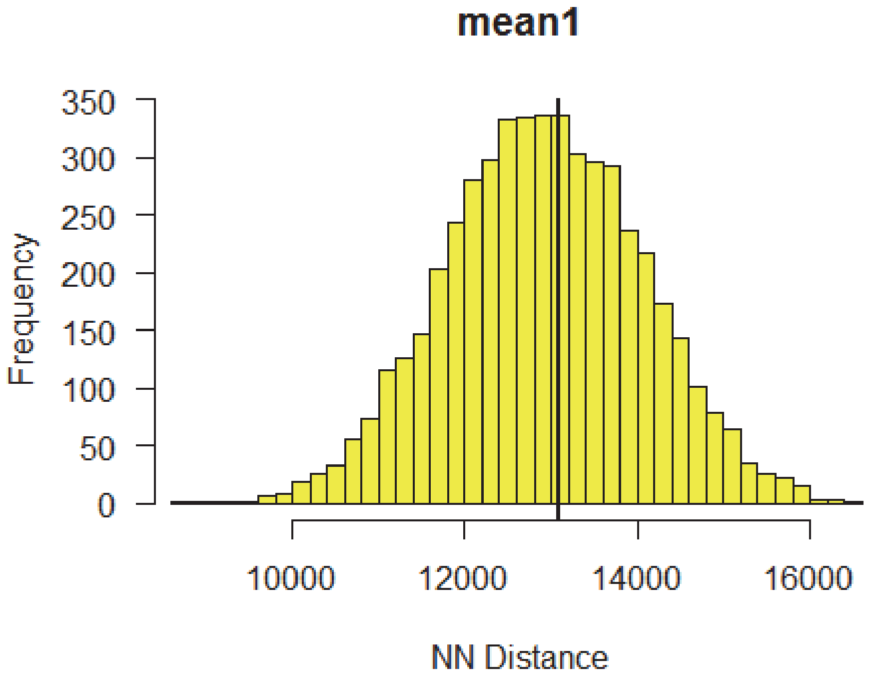
A frequency distribution is plotted for each nearest neighbour's sampling distribution and the real value is shown as a vertical black line.

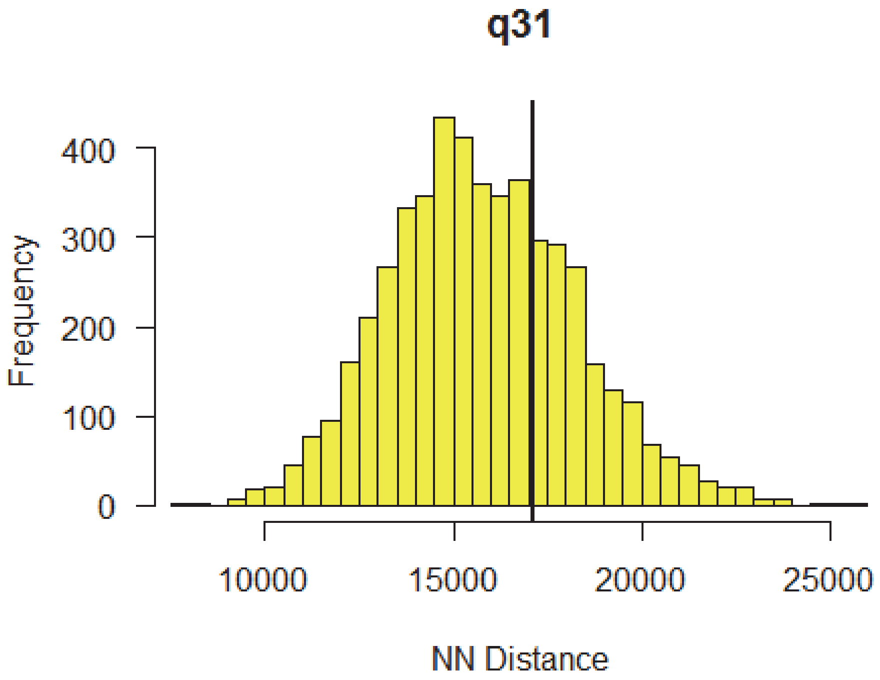
```
cnames<-names(nndists)
bins<-50
for (i in 1:length(cnames)) {
   title<-cnames[i]
   range<-round(range(nndists[,i]), digits=0)
   hist(nndists[,i], main=title, xlab="NN Distance", border="black", col="yellow",
xlim=c(range[1],range[2]), las=1, breaks=bins, prob = FALSE)
   abline(v=nndists[1,i],lty=1,lwd=2,col="black")
}
```

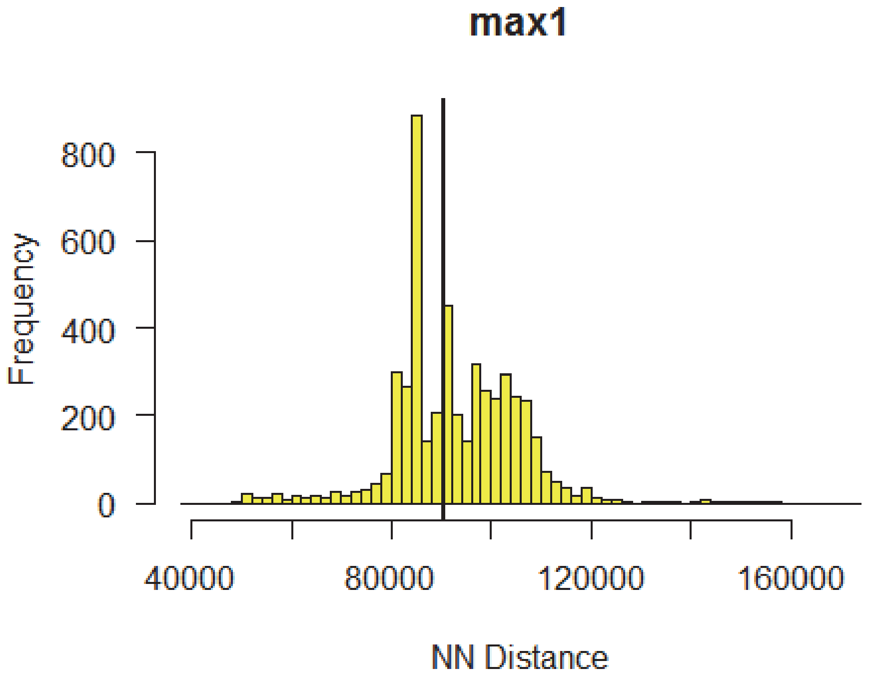

min1
Frequency
250
200
150
100
50
0
0
500
1000
1500
2000
2500
3000
NN Distance

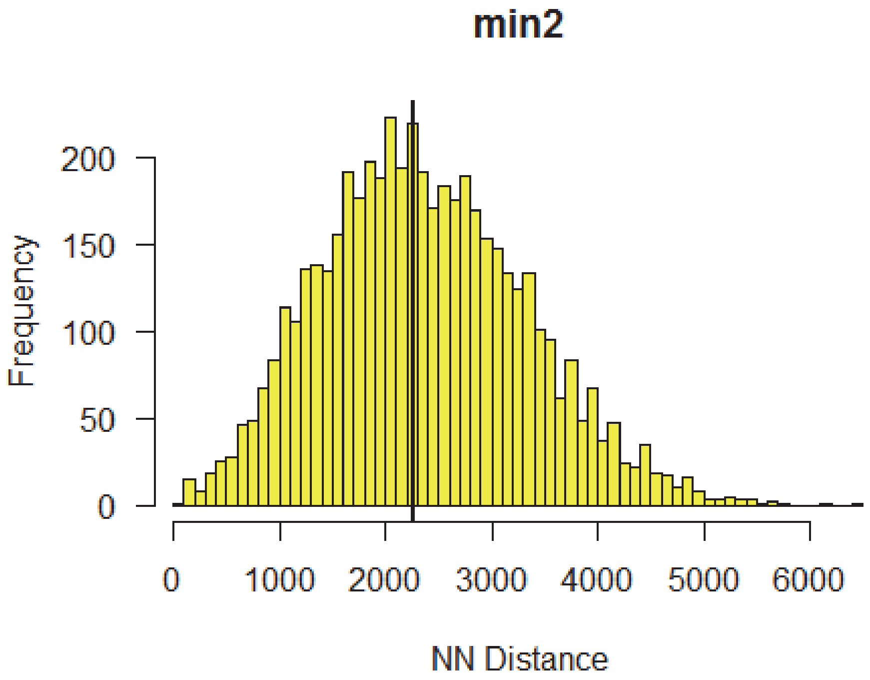

q11
Frequency
250
200
150
100
50
0
2000
3000
4000
5000
6000
7000
NN Distance

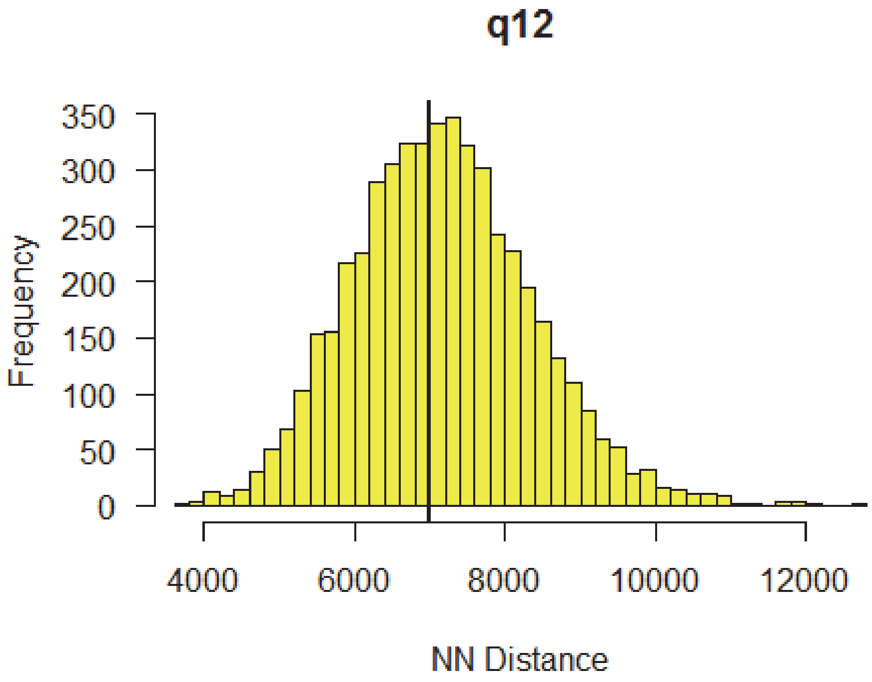

med1
Frequency
350
300
250
200
150
100
50
0
4000
6000
8000
10000
12000
NN Distance

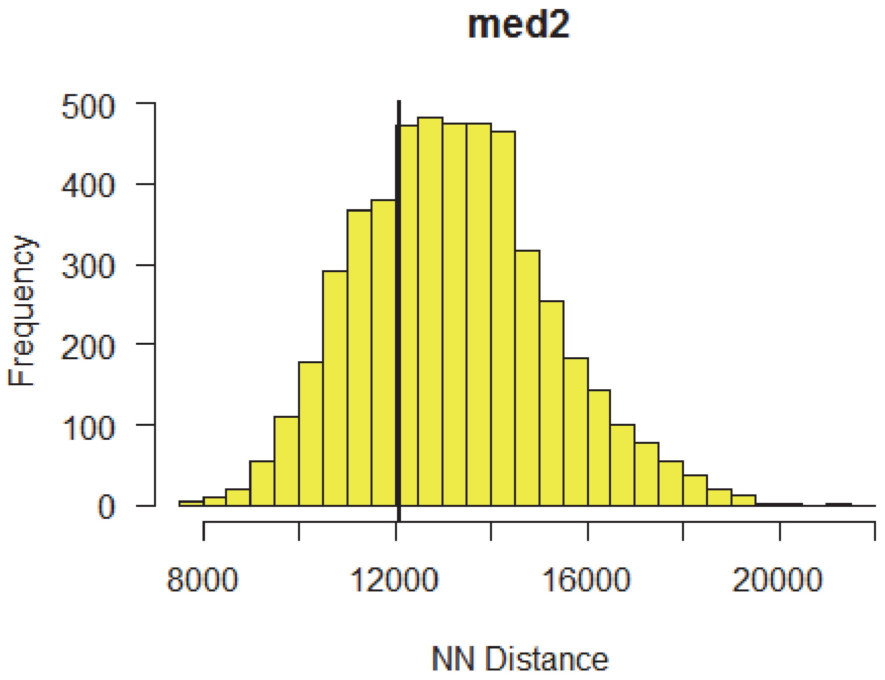

mean1
Frequency
350
300
250
200
150
100
50
0
10000
12000
14000
16000
NN Distance

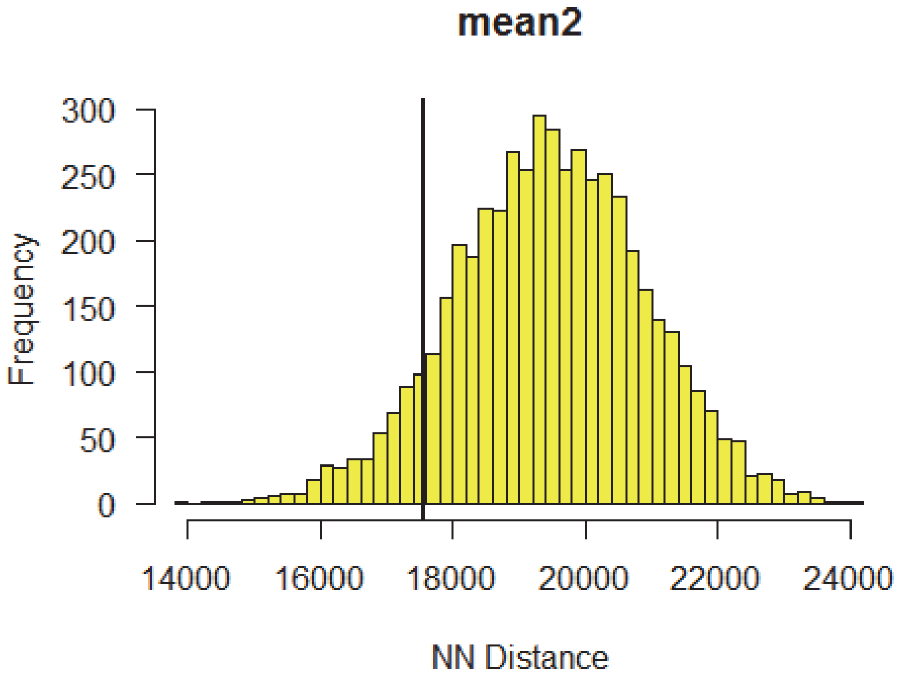

q31
Frequency
0
100
200
300
400
10000
15000
20000
25000
NN Distance

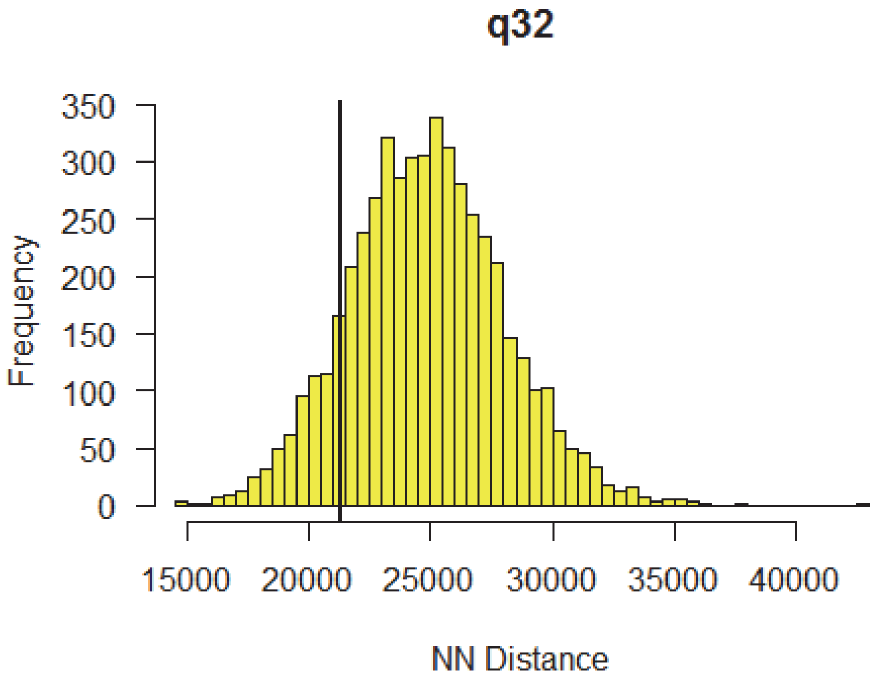

max1
Frequency
0
200
400
600
800
40000
80000
120000
160000
NN Distance

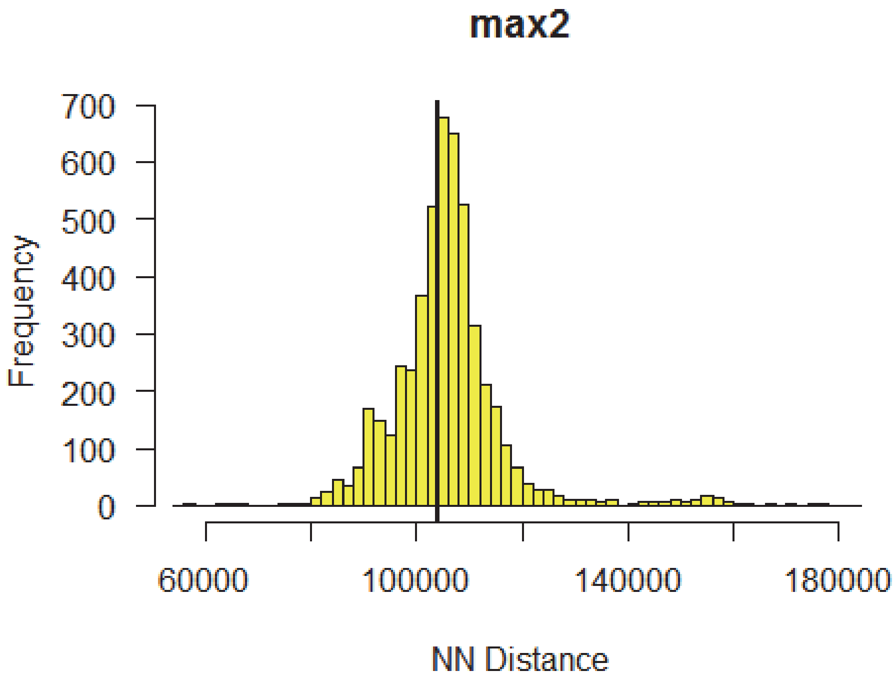

min2
Frequency
0
50
100
150
200
0
1000
2000
3000
4000
5000
6000
NN Distance

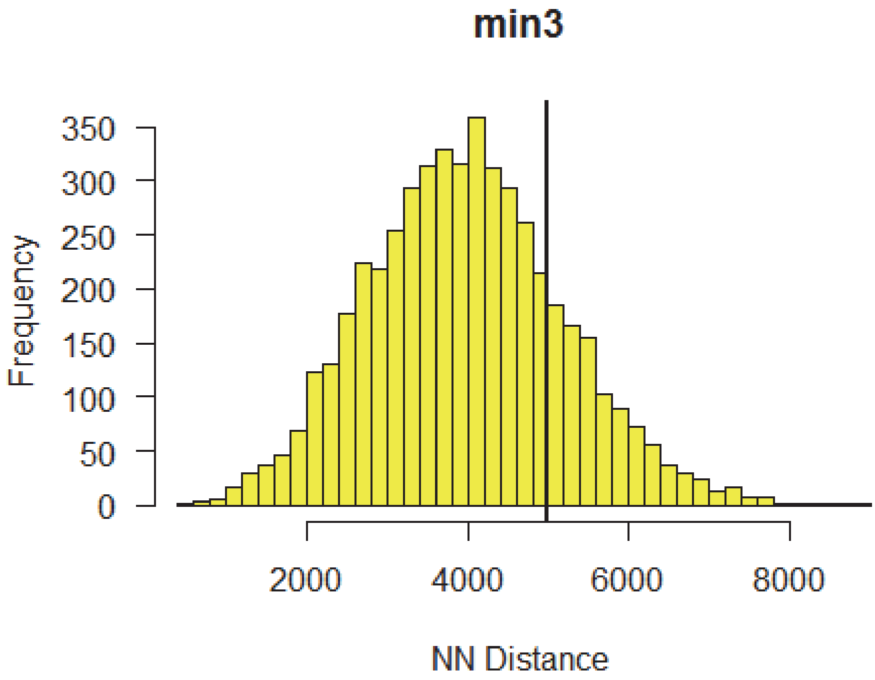

q12
Frequency
0
50
100
150
200
250
300
350
4000
6000
8000
10000
12000
NN Distance

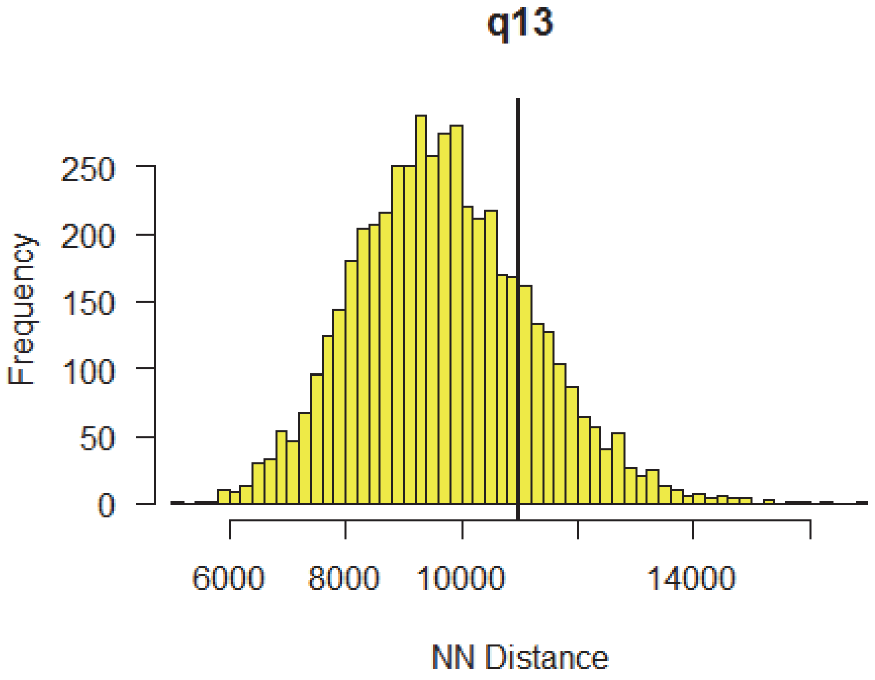

med2
500
400
300
200
100
0
Frequency
8000
12000
16000
20000
NN Distance

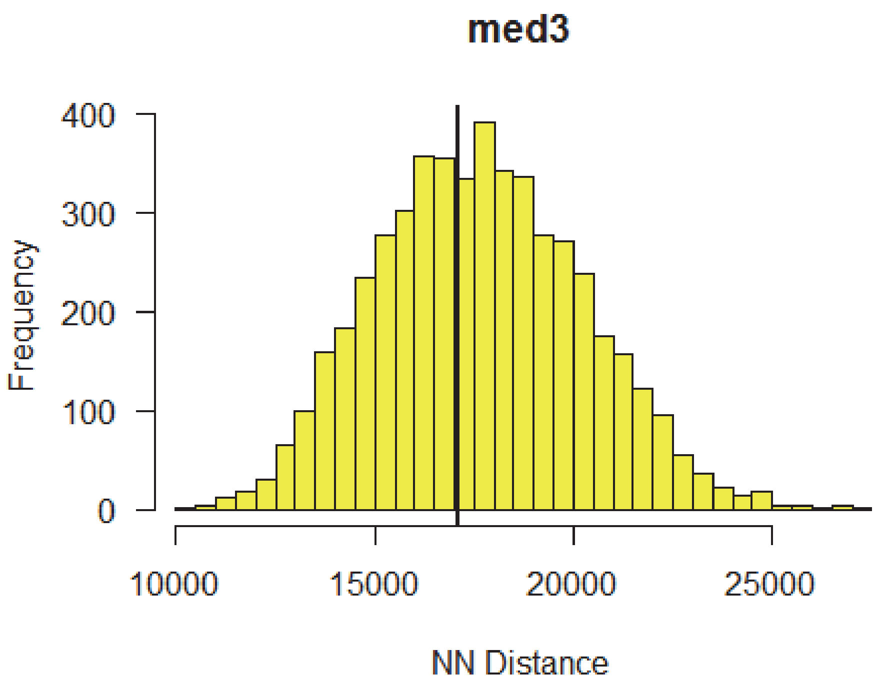

mean2
300
250
200
150
100
50
0
Frequency
14000
16000
18000
20000
22000
24000
NN Distance

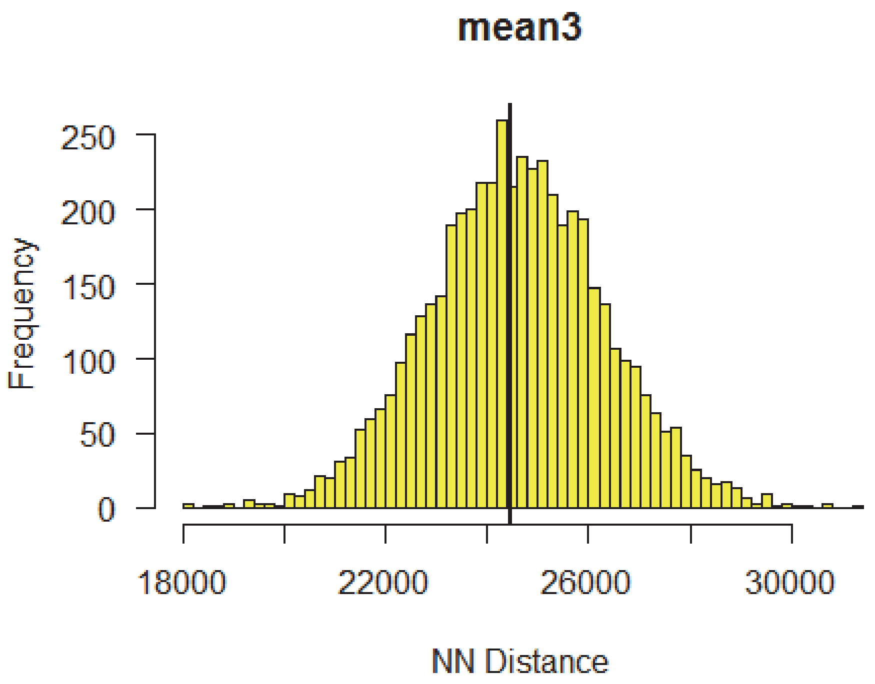

q32
Frequency
350
300
250
200
150
100
50
0
15000
20000
25000
30000
35000
40000
NN Distance

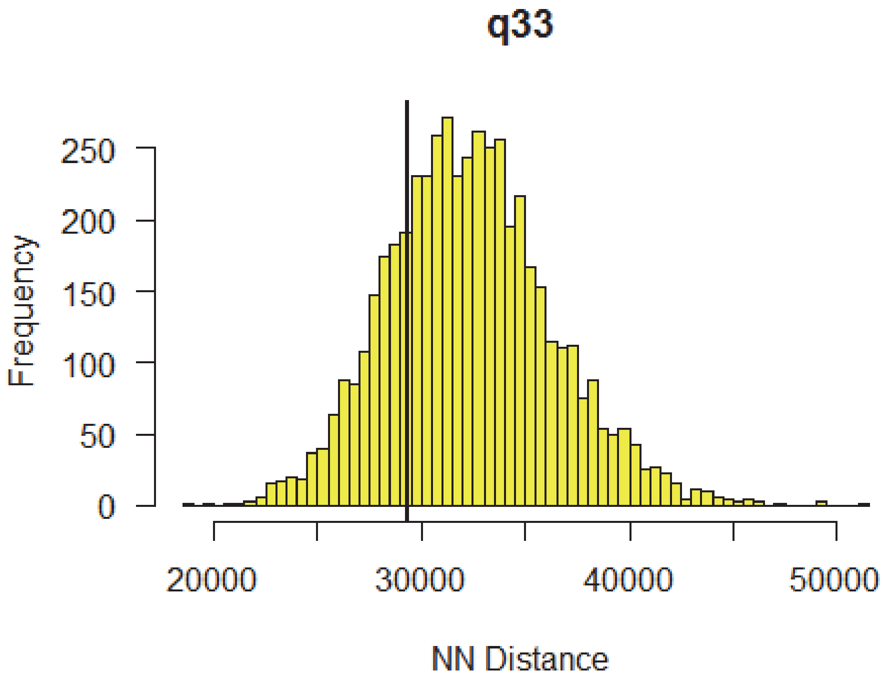

max2
Frequency
700
600
500
400
300
200
100
0
60000
100000
140000
180000
NN Distance

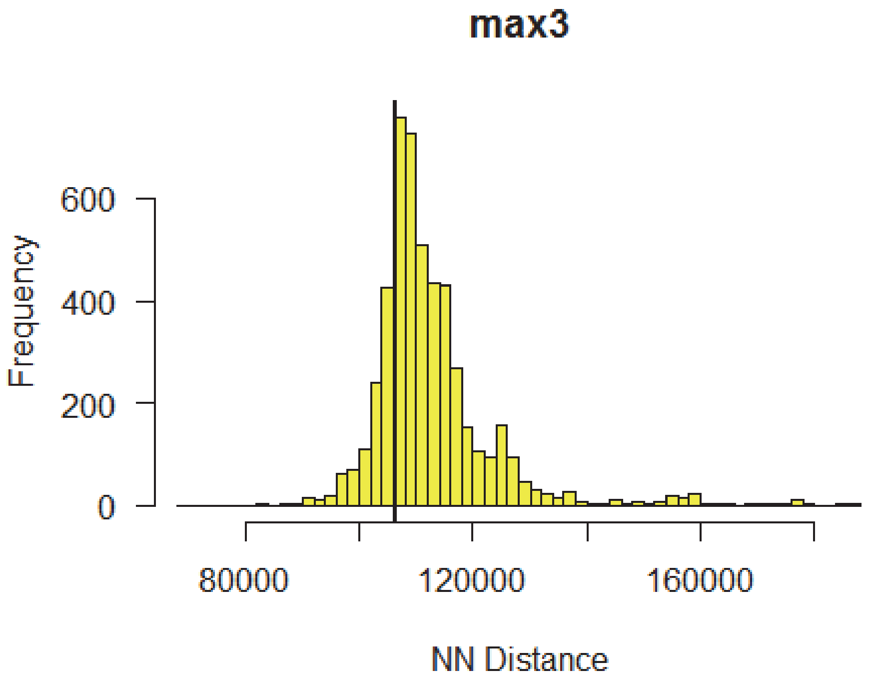

min3
Frequency
350
300
250
200
150
100
50
0
2000
4000
6000
8000
NN Distance

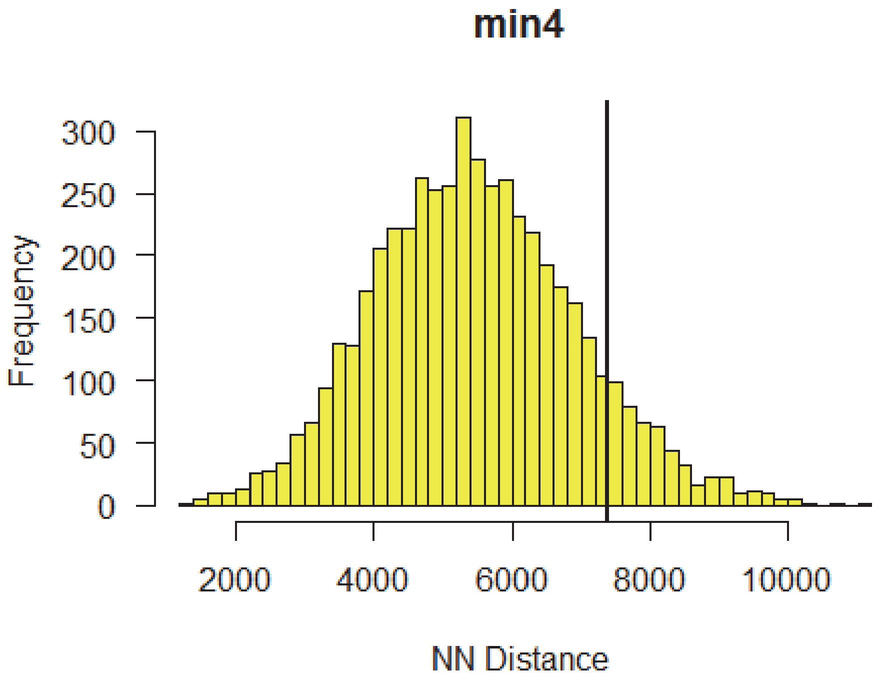

q13
Frequency
250
200
150
100
50
0
6000
8000
10000
14000
NN Distance

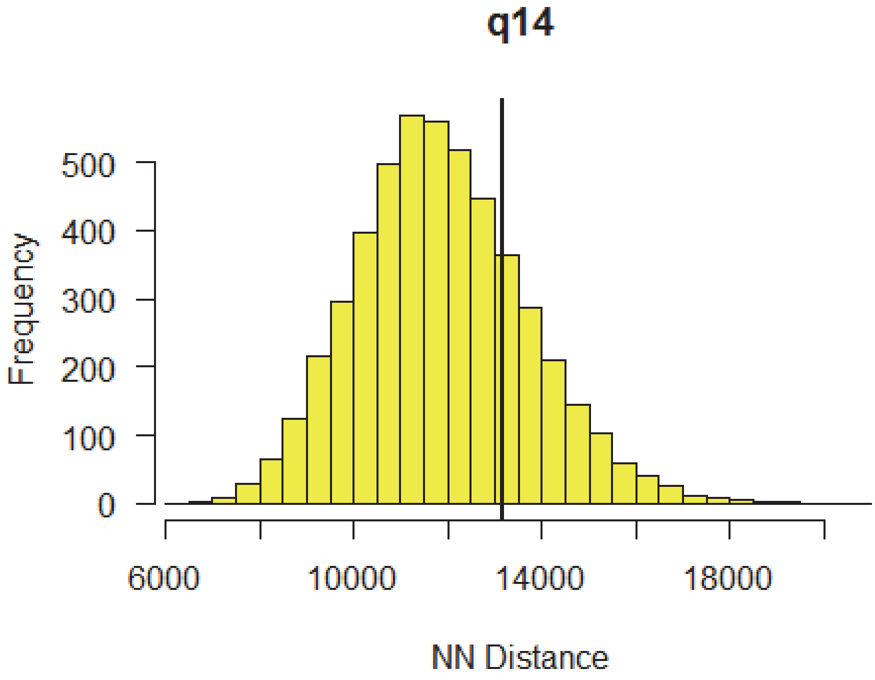

med3
Frequency
0
100
200
300
400
10000
15000
20000
25000
NN Distance

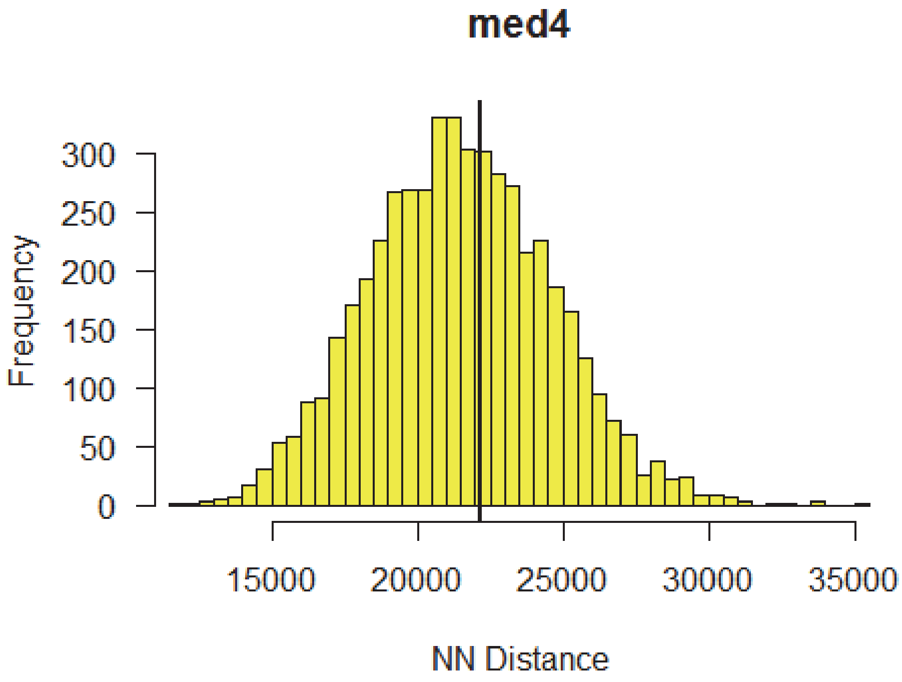

mean3
Frequency
0
50
100
150
200
250
18000
22000
26000
30000
NN Distance

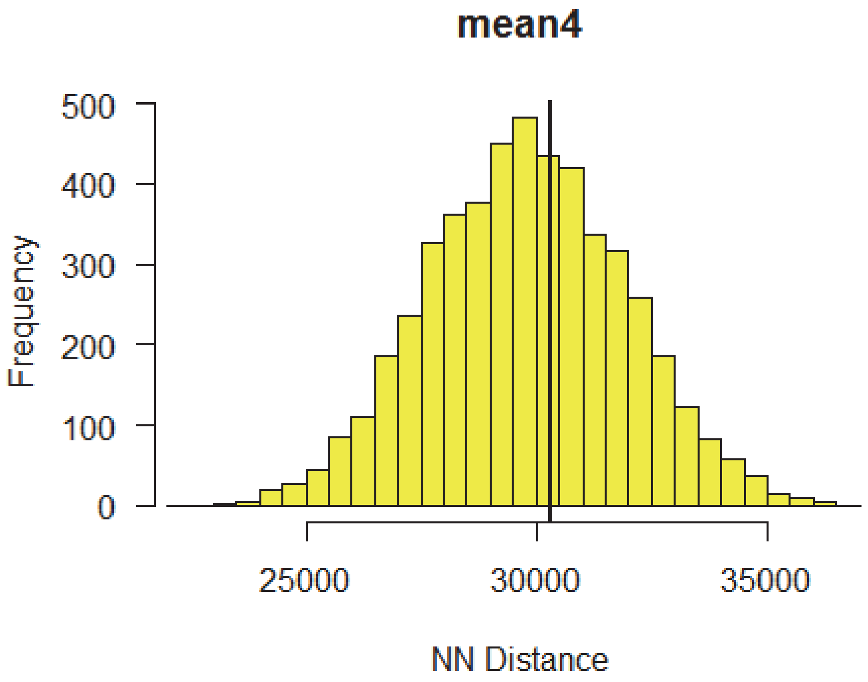

q33
Frequency
0
50
100
150
200
250
20000
30000
40000
50000
NN Distance

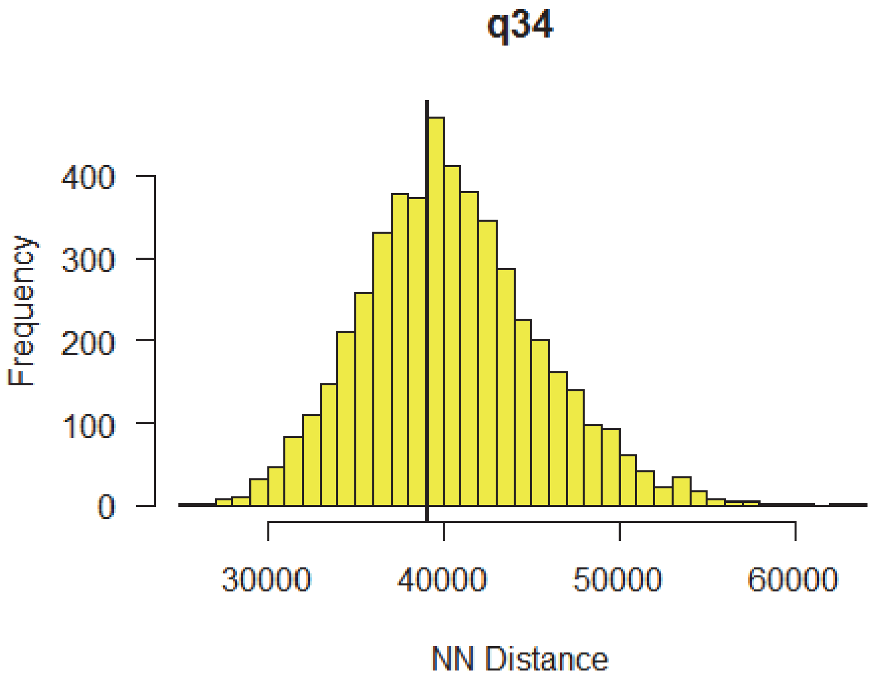

max3
Frequency
0
200
400
600
80000
120000
160000
NN Distance

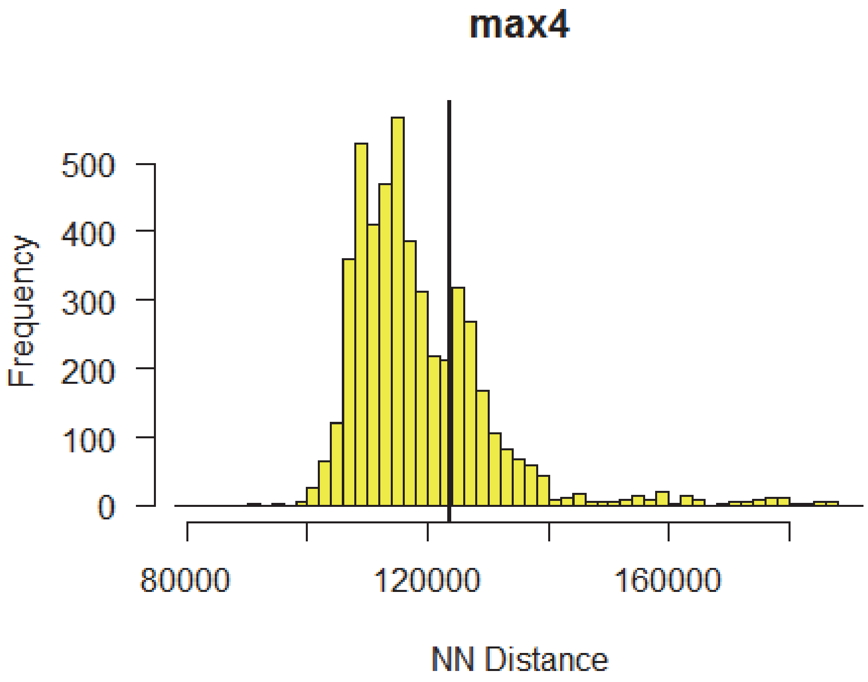

min4
Frequency
300
250
200
150
100
50
0
2000
4000
6000
8000
10000
NN Distance

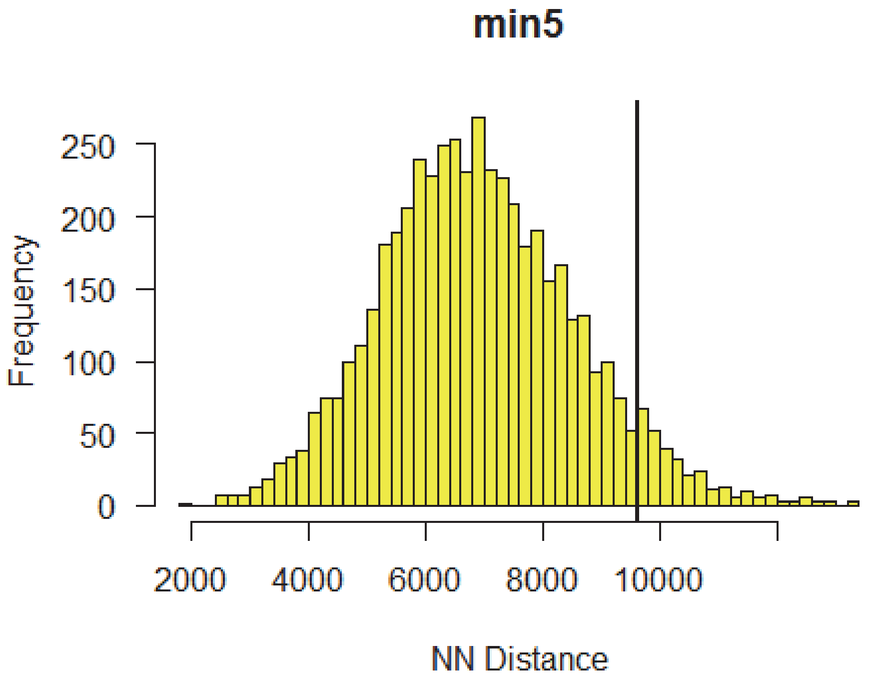

q14
Frequency
500
400
300
200
100
0
6000
10000
14000
18000
NN Distance

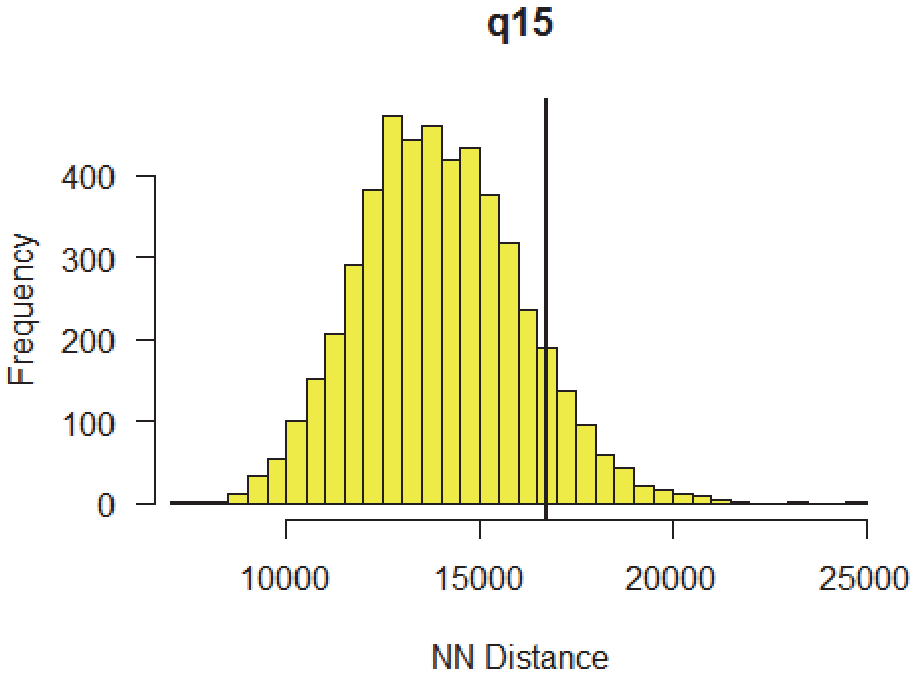

med4
Frequency
300
250
200
150
100
50
0
15000
20000
25000
30000
35000
NN Distance

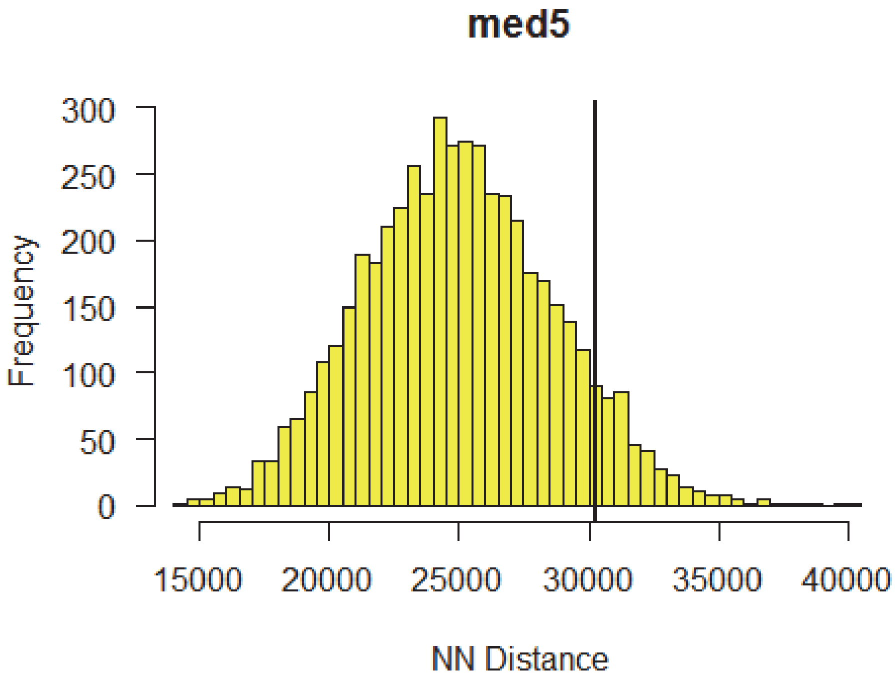

mean4
Frequency
500
400
300
200
100
0
25000
30000
35000
NN Distance

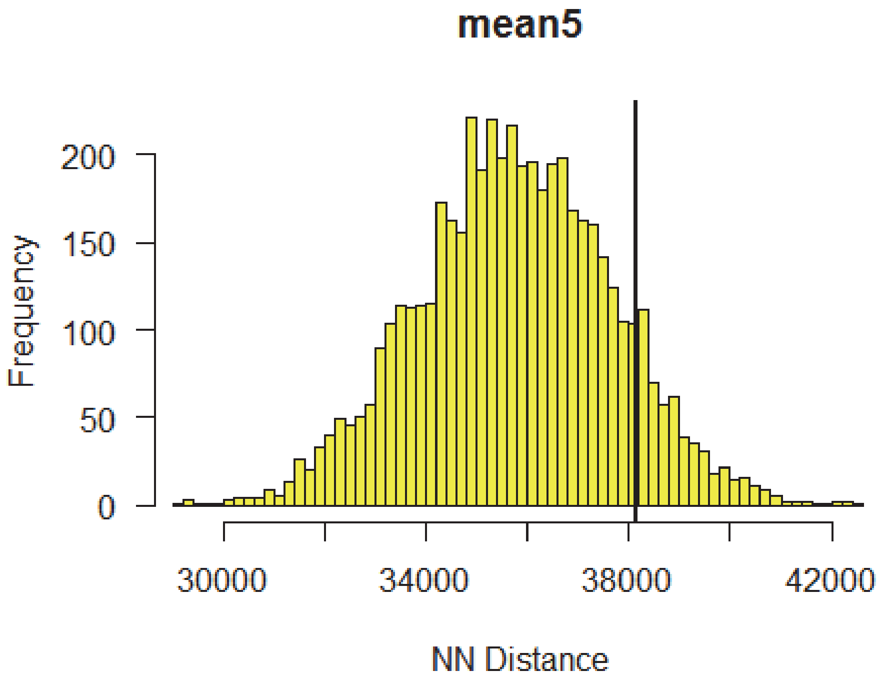

q34
Frequency
0
100
200
300
400
30000
40000
50000
60000
NN Distance

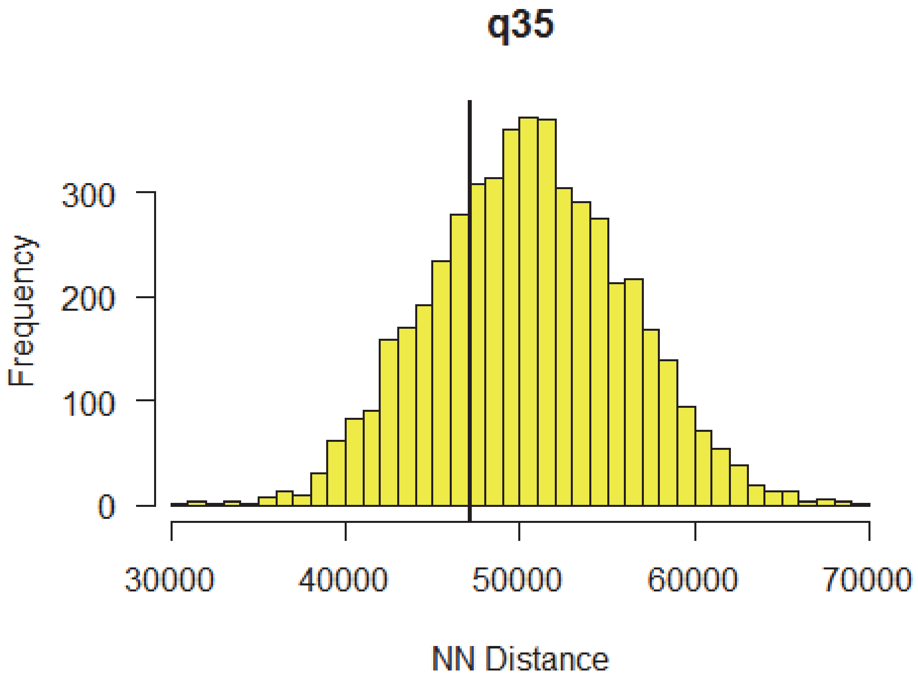

max4
Frequency
0
100
200
300
400
500
80000
120000
160000
NN Distance

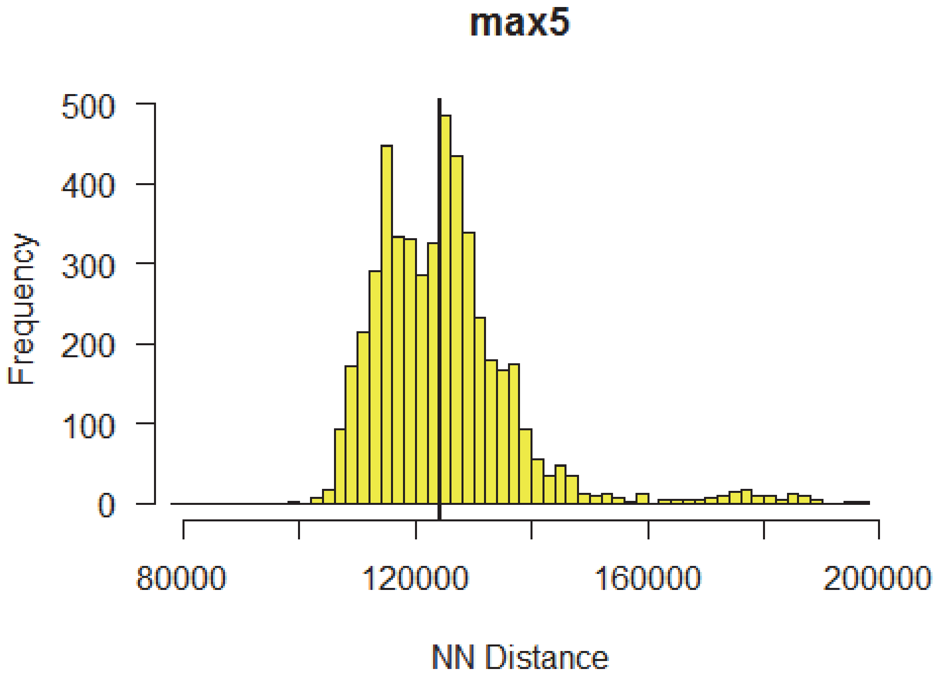

min5
Frequency
250
200
150
100
50
0
2000
4000
6000
8000
10000
NN Distance


q15
Frequency
400
300
200
100
0
10000
15000
20000
25000
NN Distance


med5
Frequency
0
50
100
150
200
250
300
15000
20000
25000
30000
35000
40000
NN Distance


mean5
Frequency
0
50
100
150
200
30000
34000
38000
42000
NN Distance


q35
Frequency
0
100
200
300
30000
40000
50000
60000
70000
NN Distance


max5
Frequency
0
100
200
300
400
500
80000
120000
160000
200000
NN Distance

ANNEX 2.10. Satellite tag nearest neighbour sampling excluding 105GPS tags but including all birds (tags with no stopped-no malfunction status)

11 February 2017

R Libraries

```
library(knitr)
library(foreign)
library(plyr)
library(FNN)
library(qdapRegex)
```

Background

See Annex 2.9.

```
xylocs<-read.csv("Kxydata_nodups_Feb17.csv", as.is = FALSE)
```

Tag metadata

See Annex 2.9. Data from 105GPS tags are removed.

```
tagmeta<-read.csv("tagmetadatajan17.csv", as.is = FALSE)
attach(tagmeta)
tagmeta<-tagmeta[which(tagmeta$Tagtype!="105GPS"),]
cases<-nrow(tagmeta)
cases1<-sum(tagmeta$susplkf)
sx<-na.omit(tagmeta[which(tagmeta$susplkf<1),c("FinX","FinY")]) # xy coords of 'failed' tags
cases0<-nrow(sx)
```

Sampling effort

See Annex 2.9.

```
daysum<-sum(tagmeta$Days)
tagmeta$dayprop<-tagmeta$Days/daysum
```

Preparing sampling

See Annex 2.9.

```
attach(xylocs)

## The following object is masked from tagmeta:
##     Days

iterations<-5000
rows<-iterations
nndists <- data.frame(min1=numeric(rows), q11=numeric(rows), med1=numeric(rows),
mean1=numeric(rows), q31=numeric(rows), max1=numeric(rows),min2=numeric(rows),
q12= numeric(rows), med2=numeric(rows), mean2=numeric(rows), q32=numeric(rows),
max2=numeric(rows), min3=numeric(rows),q13=numeric(rows), med3=numeric(rows),
mean3=numeric(rows), q33=numeric(rows), max3=numeric(rows),
min4=numeric(rows),q14=numeric(rows), med4=numeric(rows), mean4=numeric(rows),
q34=numeric(rows), max4=numeric(rows), min5=numeric(rows),q15=numeric(rows),
med5=numeric(rows), mean5=numeric(rows), q35=numeric(rows), max5=numeric(rows))
```

```
IDlist<-data.frame(matrix(ncol = cases0, nrow = rows))
set.seed(12345)
```

Random sampling

See Annex 2.9.

```
for (i in 2:iterations) {
    qsample <-
tagmeta[sample(1:nrow(tagmeta),cases0,replace=FALSE,tagmeta$dayprop),]
    lst<-qsample$TagID
    IDlist[i-1,]<-lst[order(lst)]
    xylocsample<-xylocs[xylocs$ID%in% lst,]
    lstlen<-length(lst)
    s2<-data.frame(X=numeric(lstlen), Y=numeric(lstlen))
    for (a in 1:lstlen) {
        s <- xylocsample[ which(xylocsample$ID==lst[a]), ]
        samp_idx <- sample(seq_len(nrow(s)), 1, prob=s$samp_p)
        s2[a,] <- s[samp_idx,c("X","Y") ]
    }
    nnd<-knn.dist(s2,k=5,algorithm=c("kd_tree","cover_tree","CR","brute"))
    nndo<-summary(nnd)
    nndo<-gsub("[:]",": ",nndo)
    tmp2<-as_numeric2(ex_number(nndo))
    for (j in 1:30) nndists[i,j]<- tmp2[j]
}
```

Real nearest neighbours

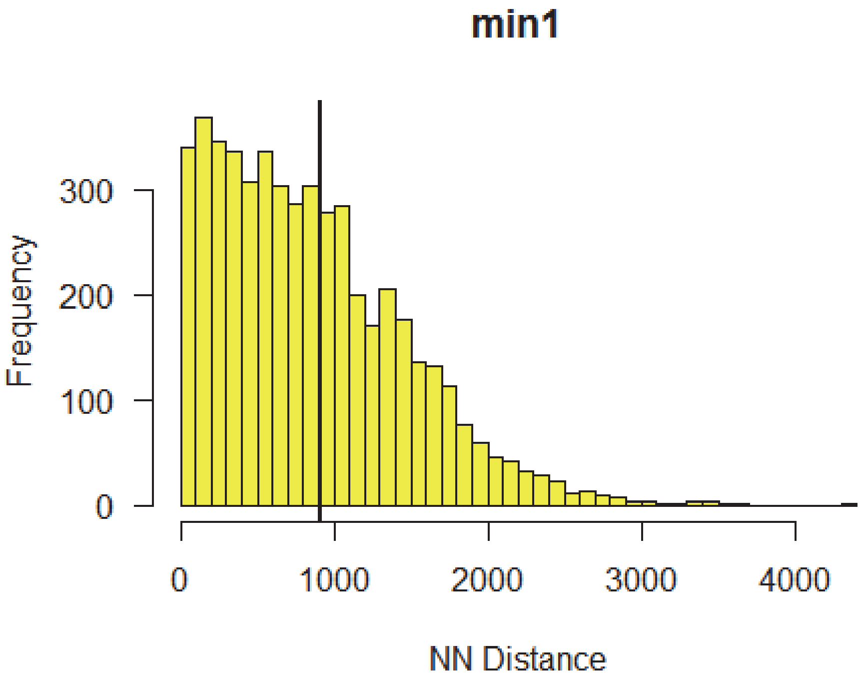
See Annex 2.9.

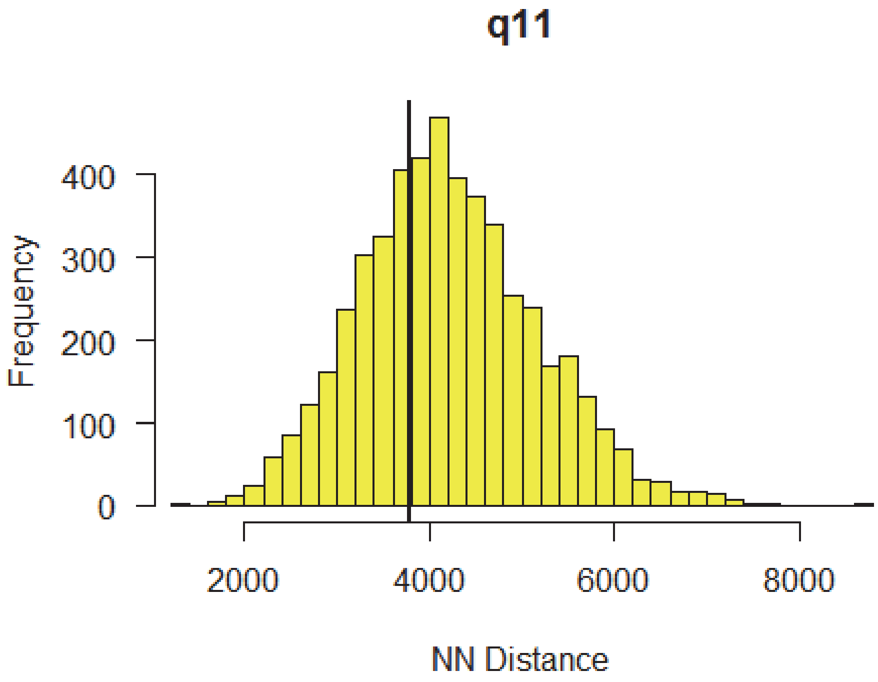
```
sx<-na.omit(tagmeta[which(tagmeta$susplkf<1),c("FinX","FinY")])
nndx<-knn.dist(sx, k=5, algorithm=c("kd_tree","cover_tree","CR","brute"))
nndo<-summary(nndx)
nndo<-gsub("[:]",": ",nndo)
tmp2<-as_numeric2(ex_number(nndo))
for (j in 1:30) nndists[1,j]<- tmp2[j]
write.table(nndists,file="nndists5_Alltags_NonSuspect.txt",sep="\t")
IDcount<-stack(IDlist)
IDcount<-as.matrix(table(IDcount$values))
```

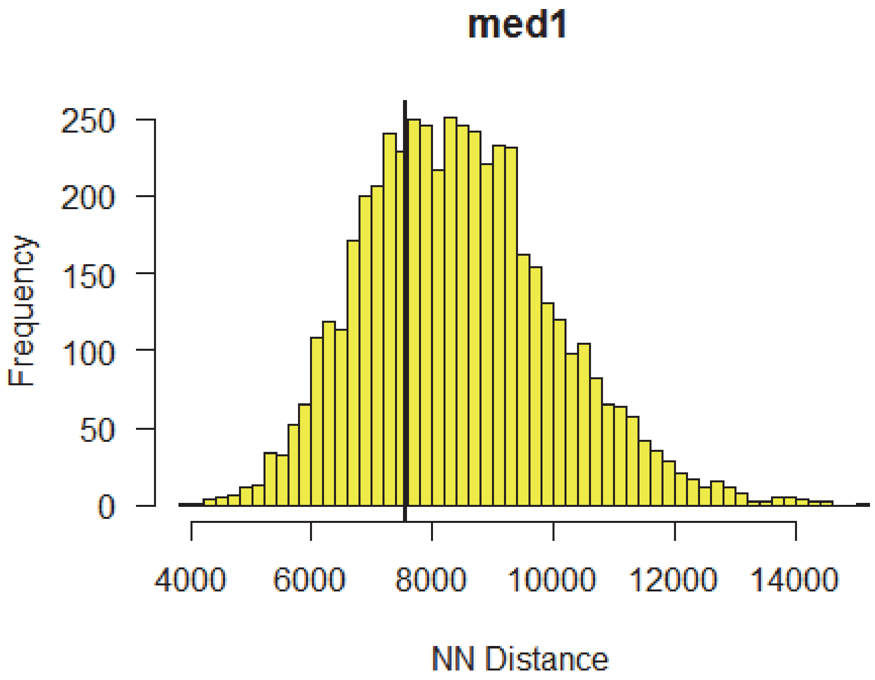
Plot the results

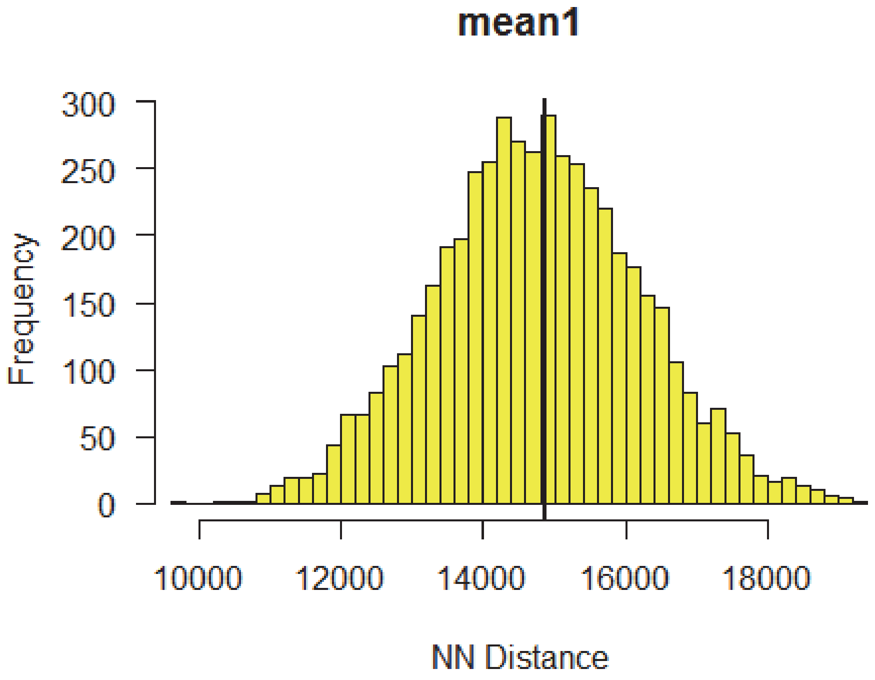
A frequency distribution is plotted for each nearest neighbour's sampling distribution and the real value is shown as a vertical black line.

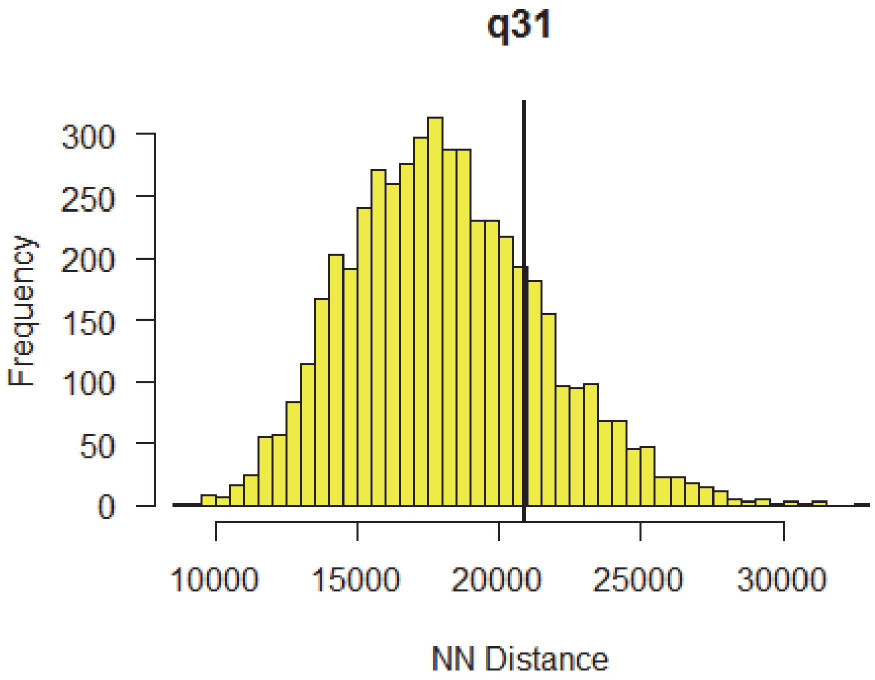
```
cnames<-names(nndists)
bins<-50
for (i in 1:length(cnames)) {
    title<-cnames[i]
    range<-round(range(nndists[,i]), digits=0)
    hist(nndists[,i], main=title, xlab="NN Distance", border="black", col="yellow",
xlim=c(range[1],range[2]), las=1, breaks=bins, prob = FALSE)
    abline(v=nndists[1,i],lty=1,lwd=2,col="black")
}
```

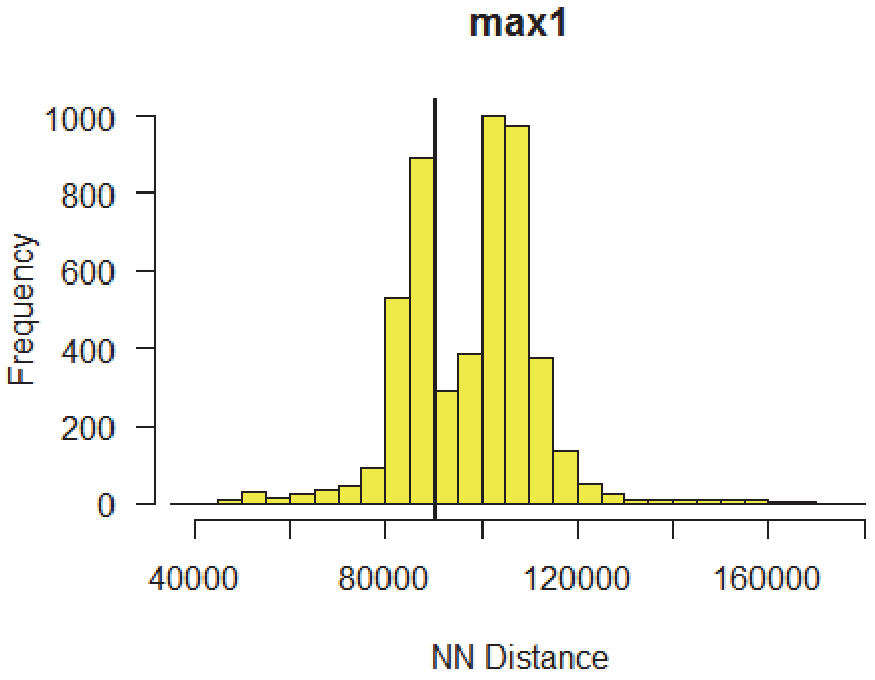

min1
Frequency
0
100
200
300
0
1000
2000
3000
4000
NN Distance

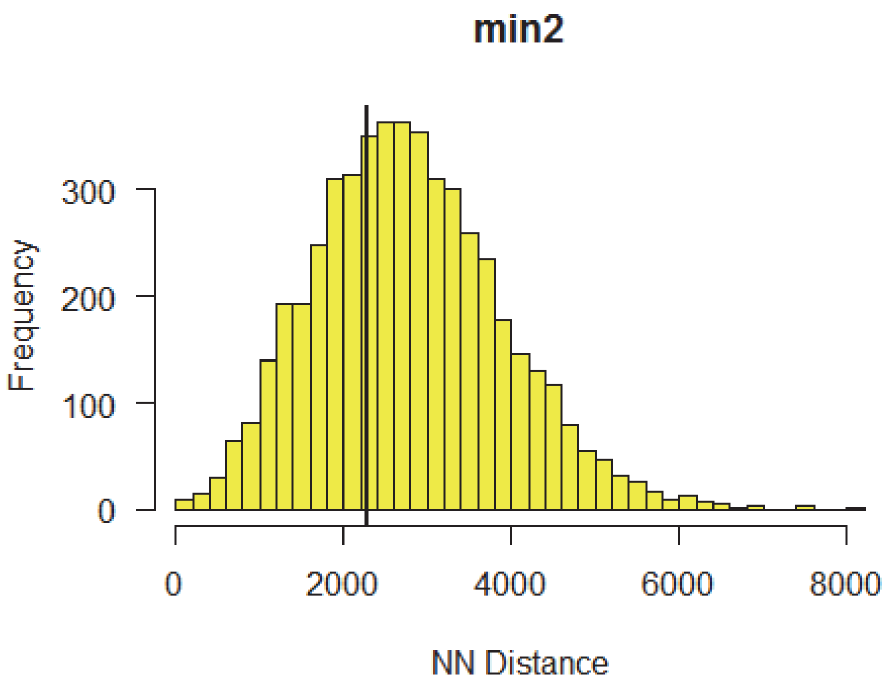

q11
Frequency
0
100
200
300
400
2000
4000
6000
8000
NN Distance

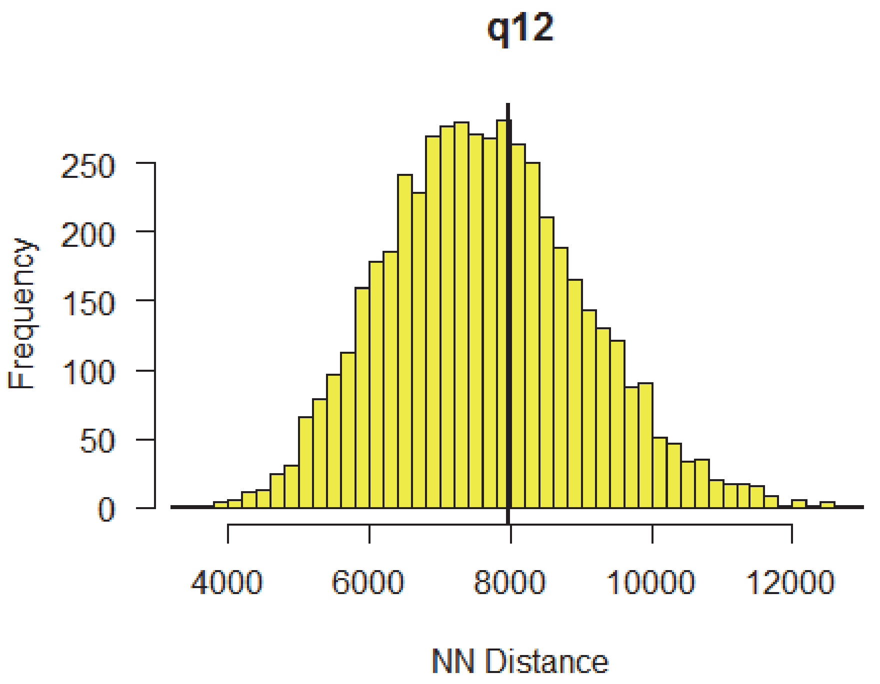

med1
Frequency
250
200
150
100
50
0
4000
6000
8000
10000
12000
14000
NN Distance

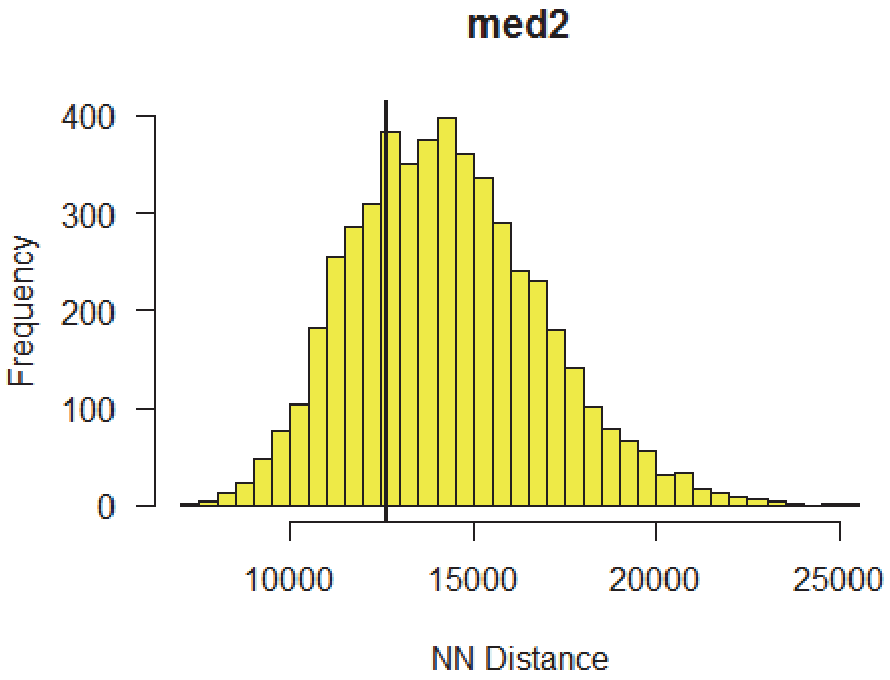

mean1
Frequency
300
250
200
150
100
50
0
10000
12000
14000
16000
18000
NN Distance

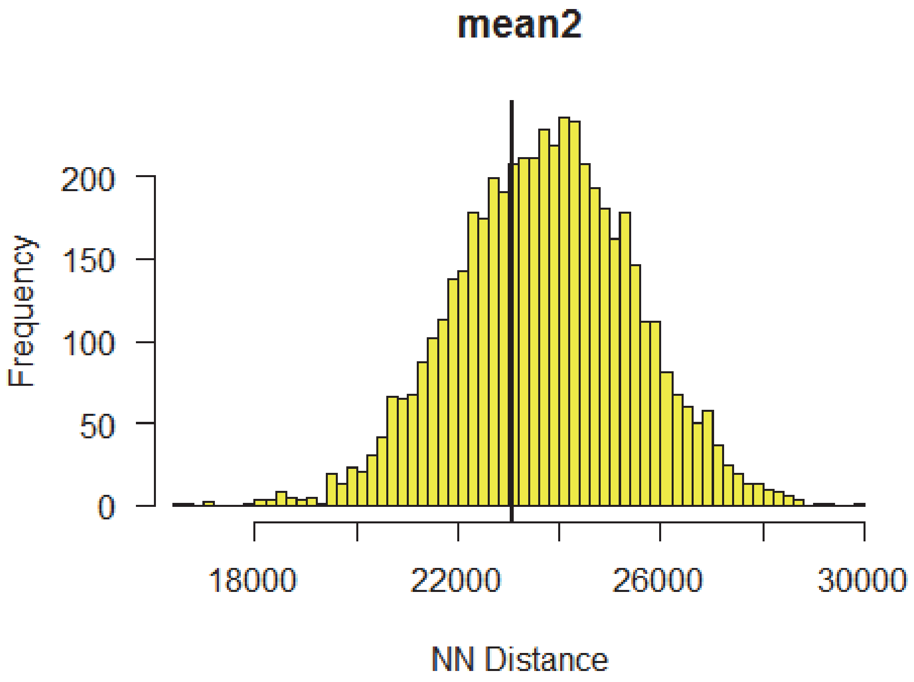

q31
Frequency
300
250
200
150
100
50
0
10000
15000
20000
25000
30000
NN Distance

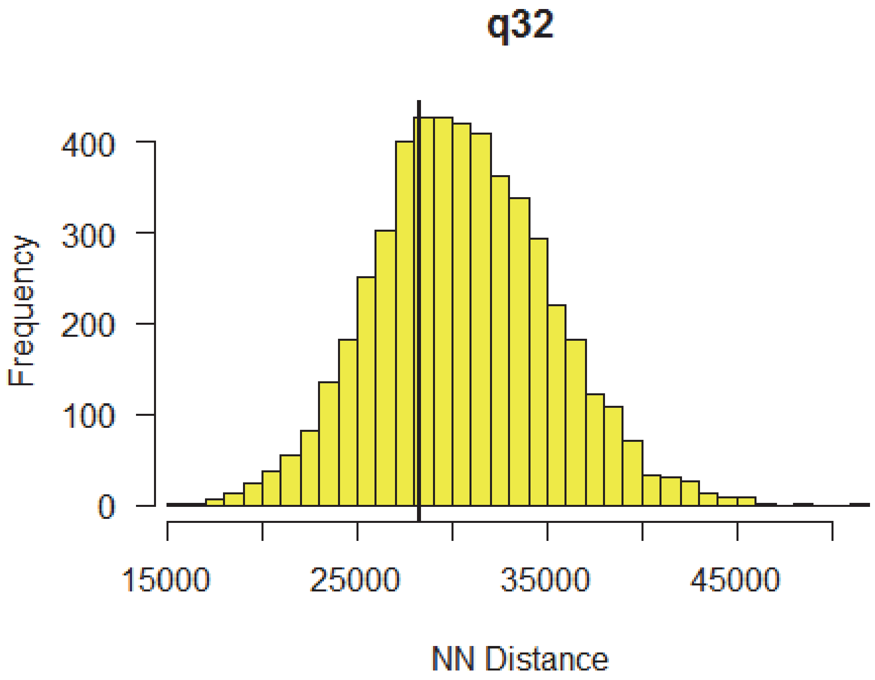

max1
Frequency
1000
800
600
400
200
0
40000
80000
120000
160000
NN Distance

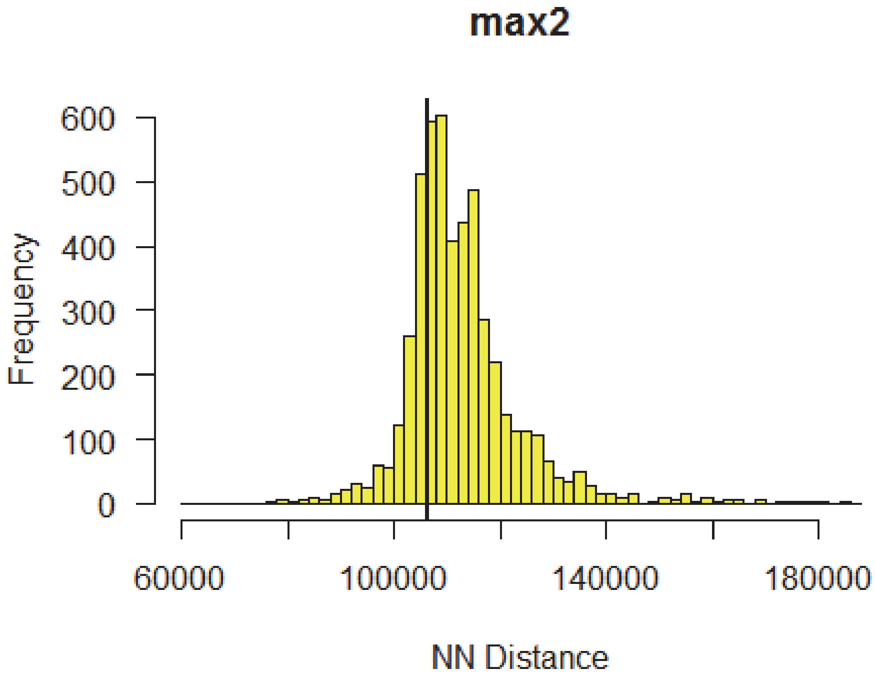

min2
Frequency
0
100
200
300
0
2000
4000
6000
8000
NN Distance

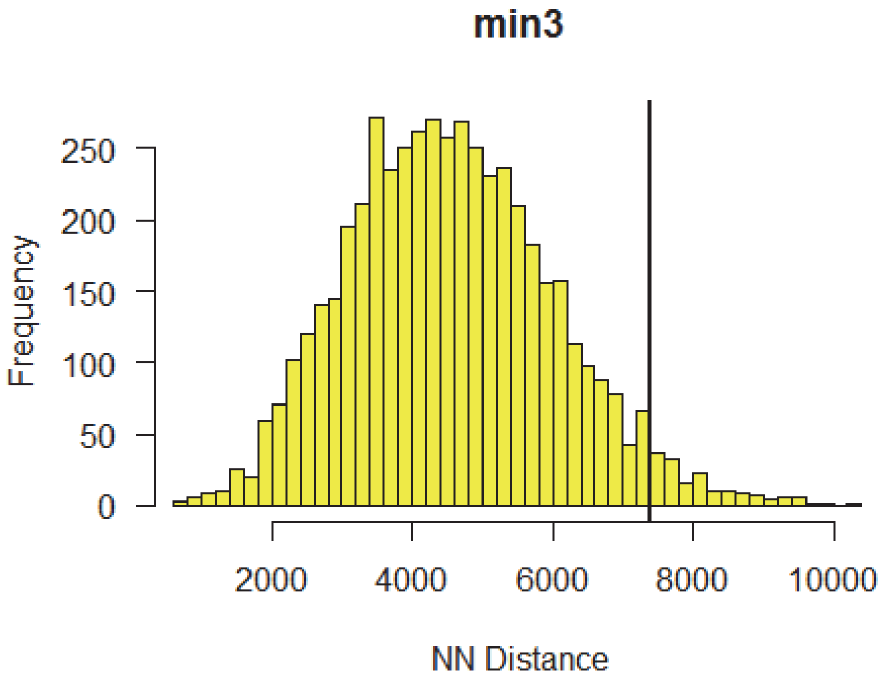

q12
Frequency
0
50
100
150
200
250
4000
6000
8000
10000
12000
NN Distance

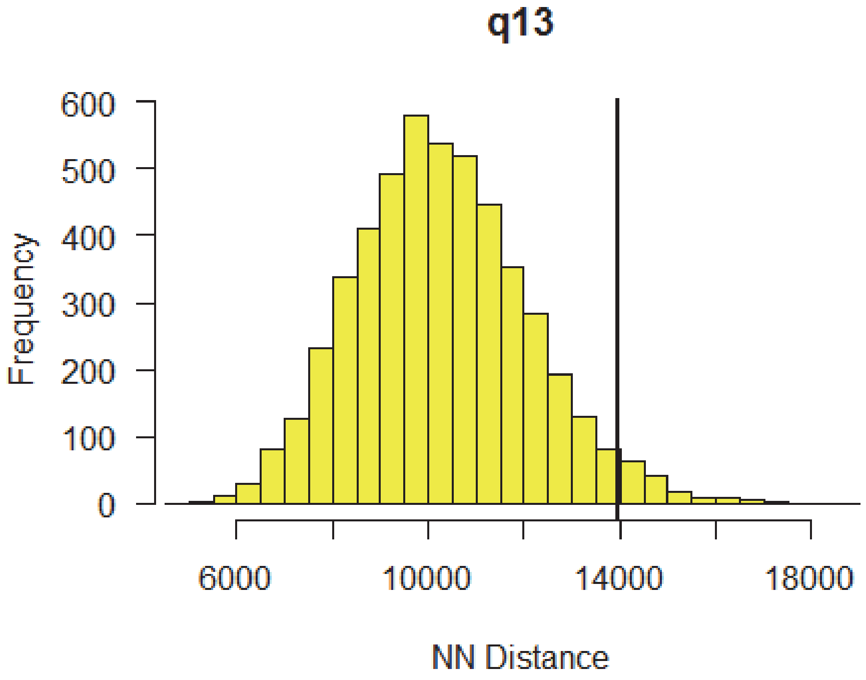

med2
Frequency
400
300
200
100
0
10000
15000
20000
25000
NN Distance

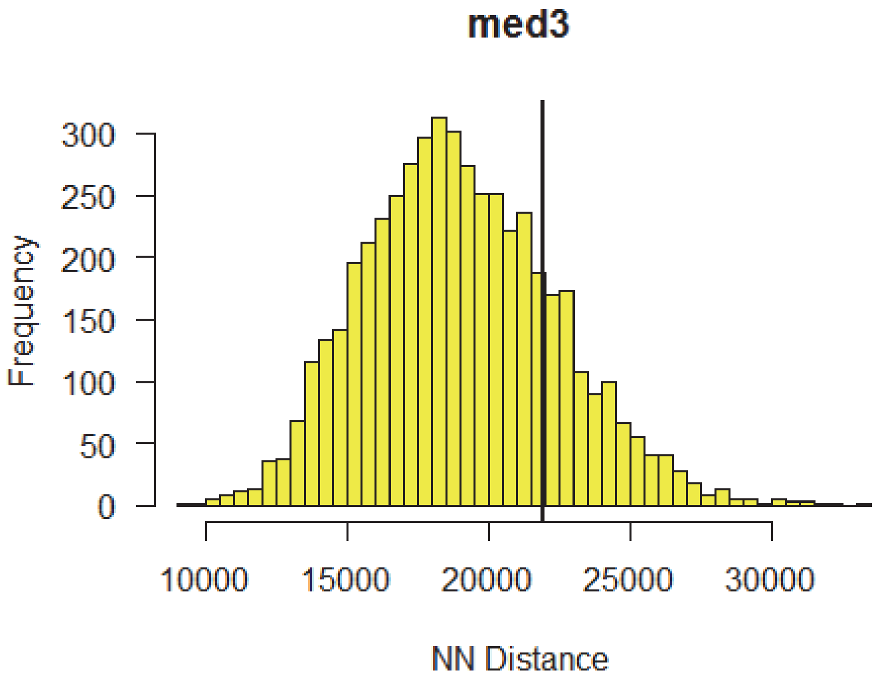

mean2
Frequency
200
150
100
50
0
18000
22000
26000
30000
NN Distance

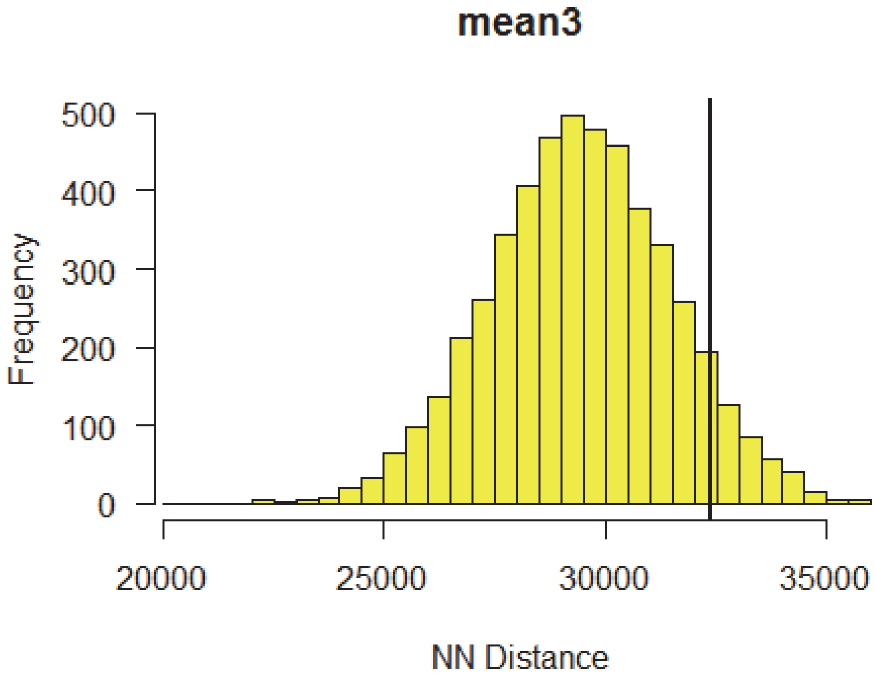

q32
Frequency
0
100
200
300
400
15000
25000
35000
45000
NN Distance

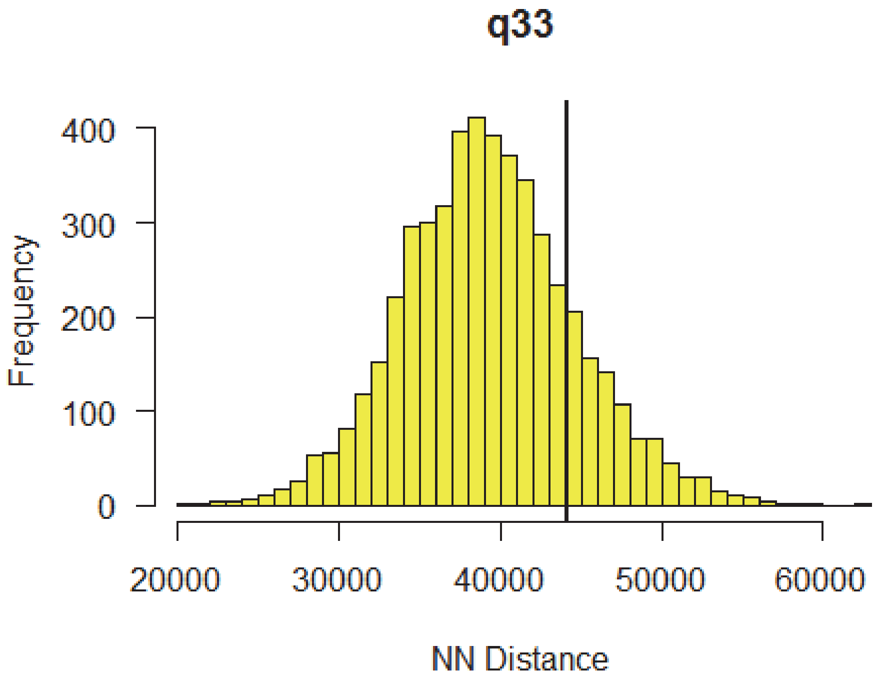

max2
Frequency
0
100
200
300
400
500
600
60000
100000
140000
180000
NN Distance

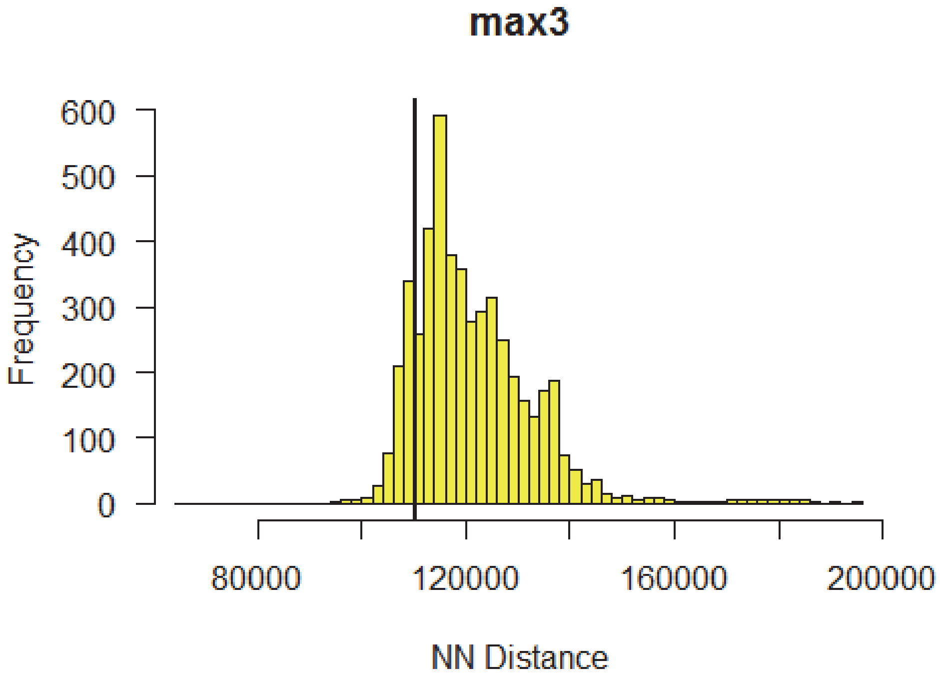

min3
Frequency
0
50
100
150
200
250
2000
4000
6000
8000
10000
NN Distance

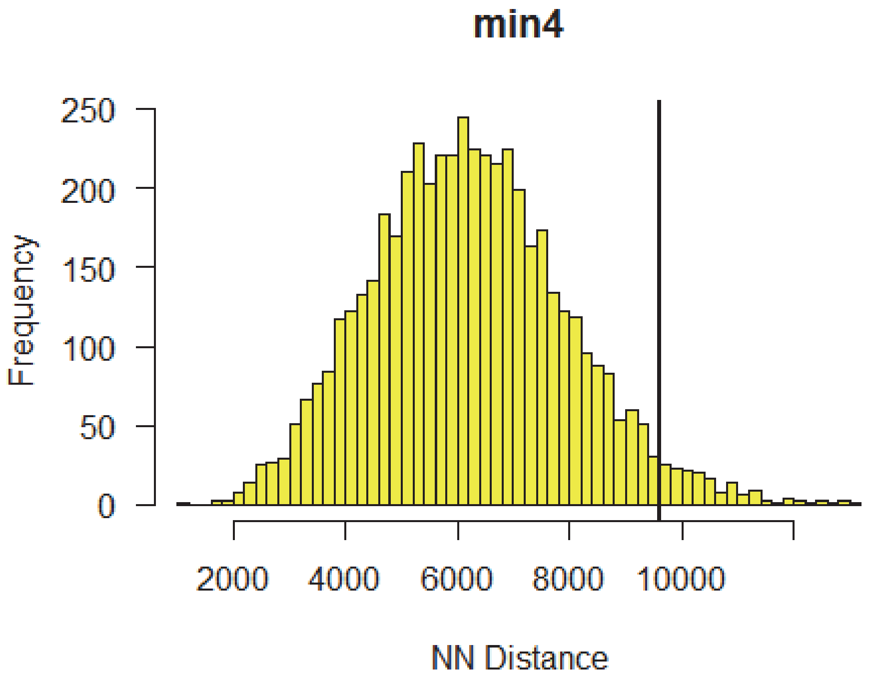

q13
Frequency
0
100
200
300
400
500
600
6000
10000
14000
18000
NN Distance

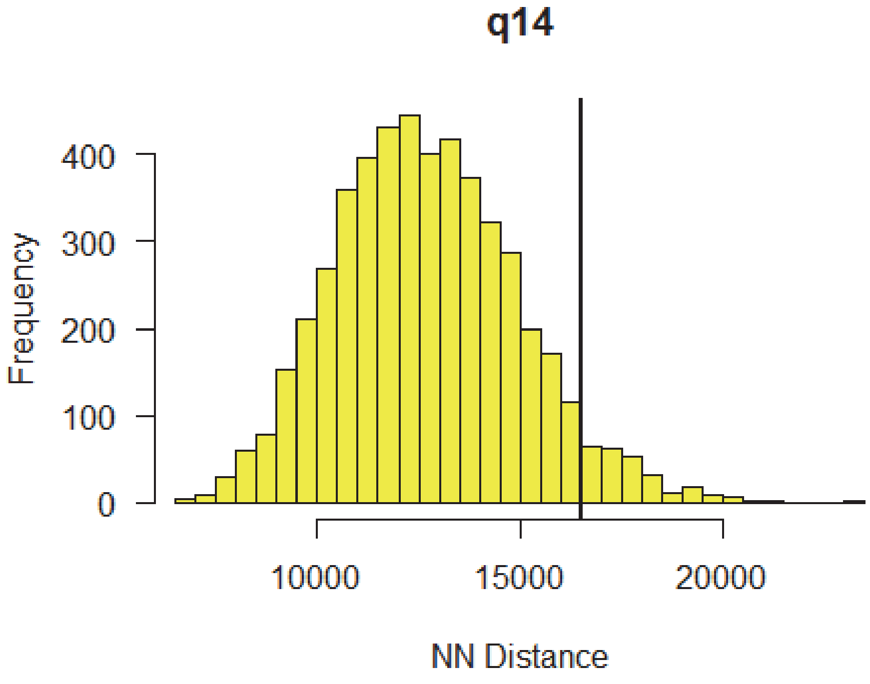

med3
Frequency
300
250
200
150
100
50
0
10000
15000
20000
25000
30000
NN Distance

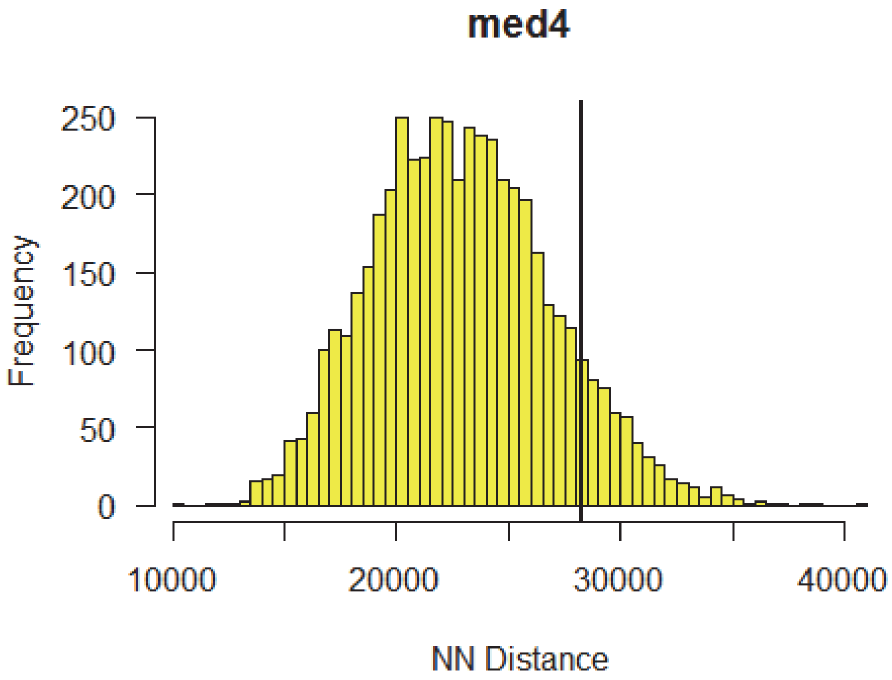

mean3
Frequency
500
400
300
200
100
0
20000
25000
30000
35000
NN Distance

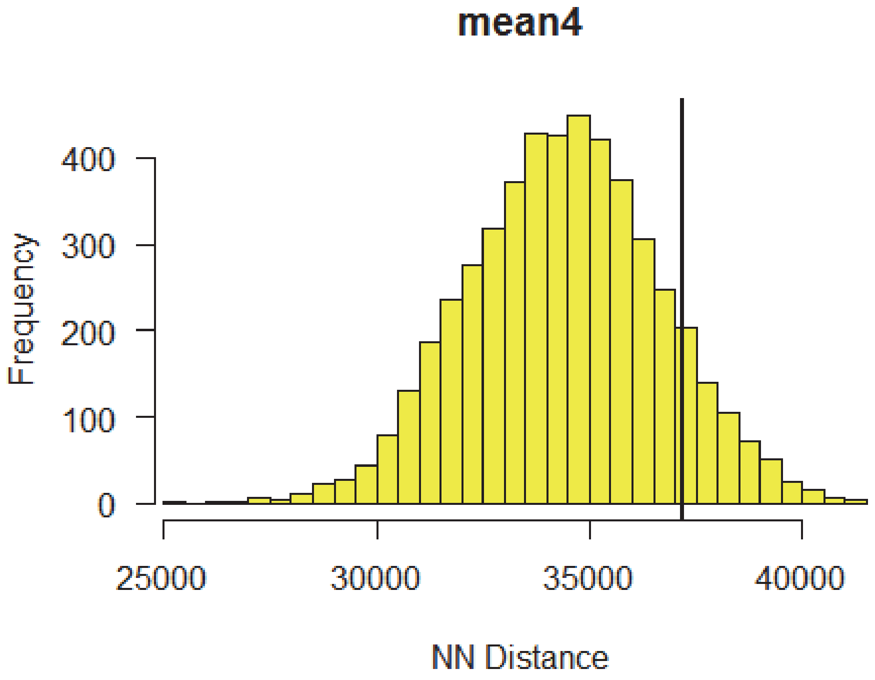

q33
Frequency
0
100
200
300
400
20000
30000
40000
50000
60000
NN Distance

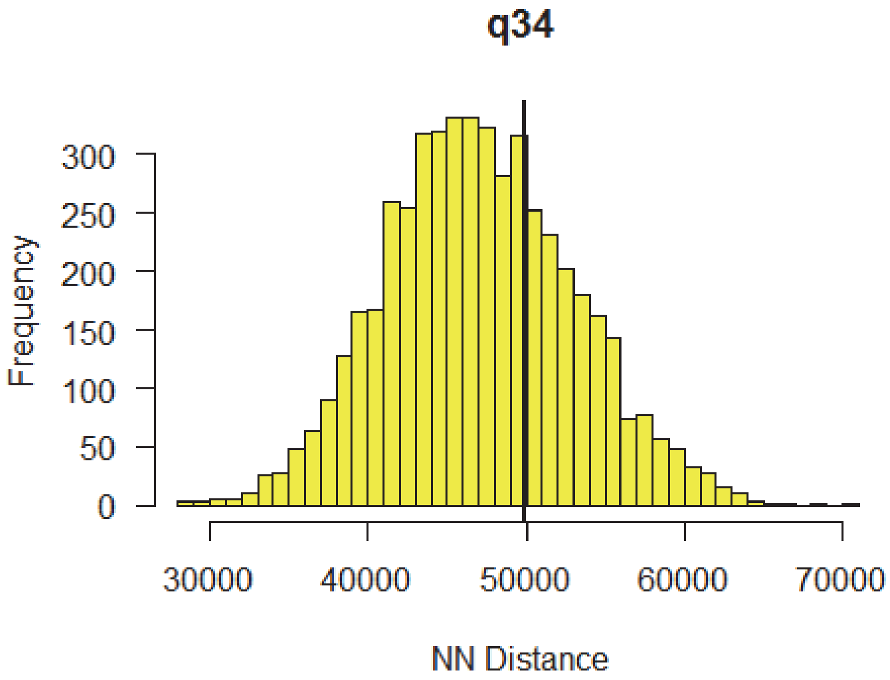

max3
Frequency
0
100
200
300
400
500
600
80000
120000
160000
200000
NN Distance

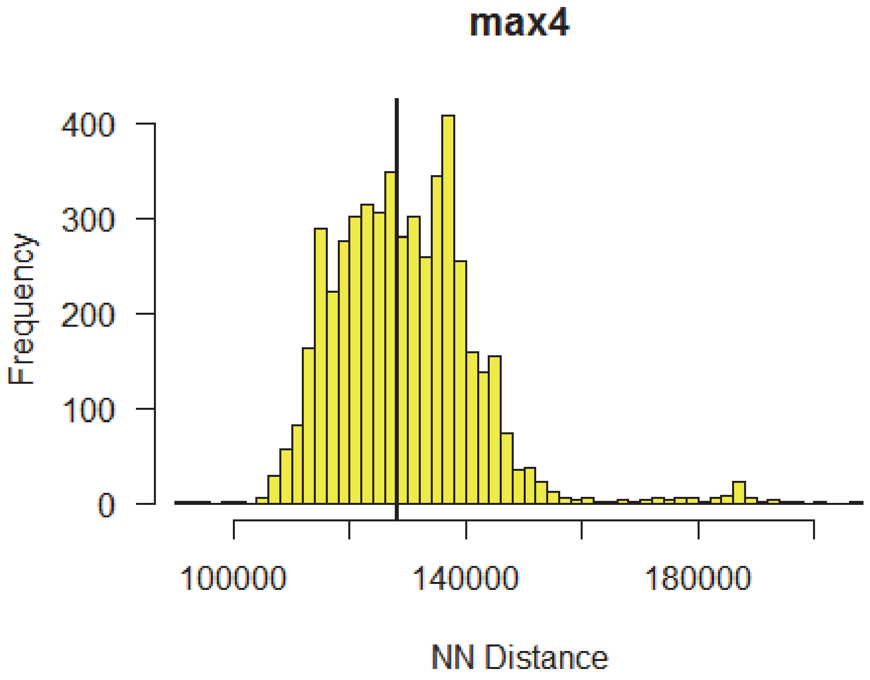

min4
Frequency
0
50
100
150
200
250
2000
4000
6000
8000
10000
NN Distance

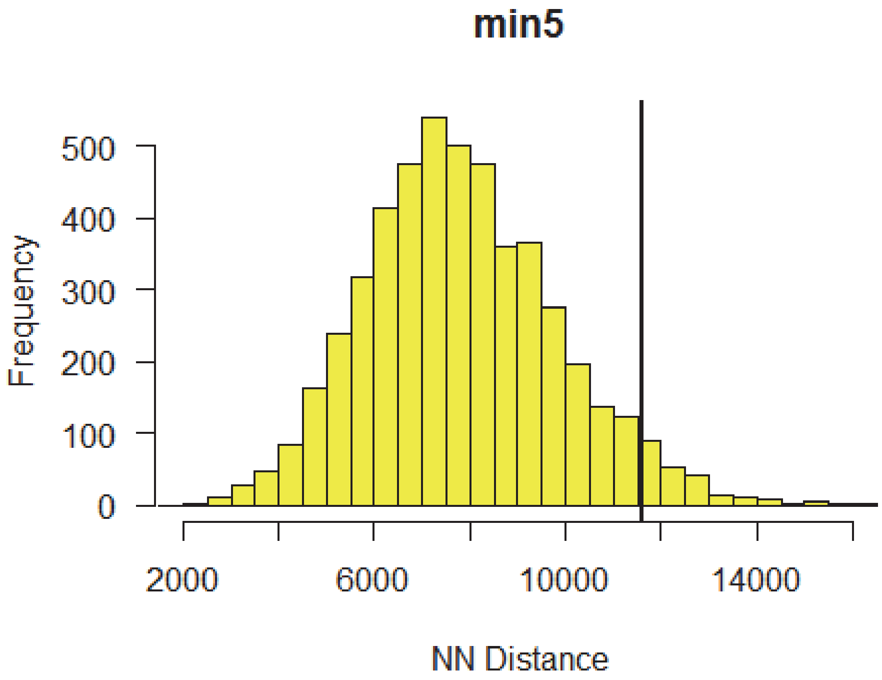

q14
Frequency
0
100
200
300
400
10000
15000
20000
NN Distance

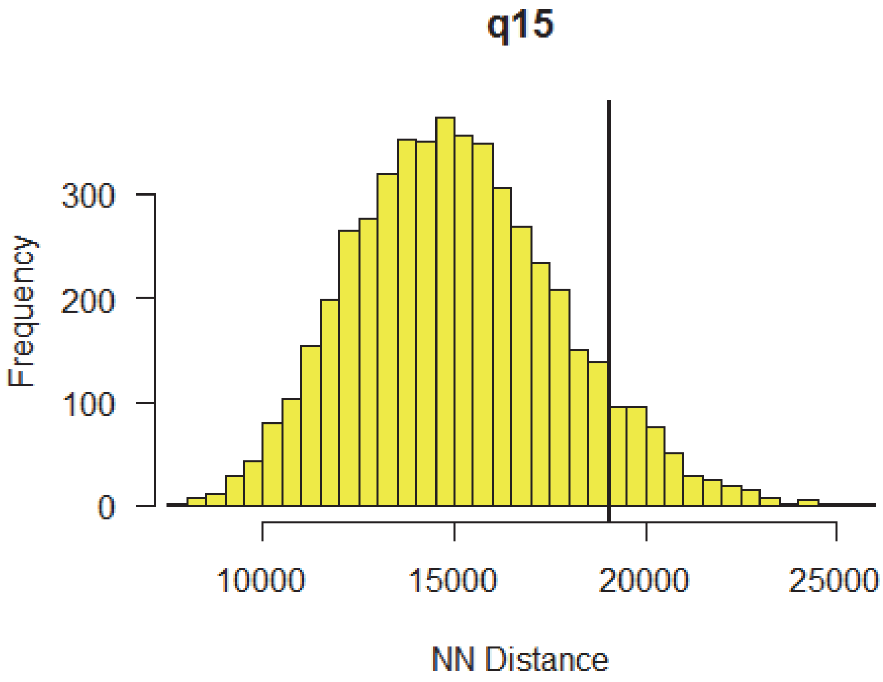

med4
Frequency
250
200
150
100
50
0
10000
20000
30000
40000
NN Distance

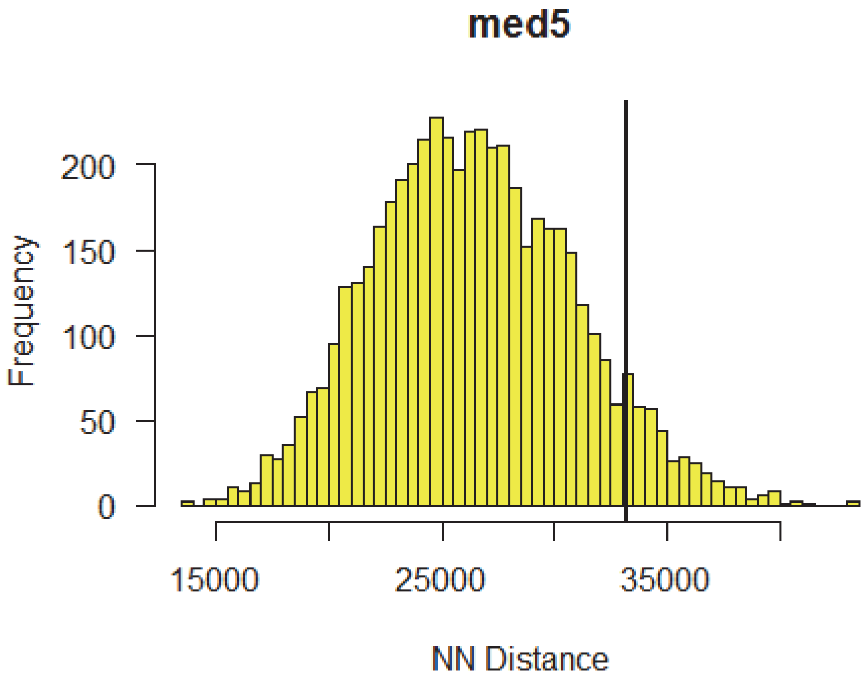

mean4
Frequency
400
300
200
100
0
25000
30000
35000
40000
NN Distance


q34
Frequency
0
50
100
150
200
250
300
30000
40000
50000
60000
70000
NN Distance


max4
Frequency
0
100
200
300
400
100000
140000
180000
NN Distance


min5
Frequency
0
100
200
300
400
500
2000
6000
10000
14000
NN Distance


q15
Frequency
0
100
200
300
10000
15000
20000
25000
NN Distance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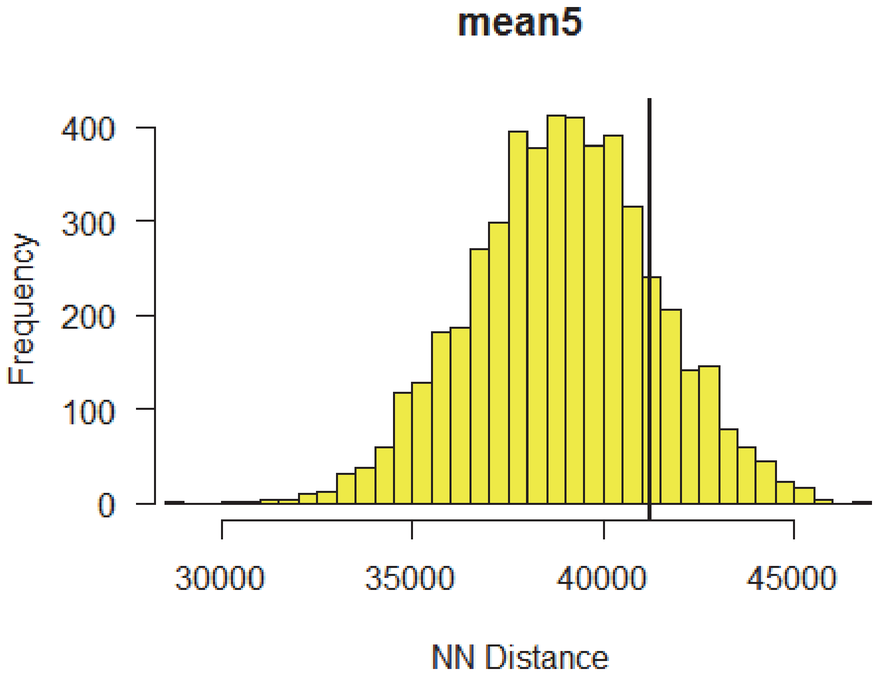
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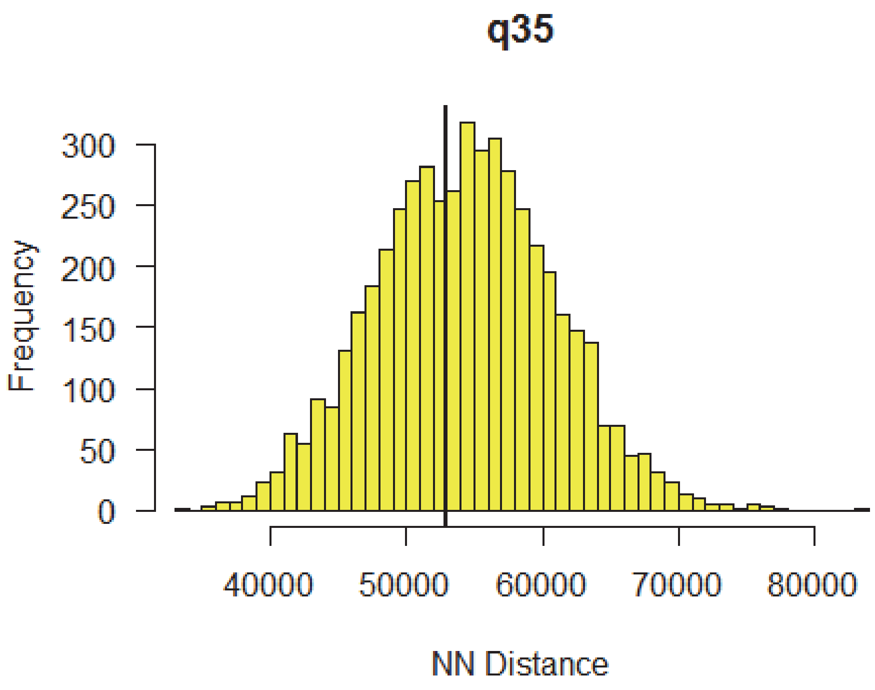
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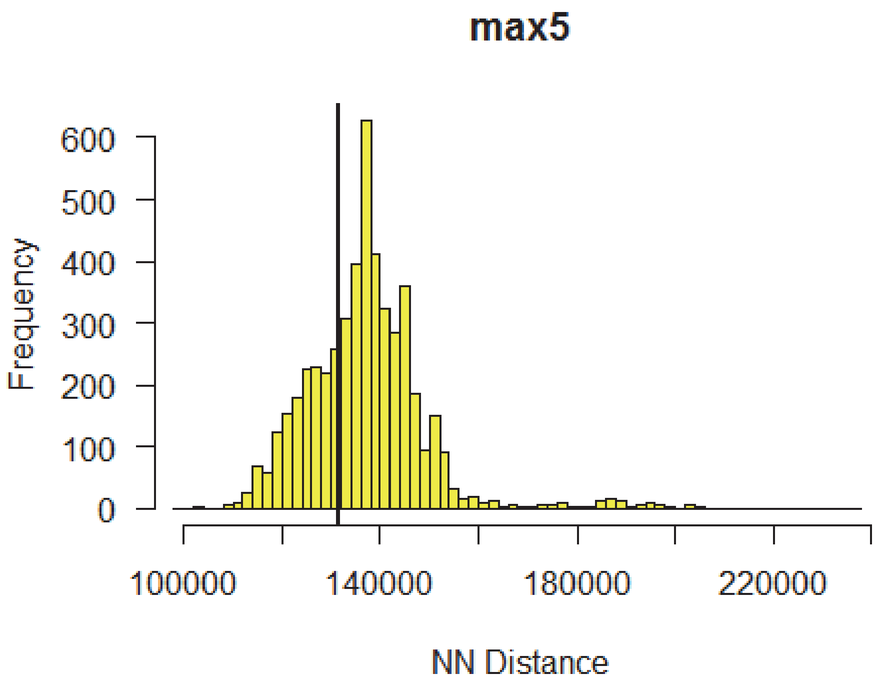
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ANNEX 3: TAGGING BEST PRACTICE

Overview of BTO Ringing Scheme training and licensing procedure

Ringing Scheme governance

- The BTO has delegated authority from the Country Conservation Agencies under the Wildlife & Countryside Act (1981) for issuing permits to ring birds. BTO organise, administer and regulate the Ringing Scheme in Britain & Ireland, with over 3000 trained volunteer ringers, ringing around 1 million birds annually (see http://www.bto.org/ringing).
- The Ringing Scheme is governed by the BTO Ringing Committee (RIN) which is itself a committee of the governing Council of the BTO. Members of RIN are qualified and experienced ringers, and among their responsibilities is the maintenance of high standards of training for all ringers.
- The trapping of wild birds, and the fitting of conventional numbered metal rings, and coloured plastic rings, to the legs of birds are activities covered by a conventional ringing permit. In addition the BTO Ringing Scheme has for many years regulated the use of special methods for trapping and marking wild birds, including fitting of harness-mounted satellite tags. This is the remit of an independent, specialist group of experts in the fields of research, technology and veterinary animal welfare known as the Special Methods Technical Panel (SMTP); this is a formal Technical Panel of the BTO Ringing Committee, and maintains oversight of efficacy of methods, bird welfare, usefulness and quality of research, and safety.

Training to ring

- Training to ring is a strictly controlled process. All Trainee (T permit) and Provisional (C permit) ringers are individually mentored by an Advanced (A permit) ringer with a Trainers' endorsement. All applicants for progression to Advanced and Trainer status are assessed in the field by a qualified, independent Trainer and applications are also reviewed by sub-Committee of RIN, the Ringing Standards Select Committee.
- Trainees are not permitted to undertake ringing activities independently. Provisional ringers can operate unsupervised but the nature of those activities can, and is highly likely to be, restricted in terms of taxonomic coverage and catching techniques by their Trainer via use of endorsements and bespoke restrictions. Applicants for a provisional permit must have processed at least 750 birds of about 40 species, which typically takes 1-2 years of regular ringing.
- Scientific researchers studying a particular species can qualify for a limited ringing permit to cover the capture and marking required by their specific research objectives, but this still requires an appropriate level of training.

Special methods

- SMTP operational protocols have been agreed by the Home Office Animals Scientific Procedures Inspectorate, to which the SMTP sends a written report on an annual basis and with which the SMTP meets annually. Methods are only considered by the SMTP if the level of potential harm to individual birds is less than that described in the Animal Scientific Procedures Act (ASPA) as the lower threshold.
- Special Methods endorsement applications are received via a standardized form outlining personal experience, evidence of similar practice elsewhere, potential risk/level of harm and means of mitigation, research aims and data archiving details, where possible supported by published literature.

- All applications must be suitably detailed to assess (a) the risk of harm to birds, (b) the probability of delivering the expected data and (c) whether the findings would be of sufficient value to justify the risk (including potential for publication). In exceptional circumstances the panel may request additional input from the Home Office concerning the evaluation of criterion (a). The SMTP is at liberty to consult additional external referees and impose changes/restrictions in relation to methods used, sample sizes and training required.
- All individuals holding endorsements must report to the SMTP annually for evaluation; this report must include numbers of individuals marked/sampled and a summary of the success or failure of the method, documenting any impacts on birds and cases of equipment failure. If evidence of harm at or above the ASPA lower threshold is detected, permission may be withdrawn or modifications requested.
- A documented subset of well established procedures may be agreed by the SMTP Secretary without circulation to the Panel; this subset includes fitting of wing tags to some regularly tagged species but does not include fitting of harnesses to any species.

Harness use

- The SMTP provides details of design and fitting procedure for well-proven harness types; any deviation from these guidelines must be approved in advance by SMTP
- All new applicants (including those who have previously worked with different species/ harness designs) must receive field training from experienced harness users.
- Details of the person who fitted each harness, harness size and the body size of the bird must be submitted to SMTP for every individual tagged to provide an audit trail.
- For newer harness designs or rarely marked species, the SMTP may require a control group to be established.
- The capture data for every tagged bird are submitted to the BTO Ringing Scheme as per standard Ringing Scheme protocol and records of all birds reported injured or dead must be reported to the SMTP whether or not there is evidence that the harness may have been a causal factor.

Patagial wing tags

- Applications for tagging endorsements are only approved for those species where there is no indication that the tag will interfere with flight or foraging, and where identification in flight is essential to the project.
- The SMTP provides details of the fitting procedure and specification of tags and all materials involved; any deviation from these guidelines must be approved in advance by the SMTP.
- All new applicants (including those who have previously worked with different species) must receive field training from experienced tag fitters.
- Observations from the fieldworker and members of the public are submitted to the BTO Ringing Scheme as per standard Ringing Scheme protocol. Records of any issues encountered are submitted to the BTO Ringing Scheme and passed to the SMTP for consideration.

17 March 2017

Jez Blackburn, BTO Licensing Officer
Dave Leech, Head of BTO Ringing and Nest Record Team

www.snh.gov.uk

ISBN: 978-1-78391-455-5

Policy and Advice Directorate, Great Glen House,
Leachkin Road, Inverness IV3 8NW
T: 01463 725000

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