

South African Country Study on Climate Change

**Plant Biodiversity:
Vulnerability and Adaptation Assessment**

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Summary

This report attempts to predict how plant biodiversity in South Africa will be affected, given climate change scenarios generated by three general circulation models. A combination of approaches is used, based primarily on bioclimatic modeling techniques, to provide spatially explicit predictions of the future distributions of South African biomes and selected key plant species, and to quantify and assess threats to current centres of plant endemism and nature reserve areas. These approaches rest heavily on the availability of extensive geospatial databases.

Under the scenarios postulated, it appears that a number of key generalizations can be made with regard to future patterns of plant distribution and diversity. Firstly, the bioclimate of the country shows warming and aridification trends which are sufficient to shrink the area amenable to the country's biomes to between 38 and 55% of their current combined areal coverage. The largest losses occur in the western, central and northern parts of the country. These include the virtual complete loss or displacement of the existing Succulent Karoo Biome along the west coast and interior coastal plain, an extensive eastward shift of the Nama-karoo Biome across the interior plateau, and contraction of the Savanna Biome on the northern borders of the country, and its expansion into the Grassland Biome. The species rich Fynbos Biome does not suffer extensive loss of areal cover but may nevertheless lose many species. Analyses of species range shifts concur generally with these biome-level patterns, with the majority of 44 species analysed showing reduced range sizes. However, the species level analysis also indicates that species composition is likely to change in all biomes and even areas apparently "vacated" by biomes should continue to support a noticeably impoverished species mix. The change in species composition will also lead to major vegetation structural changes in some biomes, notably in the Grassland Biome where virtually the entire existing biome will be susceptible to a potentially large number of invading savanna tree species. The majority of the 16 centres of endemism studied also show significant deterioration of bioclimate, with more than half predicted to experience bioclimatic conditions completely unlike those of today. Nature reserves of the arid west and central parts of the country also experience a complete alteration of bioclimate, while those of the eastern and highland regions are better buffered.

We propose seven possible adaptation strategies. These include: the establishment of a biodiversity monitoring network, the application of sound vegetation

management policies, the wise use and possible expansion of the protected area networks, focused attempts at ex-situ conservation, the refinement of national contributions to global greenhouse gas emission policy, future possible plant translocation action, and finally, tolerating loss, a mechanism for assessing the value of biodiversity elements to assess their relative importance in the event of unavoidable sacrifices.

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Introduction

The South African Country Study is one of the first of its kind to address the issue of biodiversity responses to climate change explicitly. This issue is an enormous challenge botanically because the subcontinent contains an extremely diverse flora distributed in ecologically distinct biomes. South Africa includes one of the world's six floral kingdoms (the Cape region) entirely within its boundaries and also includes almost all of the succulent Karoo, the richest arid flora on earth. Biodiversity is important for South Africa because of its importance in maintaining ecosystem function, the proven economic value of South Africa's biodiversity resources, and its role in supporting subsistence lifestyles. Aspects of ecosystem health such as sustained primary production, soil retention, and water yield and water quality, are likely to be closely linked with ecosystem biodiversity in general, and plant diversity in particular.

In general, plant richness in South Africa may be correlated with climatic variables and environmental variability at both regional (Cowling *et al.* 1997) and local scales e.g. Cowling *et al.* (1994). Thus changing climate could have direct impacts on plant diversity in the country (Midgley & O'Callaghan 1993). Plant species densities are spatially variable across South Africa, and characterized by extraordinarily rich "hotspots" or centres of endemism (Cowling *et al.* 1994). Significant climate change in any of these hotspots has the potential to cause the loss of large numbers of species. Biomes defined on the basis of plant life form dominance are climatically distinct (Rutherford 1997), and major ecotones (e.g. karoo-grassland [Hoffman & Cowling 1990]) fluctuate in life form dominance according to climatic oscillations. These observed and documented patterns underscore the pivotal role of climate in determining the composition of South Africa's flora. However, the role of disturbance through fire and grazing is acknowledged to override or interact with climate control of vegetation in certain parts of the country. In these areas, changes to disturbance patterns have the potential to cause rapid vegetation changes (this provides cause for concern, but also may serve as a lever for effective management if disturbance effects are correctly interpreted and understood). It is also important to note that the ability of plants to alter their geographic distribution in response to changing climatic controls is constrained by their possible requirements for specific soil types (which are not related to climatic patterns), and by radical transformation of land by humans.

There is very little proven theory that relates biodiversity to climate, and so there is little recourse to developing a research approach to this issue based on first principles. This is in sharp contrast to predictions in the field of many agricultural crop species, for example, which are underpinned by extensive physiological knowledge, and prior knowledge of the crop geographical distribution. There are more than 20 000 natural plant species compared with less than 200 crop species. Their distributions are generally inadequately known, and detailed physiological and life history knowledge is lacking. Furthermore, predictions are complicated by potentially important interactions between plant species in nature, between plant and animal species, and by naturally occurring disturbances such as fires. Any predictions of biodiversity change are subject to high levels of uncertainty, and must be viewed with healthy skepticism. In past analyses of effects of climate change on the South African ecosystems (e.g. Hulme 1996, Shackleton *et al.* 1996) direct effects of climate change on species diversity have not been addressed (but see Graves & Reavey 1996).

Our approach has been pragmatic and empirical in the main, but at the same time we have attempted to develop new tools which may be improved into the future as the need for more precise estimates increases.

Awareness of climate change issues among interested and affected parties

In order to gauge the opinions of interested and affected parties to the issues surrounding climate change and biodiversity, a workshop was held (South African Association of Botanists Annual Research Meeting, University of Cape Town, January 1998). Following this, questionnaires were sent to 140 persons involved in research and management of natural systems, yielding over 40 replies.

Forty four percent of respondents judged that climate change would impact significantly on biodiversity and vegetation within 30 years and a further 27% felt that impacts would be seen within 50 years. Seventy seven percent felt that climate change would affect their work in the future, but only 35% acknowledged that climate change was explicitly included as a planning issue by their employing organization, and only 30% were aware of analyses of climate change as a threat. However, climate change was rated (on a par with pollution) as a less significant threat to biodiversity than land conversion and land over-utilization, respectively.

In terms of prediction requirements of specific threats, respondents rated rainfall variability and disturbance regime changes as most important (unfortunately, predictions of these are not provided by current modelling efforts). Changes in aridity, human population density and fire frequencies were rated as of intermediate importance. Least important ratings were assigned to changes related to minimum temperature predictions, such as frost occurrence and changes in the grassland/savanna biome boundary and the grass/tree balance in savannas.

These opinions reveal an apparent lack of preparedness of many organisations relative to climate change. There is a surprising lack of concern over temperature change *per se*. The obvious and appropriate focus on land-use change will necessarily overshadow attempts to raise the profile of climate change as a threat, but this needs to be done to ensure adequate preparation by the custodians of biodiversity. This would be facilitated by an integrated assessment of the relative impacts of climate and land-use change on biodiversity, and their probable interactions.

Paleobiogeographic patterns in Succulent Karoo and Fynbos biomes

It is useful to explore vegetation change in the past to gauge the potential impact of climate change in the future, and the adequacy of models for prediction. Climate changes during the late Pleistocene and Holocene reveal (albeit incompletely) the results of a “natural experiment” in global warming which has taken place on a grand scale. We attempted bioclimatic reconstruction of past distributions of Succulent Karoo and Fynbos biomes because these biomes are unique to South Africa, they are spatially constrained to the unique winter rainfall region, and they contain extraordinary levels of biodiversity in a global context. In different parts of the world, reconstructions of past vegetation have mainly been done by directly investigating the paleobotanical record at key sites. However powerful though, paleobotanical studies suffer from being point-based subsamples of local floras. We developed models to predict possible distribution of biomes under past climates and then tested these predictions against available paleobotanical and biogeographic evidence.

Paleobioclimatic modeling is particularly challenging because general circulation models (GCM's) provide paleoclimatic data that is limited in scope and spatial resolution. This demands that the development of climatic envelopes for the modelled vegetation entities be based on quite rudimentary parameters, such as mean annual rainfall, mean annual temperature and potential evapotranspiration. Our analysis was therefore

constrained to only temperature- and rainfall-based climate criteria. These were minimum temperature of the coldest month (T_{\min}) mean annual rainfall (MAR) and a water balance estimate (WB) given by the difference between MAR and an estimate of potential evaporation (PE) [13], such that $WB = (MAR - PE)$. We determined iteratively the values of the most significant envelope limitant (which was WB), so that the error between mapped vegetation distribution and modelled distribution was minimised, and the current distribution of the two biomes did not overlap.

Our results show that at the last glacial maximum (LGM), the Fynbos bioclimatic envelope (FYE) possibly had a considerably greater extent along the west coast and the western interior, replacing much of the Succulent Karoo bioclimatic envelope (SKE). At 18 kBP SKE was limited to two separate areas, an extensive plain, the Knersvlakte (South) and montane Richtersveld (North). The biome expanded as climates warmed between 12 and 6 kBP to reach its present range, and Fynbos (including renosterveld shrublands) contracted into its current montane distribution. These reconstructions were tested against available palynological records for the period and found to agree with the record of indicator groups of both biomes, and with current patterns of relictual Fynbos vegetation, and with Succulent Karoo centres of endemism.

We suggest that in the western and southern Cape, climatic oscillations of intermediate amplitude over at least the past 1.5 million years have caused biome and component plant species distributions to shift, and probably fragment during contraction phases, favouring both sympatric and allopatric speciation. Subsequent expansion may also have increased the likelihood of secondary contact, favouring hybridisation and associated speciation. The existence of landscape-scale refugia has been critical in allowing species richness to be retained during phases of retreat. The apparent fit between our model predictions and the observed paleobotanical and biogeographic record lends some confidence to the methods we have used to predict climate impacts on vegetation, at least for these western biomes. These results suggest that southern Africa plant biodiversity as a whole may not have been widely decimated in the long term by past climatic changes. However, it is important to note that future predicted climate changes threaten to increase temperature above the maximum level experienced for at least the past 1.5 to 2.5 million years.

Bioclimatic changes

Predictions utilise climate scenarios generated by CSM and HadCM2 with and without sulphates. The Genesis Model was not included since it is an older generation model which does not incorporate a fully dynamical ocean model (Hewitson 1999).

We used five relatively independent climatically-derived parameters we consider critical to plant physiological function and survival. These are mean minimum temperature of the coldest month (Tmin), heat units (annual sum of daily temperatures ($^{\circ}\text{C}$) exceeding 18°C [HU₁₈]), Annual Potential Evaporation (PE), Winter soil moisture days (SMDwin), and Summer soil moisture days (SMDsum). Climate envelopes were defined by the upper and lower limits of each parameter. While there is little experimental work to rely on locally, we consider these limits as the minimum basic set for defining a bioclimatic envelope in South Africa's indigenous flora. Tmin is likely to discriminate between species based on their ability to assimilate soil water and nutrients, and continue cell division, differentiation and tissue growth at low temperatures (lower limit), and chilling requirement for processes such as bud break and seed germination (upper limit). Heat units discriminate between species based both on their requirement for a minimum temperature to complete growing cycles (lower limit), and ability to tolerate excess tissue temperature (upper limit). PE discriminates through processes related to transpiration-driven water flow through the plant, and xylem vulnerability to cavitation and water transport efficiency. Soil moisture days in winter and summer discriminate through determining the intensity and duration of seasonal drought stress and growing opportunities, which are especially crucial for seedling recruitment and the survival of this sensitive plant life stage.

In summary the main trends of the three climate change scenarios are as follows. Tmin increases by at least 2°C ($>3^{\circ}\text{C}$ in one scenario) in the northern part of the Northern Cape Province, western North West Province and northern parts of the Northern Province. Smallest increases ($< 1.2^{\circ}\text{C}$) tend to occur at spots along the coast. The areal extent of the frost prone region in centre of the country shows a major reduction. Heat units range from little change on high mountain tops to $>20\%$ in the northern parts of the country, especially the north-eastern part of the Northern Province. Largest areas of increases (at least 550mm) in PE occur in the north-central parts of the Northern Cape Province with lowest increases in KwaZulu Natal and Eastern Cape Provinces and/or southern parts of the Western Cape Province, depending on scenario. Large decreases

in SMDwin are predicted in the winter rainfall area of Namaqualand and lesser decreases in part of the lowlands of the Western Cape Province. The range of values of SMDsum broadens marginally. Significant decreases occur in the western interior part of the country.

Potential biome movements

South Africa has five spatially dominant biomes, namely Fynbos, Succulent Karoo, Nama-karoo, Grassland and Savanna, with two biomes of small geographic extent, the Desert and Forest (Figure 1). Fynbos and Succulent Karoo are unique biomes worldwide, and both are noted for their extraordinary levels of richness and endemism. The Grassland biome is unique to Africa, and contains many endemic species, although not traditionally recognised as a centre of endemism. Nama-karoo is found in South Africa, Namibia and Botswana, and has a low level of plant biodiversity and endemism, but does extend into three centres of endemism associated with surrounding biomes. Savanna is the biome most typical of Africa, and is the biome least unique to South Africa.

The dominant five biomes (Rutherford & Westfall 1994; Rutherford 1997) were successfully delineated in South Africa using the five selected bioclimatic parameters. This approach is equivalent to modeling a theoretical species which covers the full extent of a given biome but enters no other biome. Relatively few endemics behave in this way. This never-the-less useful first approximation should be seen in the context of the following section which shows that many species within a given biome are not likely to respond equally to climate change.

The three climate scenarios generated comparable predictions for biome spatial shifts (Figure 1). The area covered by bioclimatic envelopes reduces from 100% of the country for the present day to between 38% and 55% of the country for the three future scenarios. This implies that about half of South Africa's land surface area may experience a novel, and far warmer and drier bioclimate into the future. The biomes retreat onto highland areas of the southern Cape fold mountains and the central plateau and Drakensberg highlands, and the southern coastal plain. The west coast, central Bushmanland and Nama-karoo region, and northern and north-eastern borders all show biome retreat. It must be stressed that Savanna and Nama-karoo biomes currently occur in warmer and drier regions north of South Africa's border, which would imply that elements typical of these biomes but currently found north of the Limpopo and Orange

Rivers would have an opportunity to move southward into this country. However, the new existence of a desert-like environment in the western and central part of the country seems likely into the future.

The most disconcerting result is for the unique and immensely species-rich Succulent Karoo biome, which disappears almost completely from its current range on the western coastal and inland plain, with a relocation to the southern Cape (highly unlikely given the need to cross the Cape Fold mountains and many disturbed and transformed landscapes with different geologies and soil types). This change alone threatens to eliminate a sizable portion of South Africa's succulent plant diversity in a single swoop. Elements of the small extension of Succulent Karoo into Namibia may, as described for the possible southward movement of Nama-karoo and Savanna elements, replace some elements eliminated in the Succulent Karoo. However, many of these potential immigrant species are highly localized endemics with probably very poor migratory ability.

The Nama-karoo also shows a dramatic retreat from its current occupation of the central interior plateau, to a much restricted region in the eastern Cape, where it replaces part of the Grassland biome.

The Savanna biome is predicted to encroach onto the Grassland biome along almost all borders of the latter, reducing its extent considerably. This change, in conjunction with the human stresses on the Grassland biome, result in its virtual confinement to high altitude refugia in the Drakensberg range. Savanna itself retreats from the northern and eastern border of the country, again suggesting the opening of opportunities for incursion of more arid- and/or heat-adapted elements from across our borders.

Although the species-rich Fynbos biome is the sole biome that retains much of its current extent, due to the buffering afforded by steep and extended altitudinal gradients, a significant portion of its species may be lost (see section on centres of endemism).

Potential species movements

We determined the formal bioclimatic envelopes of 44 plant species in detail (after initially screening a much larger set for representative response types), using the bioclimatic parameters listed and essentially following the approach discussed in Rutherford *et al* (1995) and Rutherford *et al* (1996). All available databases and other

sources were used. The ACKDAT database, the PRECIS database and taxonomic accounts and revisions were used for determining distributions and the CCWR databases, databases at the School of Bioresources Engineering and Environmental Hydrology and the CRES database (the last mentioned was used only north of South Africa and after scaling using regression with South African data) for environmental data. The absolute environmental limit values were used, that is, without any truncation of the environmental envelope. More than half the species listed in Table 1 had an estimated bioclimatic fit of greater or equal to 85%. Our choice of species was guided by needs (sometimes conflicting) to include species that are representative of the biomes of South Africa (both endemic to South Africa and occurring naturally across our borders) and representative of bioclimatic response types, to include at least a group of species recognisable to the lay public and to land managers as “important” or “useful”, and to cover a range of dominant growth forms of plants (such as grasses, shrubs, trees, succulents). We also explored the responses of some species currently occurring naturally within 100km of the South African border but not in South Africa. There were important practical issues governing the selection process such as inadequate species distribution data, exclusion of rare species with limited distributions (and thus inadequate confidence in the derived bioclimatic envelopes), or a clear inability to match species distributions with bioclimatic regions (see Section on Caveats and mitigating factors).

We did not include results for alien invasive species that originated from other continents but recognise the very important negative effect that these plants can have on South African biodiversity. It is difficult to determine which of the many invasive species have reached equilibrium with current environment. Their apparent climatic envelopes derived locally need to be checked against those derived within their continent of origin. An analysis by Richardson et al (in press) using an earlier scenario of climate change in South Africa, does indicate sometimes significant geographical shifts in a number of alien invasive species in South Africa.

Savanna

Our analysis indicates that there may be a major rearrangement of plant species in the area of the current Savanna Biome. Several woody plant species, such as *Bolusanthus speciosus* (Figure 2) and *Combretum apiculatum* are indicated to greatly reduce their current range in the Northern Province. Some species, such as *Sesamnothamnus lugardii* of the Limpopo lowveld basin, are likely to disappear or nearly

disappear from South Africa (Figure 3) although species like this example with especially long-lived adults may persist beyond the point of doubling of CO₂, but lack recruitment. Viable populations of some species such as *Colophospermum mopane* should, for the most part, persist in these lowveld areas. Many species currently limited to the lowveld areas may move into newly suitable climate areas of the higher altitude savannas of the middleveld (e.g. *Bolusanthus speciosus* (Figure 2) and *C. mopane* (Figure 4). *C. mopane* may also invade the Mpumalanga lowveld areas. In fact, the worst case scenario (HadCM2 – without sulphates) indicates that most of the southern half of the Kruger National Park may be invaded by this species (Figure 4) which may, in turn, create a major challenge for maintaining the currently high levels of larger mammal diversity in this area (see Adaptation Strategies Section below). Another possible source of novel additions to the changing biodiversity mix in the area of the current Savanna Biome, is that from north of South Africa's borders. For example, one of the dominant Miombo tree species of south-central Africa (*Brachystegia spiciformis*), which occurs about 100km outside our borders, could potentially find newly suitable climate areas for establishment in South Africa, especially along the higher rainfall interface areas between the Savanna and Grassland Biomes in the north-east (Figure 5). However, dispersal of this particular species across the greater Limpopo valley gap would be most unlikely to occur unassisted.

Grassland

Many shrub and tree species are predicted to potentially invade the current and even the apparent reduced area of the Grassland Biome in the future (see Section on Biome changes above). From the north and east, these include *Aloe marlothii* (Figure 6) and *Erythrina lysistemon* (Figure 7) as well as species like *C. apiculatum* which, with their capacity to dominate some savanna communities, could result in the transformation of most of the area of the Grassland Biome to savanna structural types. There are also woody species, including *Grewia flava*, from the arid savannas further west that are indicated to invade deep into the current Grassland Biome. The rate at which such species may be able to colonize the Grassland Biome, as elsewhere, depends on a large number of factors (see Section on Caveats and mitigating factors). However, the Grassland Biome is one of the most radically transformed biomes in South Africa and the presumed resultant lower permeability of the landscape to plant migration may restrict rates of colonization by some species, for example, *A. marlothii* (Figure 8). Almost

certain additional future changes in land transformation are likely to exacerbate such effects. In contrast to the foregoing, some woody plant species which already extend into several parts of the Grassland Biome are not indicated to greatly expand within this Biome (for example, *Protea caffra* – Figure 9). Some other woody plants associated with the Grassland Biome, for example *Leucosidea sericea*, show considerable areal contraction but very little areal gain with movement to higher altitudes. The scenarios used also indicate potential changes in herbaceous plant species composition of the current area of the Grassland Biome. While species with wide climatic tolerances such as the important grass, *Themeda triandra*, are expected to persist in the area, cold-adapted grasses such as *Catalepis gracilis* are likely to have their ranges greatly reduced (Figure 10). Various grass species might also invade further into the area of the current Grassland Biome, for example, *Aristida meridionalis*, from the west.

Succulent Karoo

The potentially serious effects of climate change on the Succulent Karoo Biome are supported by analyses of individual species. The existing areal extent of common species such as the shrub *Didelta spinosa* and the common grass species, *Cladoraphis cyperoides*, of the coastal belt, may be drastically reduced (Figures 11 and 12). Many of these more widely spread species that occur in the Succulent Karoo Biome may best survive in areas where they currently extend into the Fynbos Biome (for example, the succulent *Tylecodon paniculatus* and above-mentioned *C. cyperoides* – Figure 12). The current area of the Fynbos Biome may also offer limited opportunities for colonization by some of these species. However, some other common species may persist in the current area of the Succulent Karoo Biome, at least for the best-case CSM scenario. This scenario indicates that weedy species such as the leaf-succulent *Augea capensis* should persist in most of the area of the current Biome although even this species may not survive in the Knersvlakte and Tanqua Karoo (Figure 13). Other species of the biome may suffer significant reduction in Namaqualand but, in contrast to both Hadley scenarios, may survive in areas of higher altitude in this region (for example, *T. paniculatus*), according to the CSM scenario. The rich assemblage of species with narrower tolerance limits in the Succulent Karoo Biome may be expected to be more adversely affected by climate change than the group of generalists (see Section on Centres of Endemism).

Nama-karoo

Species compositional changes indicated for the Nama-karoo Biome include a withdrawal from the north west of typical shrub species as *Rhigozum trichotomum* and *Pentzia incana* (Figure 14) and its only partial replacement by weedy generalist such as *A. capensis* (Figure 13). The projected areal loss in the west is considerably greater than potential extension area to the east for many species characteristic of this biome. In the area of gradual transition from Nama-karoo to Savanna in and around the southern Kalahari region, some species are potentially severely affected. For example, the current distribution area of the tree species, *Parkinsonia africana*, and the grass species, *Stipagrostis amabilis*, may become almost totally unsuitable and the projected area of potential future suitability is mostly disjunct from their existing area (Figures 15 and 16). Not only might this require highly fortuitous dispersal but a species such *S. amabilis* that is largely limited to sand dune formations may be forced out into areas that are climatically suitable but that largely lack the appropriate substrate. As with the Succulent Karoo Biome, the Nama-karoo Biome may, at first view, be likely to experience a net species loss. However, in theory, a number of non-South African species from southern Namibia and the Namib Desert might be able to establish in these biomes in terms of suitable climate. One such species is the succulent *Crassula ausensis*, which occurs about 100km across the South African border in Namibia. However, in this case, only the CSM scenario may indicate suitability of the southern Kalahari in future (Figure 17) and the sandy soils of much of the area may be unsuitable for this species which is associated with rocky conditions. It appears that a best estimate for the future of arid biomes of South Africa is a net loss of species and a pronounced increase in area of true desert biome.

Fynbos and Forest

The distribution of widespread species of the Fynbos Biome contract along the northern edge, but persist along parts of the mountain chains and the southern coastal plateau (for example, *Protea repens* – Figure 18). Species, such as *Olea exasperata*, that are concentrated along the coast of the Fynbos Biome persist, except at their western and eastern extremities. *Euclea racemosa* is predicted to have a similar fate but with significant range contraction up the west coast with climate change. The combination of altitudinal variation and some areas of less extreme climatic change than that predicted for many other parts of the country, should raise the probability of survival

of at least some other common fynbos species. Many other species are likely to be stripped from the floral kingdom - see Section on Centres of Endemism. Species of the Forest Biome and of the many forest patches to the north-east, for example *Ocotea bullata*, may behave like some widespread fynbos elements with much reduced areal extent but well distributed survival patches. However, future conditions may exclude more forest species on the Northern Province and Mpumalanga escarpments.

Compatibility of bioclimatic analyses

Species level bioclimatic analyses are a refinement of the biome level approach, and do not produce results entirely congruent with that coarser analysis. The species-level analysis is a necessary effort which provides a richer and more realistic picture of projected changes. Although the number of species formally analyzed is small, we believe that they represent many more species' responses to climate change. The species level results confirm the expected major adverse impact of climate change on the Succulent Karoo Biome. However, they also indicate that that some form of highly impoverished flora is likely to persist or take its place, possibly supplemented with species from the current Desert Biome. The most severely affected parts of the Succulent Karoo and Nama-karoo Biomes may be converted to Desert Biome. The species level results also indicate that almost the entire current Grassland Biome may be invaded by tree species and thus form part of an expanded Savanna Biome.

Centres of endemism

We analysed the effect of climate change on the distribution of bioclimatic envelopes which currently characterise 16 centres of endemism identified in South Africa. These comprised the 15 centres of endemism recognised by van Wyk & Smith (*in press*) as well as their Cape Floristic Region (corresponding approximately to the Fynbos Biome) which they rank at a higher level. Using this technique, we were able to derive an estimate of the proportion of these areas of centres of endemism that would remain within their bioclimatic limits. Some, but not all, centres are also associated with high floristic richness. The high floristic richness of some major ecotonal zones needs further research.

Results show that few centres of endemism retain even as much as 40% of their area within the current bioclimatic envelope (Table 2). Between 45% and 75% of these centres experience a completely novel bioclimate into the future, depending on climate

scenario used, with the HadCM2 (without sulphate) scenario showing the most negative changes. The Knersvlakte Centre is worst affected in all three scenarios. This centre is situated within the Succulent Karoo Biome and contains at least 150 species/infraspecific endemic taxa out of a total of approximately 1000 (van Wyk and Smith, *in press*). The Centre is particularly rich in dwarf succulents with at least seven succulent genera endemic or near-endemic. The two centres of endemism least affected in all three scenarios and which contain highest number of estimated endemic species/infraspecific taxa are the "Cape Floristic Region" Centre (at least 5600 out of about 8000) and the Drakensberg Alpine Centre (at least 400 out of about 2200, [van Wyk and Smith, *in press*]). Possible consequences of climate change in the Cape Floristic Region have been broadly discussed when dealing with the Fynbos Biome in previous sections. The Fynbos Biome is very rich in species so that any change in its boundaries is likely to cause substantial loss. For example, the Biome's northern arm is particularly threatened by climate change and contains many unique species. Detailed analysis of the possible consequences of climate changes on the endemics of this Centre (region) requires intensive individual study of their biology and development of appropriate methods. The high proportion of non-resprouters and species sensitive to changes in the fire regime (Bond, 1997) and mutualist collapse (Bond, 1995) could lead to many extinctions with climate change. The Drakensberg Alpine Centre contains at least five genera largely confined to the region. One of the best known endemic succulent species of the Drakensberg Alpine Centre is *Aloe polyphylla* (the national floral emblem of Lesotho) which amply illustrates the point that climate change should be seen in the context of other significant changes. Although this species occurs in an area that is possibly relatively better buffered against climate change, it is severely threatened in its natural habitat by collectors (van Wyk and Smith, *in press*).

Nature Reserves

We assessed the threat of climate change to plant biodiversity in 5 key nature reserves representing a range of situations in South Africa. These included arid and semi-arid situations on flat terrain in the West (Augrabies National Park, Kalahari Gemsbok National park) and in the East (Kruger National Park), and more mesic situations on more topographically diverse terrain in the East (Addo Elephant Park, Giant's Castle). We analysed the range of bioclimatic parameters currently found in these reserves in relation to the range expected under the three climate change

scenarios, in order to identify bioclimatic changes significant enough to introduce a novel bioclimate over the entire reserve area (see Figure 19 a to e). We also analysed how the proposed geographic extensions to Addo Elephant Park might increase bioclimatic buffering.

These results show how the western arid reserves on flat terrain (Augrabies and Kalahari Gemsbok National Parks) suffer completely novel, and more stressful, levels of all five bioclimatic parameters under all scenarios (the only exception is for Kalahari Gemsbok Park's SMDwin, which does not change [HadCM2 with sulphates, CSM without sulphates], or shifts upwards [HadCM2 without sulphates], Figure 19e). Species level projections using an earlier climate change scenario, generally support the anticipated adverse outcome for these arid national parks (Rutherford *et al.*, *in press*). The Kruger National Park and Addo Elephant Park show intermediate shifts, which allow parameters in the future to overlap with the range experienced currently. The most topographically diverse park, Giant's Castle, shows the smallest bioclimatic shift, illustrating the buffering effect of mountainous terrain. The proposed extensions to Addo Elephant Park have the effect of widening bioclimatic ranges in the future (by reducing the lower and increasing the upper levels), which provides a degree of buffering against climate change.

Caveats and mitigating factors

Uncertainties

This kind of study is subject to a string of uncertainties at various levels. Firstly, emissions scenarios cover a wide range of possibilities subject to political and economic decisions that are inherently unpredictable. These scenarios provide input for climate change predictions, which themselves may be far from achieving appreciable levels of certainty, especially at fine spatial resolution. However, it is important to note that all three climate change scenarios we have used here tend to predict similar outcomes at both broad biome level, and often at species level. Furthermore, our paleobioclimatic reconstruction using global climate models also produces results that concur broadly with the patterns of vegetation change recorded in the paleobiological record. This indicates that emissions scenarios are a more important source of uncertainty, as the climate models are refined and are now converging on similar predictions.

At the level of bioclimatic modelling, a plethora of uncertainties and caveats emerges. The accuracy of species environmental limits deduced from incomplete records (and occasionally erroneous records) is, naturally, often reduced. Inadequately modeled spatial climatic parameters, for example, north of South Africa and especially for areas of the data-poor Namib Desert and its interior belt also reduce accuracy of some environmental envelopes. Local-scale azonal habitats can potentially skew results although the effect is often self-corrected by the bioclimatic approach used. In some cases, poor fits between modeled and actual distributions (Table 1) suggest that other critical environmental factors, for example, soils, need to be included. Soils data at a sufficiently detailed spatial level were not available to the project. It is possible that spuriously modeled outliers (for example, Figure 4) may, in fact, represent currently suitable climatic areas that are too isolated for a species to have reached. The dispersal of plants to such climatic outliers, let alone the potential effects of climate change on dispersal agents is decidedly under-researched. There are also several instances of uncertainty regarding the taxonomic status of a taxon especially where closely related species appear to occupy vicariant-type distributions. Other drawbacks include the likelihood that not all species are equally limited by the same set of climatic parameters. It should also be noted that in this study, relative abundance of species was not taken into account, only their presence or absence. Much experimental work is needed to test the assumed climatic limits of species. Particularly important is the effect of climate on different life-stages of a species. We suspect that the establishment phase is likely to be most critical.

Two other important assumptions are made. Existing vegetation is assumed to be in equilibrium with current climate which clearly needs to be tested. Secondly, plant species are assumed to be limited by climate. We know this is not so for the species which have been intensively studied. Many other factors, especially competition also limit species range at a variety of scales. The realized niche is often smaller than a species fundamental niche. Ideally, simple species bioclimatic modeling should work best with weedy species that establish on vacant, disturbed areas in which competition is minimized. Certainly, not all species are equally amenable to bioclimatic analysis and rare localized species are likely to be least amenable although other non-climatic environmental variables can be incorporated, where available. It is also important to note that the magnitude of the climate change predicted is unprecedented.

Finally, the projected effects of climate change on plants need to be integrated with the parallel effects of expected changes in land-use and other disturbances (for example fire frequency) and the possible changes in pollinators, vectors, predators, grazers/browsers, diseases, pathogens and soil properties.

Elevated CO₂

Rising atmospheric CO₂ tends to increase the efficiency with which plants use water, light and nitrogen resources (Drake *et al.* 1997). Although it is commonly asserted that these effects are evident in C₃ and not C₄ plants, it has been shown that C₄ plants may also benefit from this CO₂ stimulation (Wand *et al.* 1999). Research on these effects in South Africa and other tropical and subtropical regions is in its infancy, and most results world-wide are for crop plants. Very few studies exist on the potential effect of rising CO₂ on biodiversity, and so we present here only the major potential impact of this factor, using theory we have developed (Midgley *et al.* 1999, Bond & Midgley *submitted*).

The direct effects of elevated CO₂ on plant function may provide an important stimulus to the success of woody plants (especially trees) relative to non-woody plants (especially grasses) in situations where they grow together. Our analysis suggests two mechanisms by which this could happen, leading to a tendency for woody plants to invade and replace grassland.

The first is based on the observation that tree saplings resprouting after fire, may have atmospheric CO₂-limited rates of carbohydrate accumulation and storage. This probably retards the rate at which their resprouts can escape topkill in the flame zone, fuelled by grasses. Elevated CO₂ will probably increase the rate of carbohydrate accumulation and storage in resprouting tree saplings, thus allowing them accelerated escape rates. This interaction between tree resprout vigour and disturbance regime may be the key, under current and historical CO₂ levels, to preventing tree dominance in moist savanna types.

The second mechanism is suggested by marked reductions in C₄ grass water use in elevated CO₂ (Wand *et al.* 1999), which have been shown in several African grass species of diverse C₄ subtypes (NAD, NAD-Me and NADP-Me [Wand & Midgley, unpublished data]). Observed reductions of up to 45% in transpiration rate at the leaf level under conditions of doubled atmospheric CO₂ translate to significant canopy-level water use reductions. This will increase absolute water infiltration below grass canopies,

and favor co-occurring growth forms such as trees, especially in more arid savanna types. Taken together, these two mechanisms suggest that rising atmospheric CO₂ will strongly favor tree success relative to grasses under a wide range of climatic conditions, and accelerate the process of tree invasion into grasslands regions, for example.

The likely impact of higher plant water and nitrogen use efficiency under elevated CO₂ will be to moderate potential effects of aridification. This will be effective, however, only where community leaf area index is sufficient to ensure that evapotranspiration is dominated by the plant, and not soil surface evaporation component. Thus in the arid and semi-arid west and central South Africa, elevated CO₂ may be relatively less effective in moderating the effects of increasing aridity.

UV-B radiation

Several broad generalizations can be made regarding potential UV-B impacts on South African vegetation (The results of detailed analyses are given in Musil *et al* 1999). For populations occupying arid ecosystems of the Desert, Nama-karoo and Succulent-Karoo biomes (22% of the 21 661 species of South Africa) negligible impacts on physiological processes are anticipated. The rationale is that UV-B resilient phenological and biochemical attributes are possessed by a large fraction of life forms occupying these arid regions, and the related physiological mechanisms of heat, drought and UV-B tolerance in plants. A possible exception is UV-B effects on seed exposed on the soil surface, which may cause heritable mutations in offspring (especially of annual plants) that may reduce fitness (Midgley *et al.* 1998, Musil & Wand [*in press*]). If this is a general phenomenon, UV-B stress will accelerate population reductions.

For populations occupying mesic areas of the Forest, Grassland and Savanna biomes, those tree or shrub species occupying the upper vegetation stratum are most likely to be sensitive to inhibition of growth and reproduction by elevated UV-B. Since the structure and composition of the outer canopy have a strong influence on the vegetation below, reported UV-B effects on leaf size and shape in forest tree species could conceivably affect light interception patterns with implications for forest composition and succession. This stress is a potential source of concern in the eastern region of South Africa where we have predicted bioclimates to remain relatively stable.

Adaptation strategies

This study indicates major changes in the arid west of South Africa and in the savanna areas in the north. In both areas, biodiversity is economically important for tourism and the natural vegetation is the main resource for livestock and game farming. We consider here 7 kinds of actions to reduce the threat of biodiversity losses (Table 3).

Biodiversity monitoring network

A primary requirement for assessing the degree and direction of climate change, and adequate adaptational response, will be an effective biodiversity monitoring system. This should be focussed in a network of areas that combine a high risk of climate change with current high biodiversity, and security of land tenure. A further recommendation would be the identification of a suite of sensitive indicator species to serve as flagship warning entities. Such species might be chosen to reveal the effects of change in different aspects of the physical environment, such as temperature sensitivity and drought sensitivity. The design of such a monitoring system would require expert input and creative lateral thinking in order to maximise the likelihood of early detection of threat. Monitoring might be site and individual-based, but might also rely on spatially extended techniques such as satellite imagery. This monitoring system could be productively linked with the proposed National Biodiversity Strategies and Action Programs (NBSAP), and the proposed development of a network of Long-term Ecological Research sites (LTERs) in South Africa, and form part of a periodic (possibly five-yearly) National Biodiversity Audit Program.

Vegetation management

In areas exposed to increasing aridity, the first sign of climate change is likely to be increasing severity of droughts and therefore more drought deaths of established plants. Years of better rains for successful recruitment of trees and shrubs are likely to become rarer in certain areas. To maintain the fabric of current vegetation, management will need to concentrate on the survival of existing plant cover because recruitment events will become rare. Current vegetation management has been based on the assumption that successional changes can be directed by adjusting herbivore numbers (livestock or game) and setting fire frequencies. Future management will need to be more opportunistic in taking advantage of rare good rainy seasons and managing extremely cautiously during, and immediately after, droughts. There has already been a shift to this form of management, especially in arid areas, over the last decade. The

greater extent of arid areas under future climates means that opportunistic, event-dependent management will have to be significantly improved to moderate climate change impacts.

In savanna regions, including the Kruger National Park, droughts are likely to become more frequent and our models predict the spread of more arid-adapted species, such as mopane. In practice, the invasion of such species depends greatly on patterns of fire and herbivore use. Park managers will have some latitude to control vegetation change in grasslands and savannas by intelligent manipulation of fire and herbivore numbers. To do so, implies clear policy objectives and improved understanding of the causes and consequences of vegetation change. Policy needs to identify preferred vegetation types and configurations, while the necessary knowledge needs to be developed to manage for these against a background of changing environmental conditions. If a laissez-faire approach is taken to global change, then the consequences for losses of flora and fauna must be recognized as, at the least, missed opportunities for a better future.

Protected area networks

Predicted changes in patterns of biodiversity provide indicators of how effective our current configuration of conservation areas will be under changing climates. Because of the many uncertainties in prediction, it would not be wise to despair of the future for areas that seem to be particularly threatened, nor can future centres of endemism be predicted with any degree of confidence. The best way of using future biodiversity scenarios to ensure adequate representation of the country's floral wealth would be:

- as strong motivation for retaining conservation areas which are predicted to show little change
- as motivation for extending protected areas to adjacent land with high topographic relief (and local climate refugia) to allow for future change.

As an example, the proposed Greater Addo Park in the eastern Cape not only makes sense in the current economic and conservation context but will also serve well for the future. Climate change scenarios are a strong additional motivation for adopting the current plan to extend the reserve.

An assessment of the current reserve network in relation to the identified major East/West axis of change is needed to identify current weaknesses, and prioritise areas

in which government acquisition of new land for reserves could be focussed. Alternatively, this analysis might identify those areas where necessary incentives, education and training might be given to land managers in order to strengthen the non-reserve maintenance of species richness. Reserve placement decisions should in future be cognisant of climate change. Criteria that maximise the buffering capacity of reserve areas must become a formal part of the reserve placement decision-making process. Policies relating to the placement of reserves in relation to each other (corridor creation) and habitat heterogeneity, for example, should be formally instituted.

In non-reserve areas, a major aim should be the prevention of further habitat fragmentation, and agricultural land-use policies should incorporate considerations of landscape fragmentation impacts on biodiversity.

***Ex-situ* conservation**

Ex-situ conservation, in seedbanks and the network of national botanical gardens, is already important in South Africa. It is likely to become even more important in the future. *Ex situ* methods comprise establishing viable populations in gardens and under controlled conditions, and gene banking. If such a solution were followed, considerations of genetic variation should motivate the collection and subsequent propagation of species. Particular effort will be needed to obtain representative material from the rich succulent flora and other threatened biodiversity hotspots. The succulent biome has already produced many species of high horticultural and economic value. Threats of excessive losses under future global change scenarios should provide strong additional motivation for collecting these species and developing their economic potential.

Global greenhouse gas emission policy

South Africa is a signatory to the global convention on climate change. It therefore has a voice in the international policy arena which sets limits to greenhouse gas emissions to help limit the magnitude of global change. Biodiversity considerations have not been a significant factor in setting greenhouse gas emissions. However, predicted biodiversity losses in South Africa are of national and international significance. They should be brought to the attention of the international community to provide additional motivation for policy measures to contain greenhouse gas emission and reduce the risk of global warming.

Direct intervention actions

For particular species, intensive rescue efforts might be warranted to the point where wild species are effectively "gardened". This kind of intervention is already occurring for a few highly threatened species, for example, the Cedarberg cedar.

Ultimately, because of limitations to plant dispersal abilities, both intrinsic to the plants, due to loss of dispersal agents and barriers posed by land conversion, it may be necessary to translocate threatened plant populations to mitigate the worst extinction effects of climate change. This kind of action is a radical intervention, and would need to take special cognisance of the biodiversity implications of introductions into the target area.

Tolerating loss

Given that it will probably be impossible to conserve all species in the face of climate change, a mechanism for prioritising intervention decisions will be crucial. We suggest the development of a cost-benefit analysis that takes into account such considerations as species ecological redundancy/equivalency, potential importance (e.g. keystone effects) and genetic variation and uniqueness. Such an analysis will require thorough testing and refinement, so we suggest it be developed and utilized in the process of reserve placement, and linked with the LTER and NBAP.

Finally, effective implementation of adaptation strategies requires information on expected rates of climate change. Despite differences between model predictions, it is clear that climate is already changing. The substantial projected future changes require that we start to seriously consider our adaptation strategies and the adequacy of our international environmental conventions.

Areas of research: recommendations

The South African research community is currently considering the development of a network of Long-term Ecological Research sites (LTERs). These will act as "ecological observatories" of change in ecosystems while also providing the necessary research base to understand and manage key ecological processes. The planned network of sites could provide the first nation-wide assessment of the real magnitude and rates of change predicted in this report, and could make a significant contribution to monitoring biodiversity changes into the future. We strongly endorse this initiative as a key step in preparing the nation for the future under global change.

Better understanding of the contingent effects of drought, fire and grazing on our ecosystems is a key research area to moderate and direct future effects of global change. South African research on drought impacts on ecosystems is still poor and fragmentary. Fire is, like drought, a key disturbance influencing vegetation. Research elsewhere has shown that the incidence of large severe fires is closely related to extreme hot dry weather conditions such as those during El Nino years. Such conditions will be more frequent in future climates and may have significant impacts on fire regimes and plant communities while also increasing risks to lives and property. There is an immediate need to analyse fire/climate/vegetation interactions for better fire management. Indeed the new Fire Act assumes that a reliable nation-wide fire risk system already exists. It does not. New research is needed on current and future fire/climate interactions, their impacts on management, and technical innovations to reduce fire hazard.

Frost limits on tree distribution have been widely discussed as a determinant of biogeographical patterns in the country, and confirmed here as a potential limiting factor for tree geographic ranges. However there has been almost no experimental study of the importance of frost in limiting tree distributions. This is an area deserving future work to predict the fate of highveld grasslands and to moderate possible effects of warming.

Increases in atmospheric CO₂ have direct, as well as indirect, impacts on plant growth. We have been unable to take direct effects into account in our biodiversity change predictions. Elevated CO₂ is likely to favour plants with carbon-rich growth forms, trees and shrubs, at the expense of plants such as grasses. This will tend to exacerbate the tendency of woody plants to invade grassy areas and thickets to replace savannas. The magnitude and rate of these effects, and ways to manage them, are important areas for future research.

Another effect of elevated CO₂ is a tendency for reduced water use for the same amount of biomass production. This will not only tend to moderate the effects of temperature increase, but could also lead to increased run-off from mountain catchments for equivalent rainfall. The magnitude of such effects, measured at a landscape scale, needs to be quantified to help guide water policy for the next few decades. The effects are likely to be greatest in grassland catchments, and decreased burning frequency might be needed to take maximum advantage of the potential effects.

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Figure captions

Figure 1 Current and future predicted distributions of the major South African biomes (Fynbos, Succulent Karoo, Nama-karoo, Savanna and Grassland), generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 2. Current and potential distribution of *Bolusanthus speciosus* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 3. Current and potential distribution of *Sesamothamnus lugardii* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 4. Current and potential distribution of *Colophospermum mopane* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 5. Current and potential distribution of *Brachystegia spiciformis* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 6. Current and potential distribution of *Aloe marlothii* subsp. *marlothii* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 7. Current and potential distribution of *Erythrina lysistemon* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 8 The effect of current levels of radical land transformation (urban areas, mining, ploughed lands and plantations but excluding degraded lands) on the potential future distribution of *Aloe marlothii* as predicted by HadCM32 without sulphates.

Figure 9. Current and potential distribution of *Protea caffra* subsp. *caffra* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 10. Current and potential distribution of *Catalepis gracilis* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 11. Current and potential distribution of *Didelta spinosa* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 12. Current and potential distribution of *Cladoraphis cyperoides* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 13. Current and potential distribution of *Augea capensis* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 14. Current and potential distribution of *Pentzia incana* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 15. Current and potential distribution of *Parkinsonia africana* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 16. Current and potential distribution of *Stipagrostis amabilis* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 17. Current (absence in South Africa) and potential distribution of *Crassula ausensis* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 18. Current and potential distribution of *Protea repens* according to three climate change scenarios and generated using simple bioclimatic modeling techniques based on five ecologically important bioclimatic parameters.

Figure 19. Current and future predicted means (filled circles) and ranges (error bars) of the five ecologically important bioclimatic parameters used in this study, assessed in five key reserve areas in South Africa. The dotted lines represent the critical upper or lower value for the current situation, indicating the level above or below which a completely novel bioclimate is introduced (a – Minimum temperature of the coldest month, b – Heat units, c – Potential evaporation, d – Soil moisture days in winter, e – soil moisture days in summer. All parameters defined in text).

Table 1 Forty four species used in an analysis of possible geographic range shifts under three climate change scenarios, within South Africa. Where the range of predictions for any given scenario bracketed zero with a wide margin of error due to a loose bioclimatic fit, the result is stated as “uncertain”. The symbol – indicates a significant reduction in range, + implies the opposite, and 0 implies no net change in range size. More than half the species listed had an estimated bioclimatic fit of greater or equal to 85%.

Taxon name	Net change HadCM2 (– sulphates)	Net change HadCM2 (+ sulphates)	Net change CSM (– sulphates)
<i>Acacia caffra</i>	Uncertain	–	–
<i>Acacia erioloba</i>	Uncertain	Uncertain	Uncertain
<i>Aloe dichotoma</i>	–	Uncertain	Uncertain
<i>Aloe ferox</i>	–	Uncertain	
<i>Aloe marlothii</i> subsp. <i>marlothii</i>	+	+	–
<i>Aristida meridionalis</i>	Uncertain	Uncertain	Uncertain
<i>Augea capensis</i>	–	–	+
<i>Berchemia zeyheri</i>	–	–	–
<i>Bolusanthus speciosus</i>	+	0	–
<i>Brachypodium bolusii</i>	–	–	–
<i>Carissa bispinosa</i> subsp. <i>bispinosa</i>	–	Uncertain	Uncertain
<i>Catalepis gracilis</i>	–	–	–
<i>Chrysanthemoides monilifera</i> subsp. <i>canescens</i>	–	Uncertain	–
<i>Cladoraphis cyperoides</i>	–	–	–
<i>Colophospermum mopane</i>	+	+	+
<i>Combretum apiculatum</i> subsp. <i>apiculatum</i>	+	+	Uncertain
<i>Didelta spinosa</i>	–	–	–
<i>Elytropappus rhinocerotis</i>	–	–	–
<i>Erythrina lysistemon</i>	0	Uncertain	Uncertain
<i>Euclea racemosa</i>	–	–	–
<i>Galenia africana</i> var. <i>africana</i>	–	–	–
<i>Grewia flava</i>	–	–	–
<i>Grewia occidentalis</i>	–	–	–
<i>Leucosidea sericea</i>	–	–	–
<i>Metalasia muricata</i>	–	–	–
<i>Ocotea bullata</i>	–	–	–
<i>Olea exasperata</i>	–	–	–
<i>Opuntia ficus-indica</i>	–	–	–
<i>Parkinsonia africana</i>	–	–	–
<i>Pentzia incana</i>	–	–	–
<i>Portulacaria afra</i>	Uncertain	Uncertain	Uncertain
<i>Protea caffra</i> subsp. <i>caffra</i>	–	–	–
<i>Protea nitida</i>	–	–	–
<i>Protea repens</i>	–	–	–
<i>Rhigozum trichotomum</i>	–	–	–
<i>Salsola aphylla</i>	–	–	–
<i>Schotia brachypetala</i>	–	–	–
<i>Sesamothamnus lugardii</i>	–	–	–
<i>Stipagrostis amabilis</i>	–	–	–
<i>Terminalia sericea</i>	Uncertain	Uncertain	Uncertain
<i>Themeda triandra</i>	–	–	0
<i>Tylecodon paniculatus</i>	–	–	–

Table 2: The impact of bioclimatic shifts predicted by three climate change scenarios on the area of “centres of endemism” retaining their current bioclimatic characteristics.

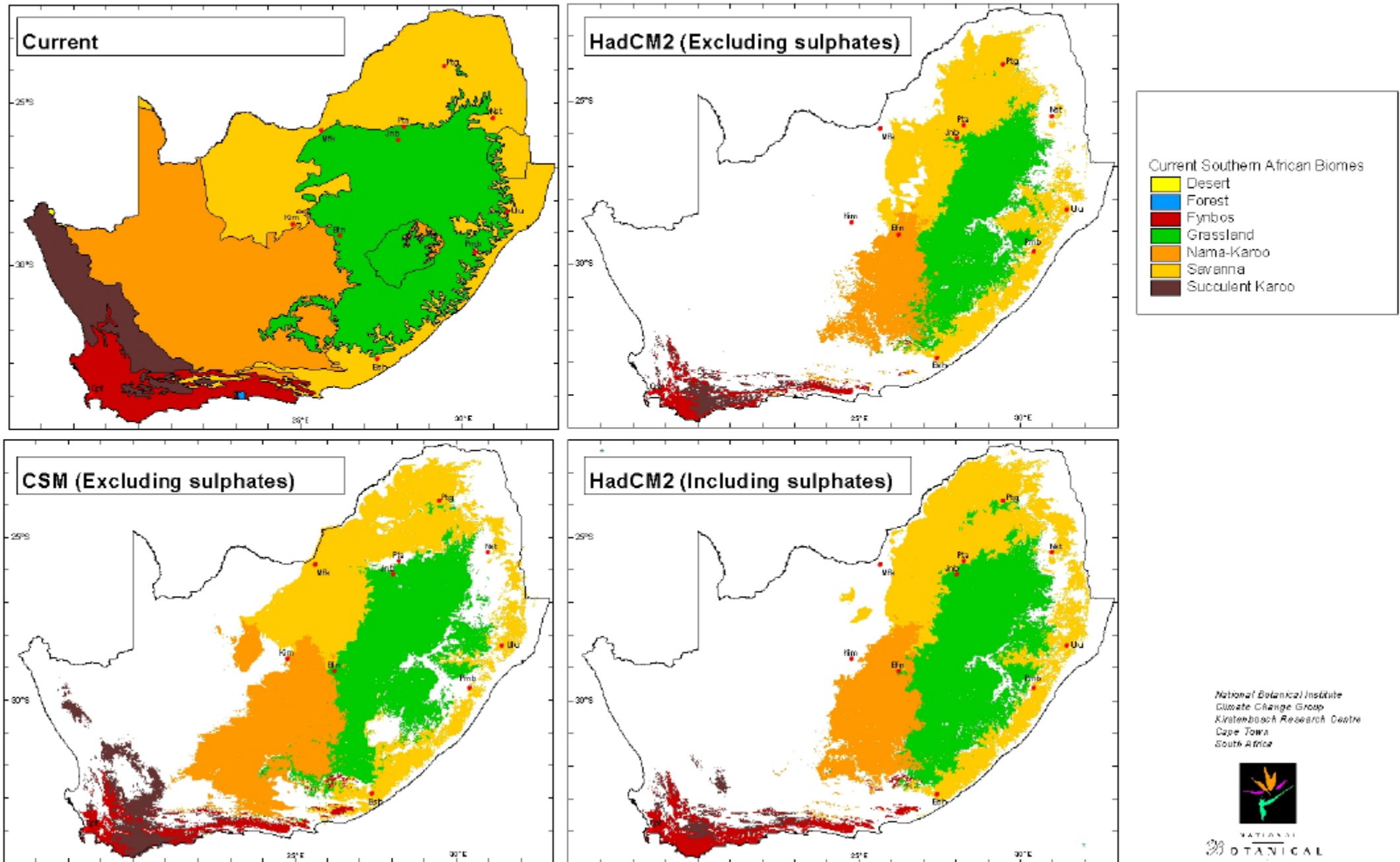
Proportional area of “centre of endemism” remaining within bioclimatic limits (%)	Number of centres of endemism HadCM2 (– sulphates)	Number of centres of endemism HadCM2 (+ sulphates)	Number of centres of endemism CSM (– sulphates)
0	12	8	7
1-10	1	3	6
11-20	1	0	1
21-30	0	1	1
31-40	2	2	0
>40	0	2	1

Table 3 Selected biodiversity adaptation options

Adaptation Option	High Priority	Target of Opportunity	Effectiveness	Other Benefits	Low Costs	Low Barriers
Biodiversity monitoring network	Yes	Yes	Yes	Yes	No	No
Vegetation management	Yes	Yes	Yes	Yes	Yes	Yes
Protected area networks	Yes	Yes	Yes	Yes	No	No
Ex-situ conservation	Yes	Yes	Yes	Yes	No	Yes
Global greenhouse gas emission policy	Yes	Yes	No	No	No	No
Plant translocation actions	No	Yes	Yes	Yes	No	No
Tolerating loss	No	Yes	Yes	No	Yes	Yes

Current and potential distribution of South African biomes

Figure 1



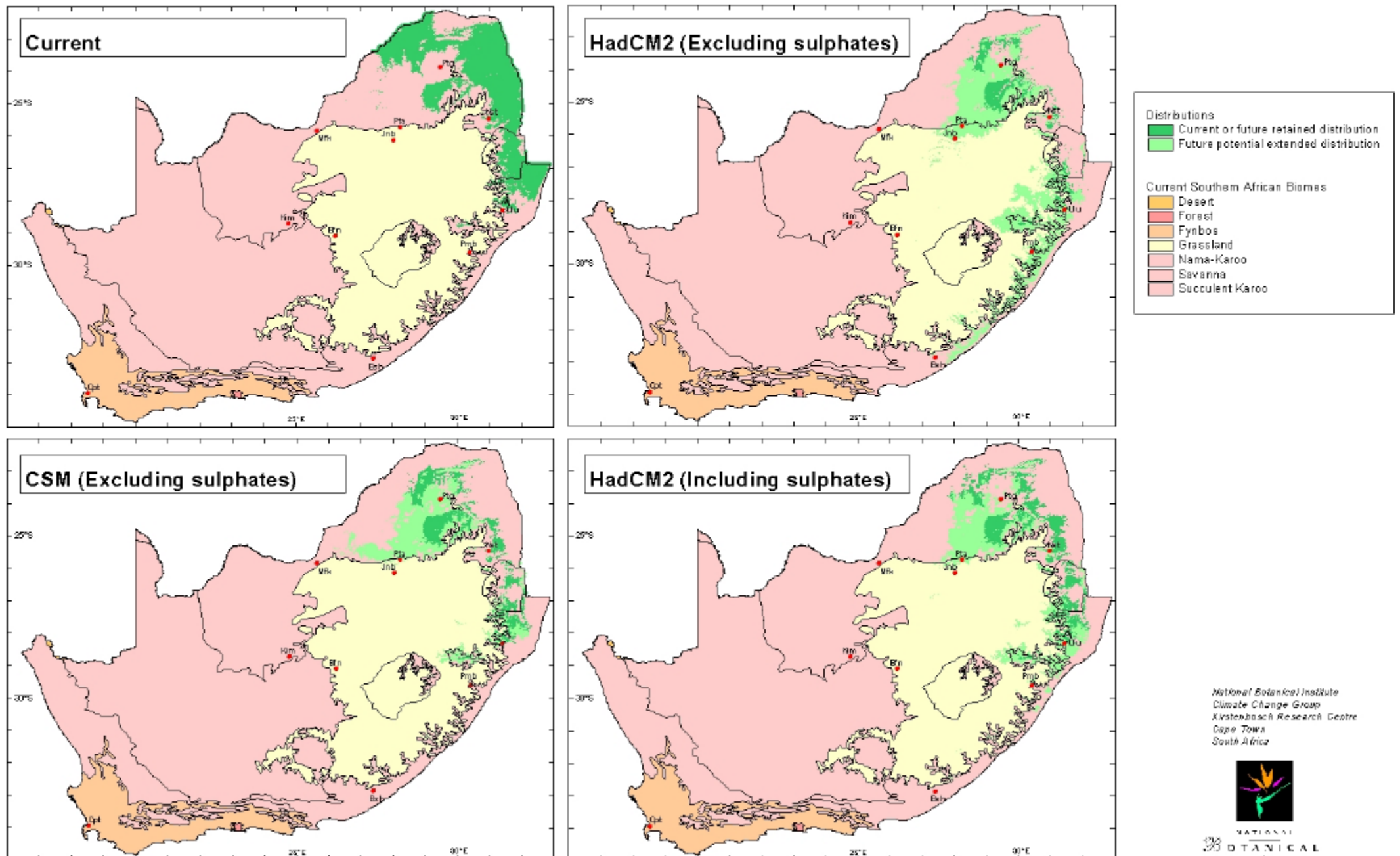
National Botanical Institute
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Kirstenbosch Research Centre
Cape Town
South Africa



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INSTITUTE

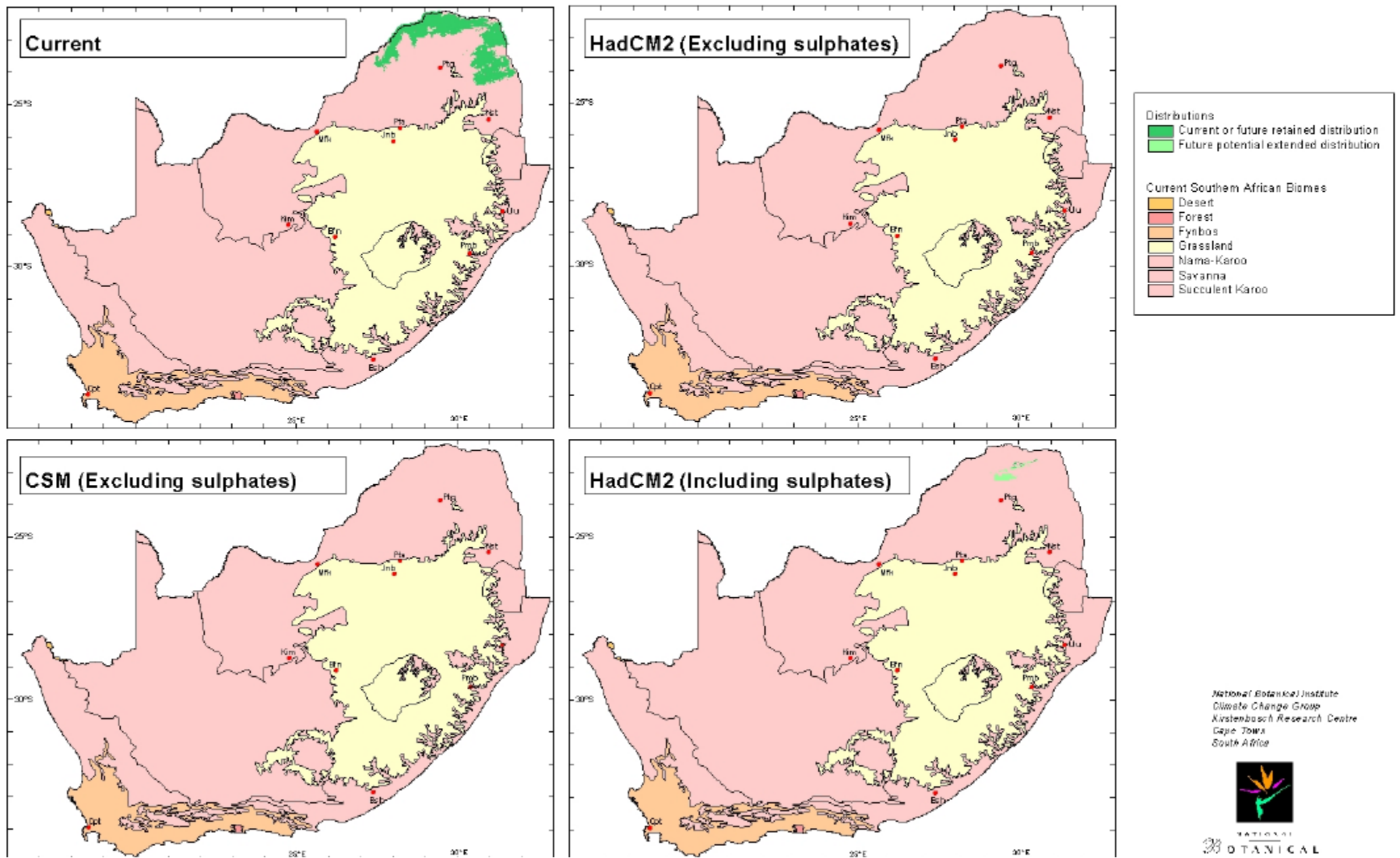
Bolusanthus speciosus distribution: current and future

Figure 2



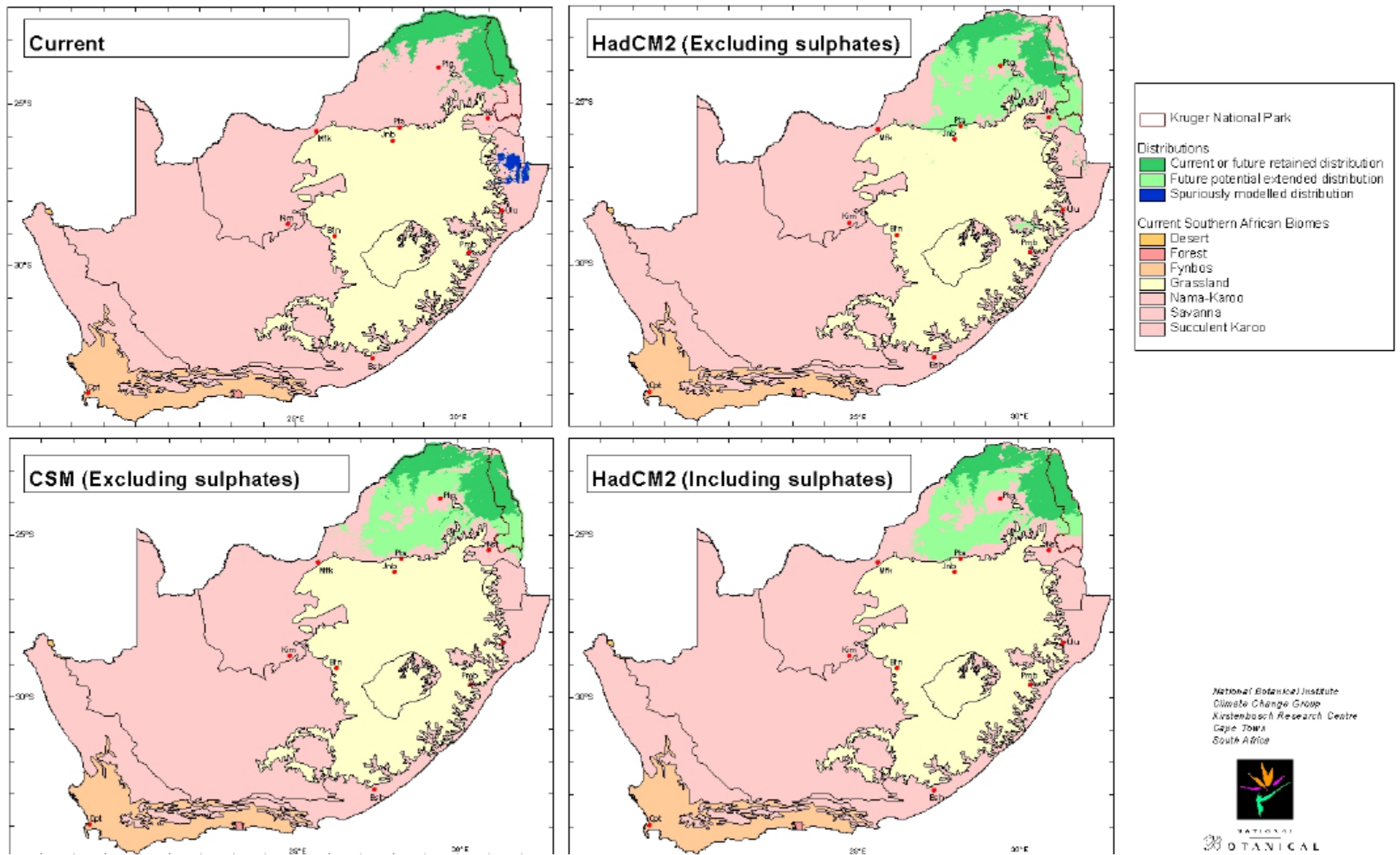
Sesamothamnus lugardii distribution: current and future

Figure 3



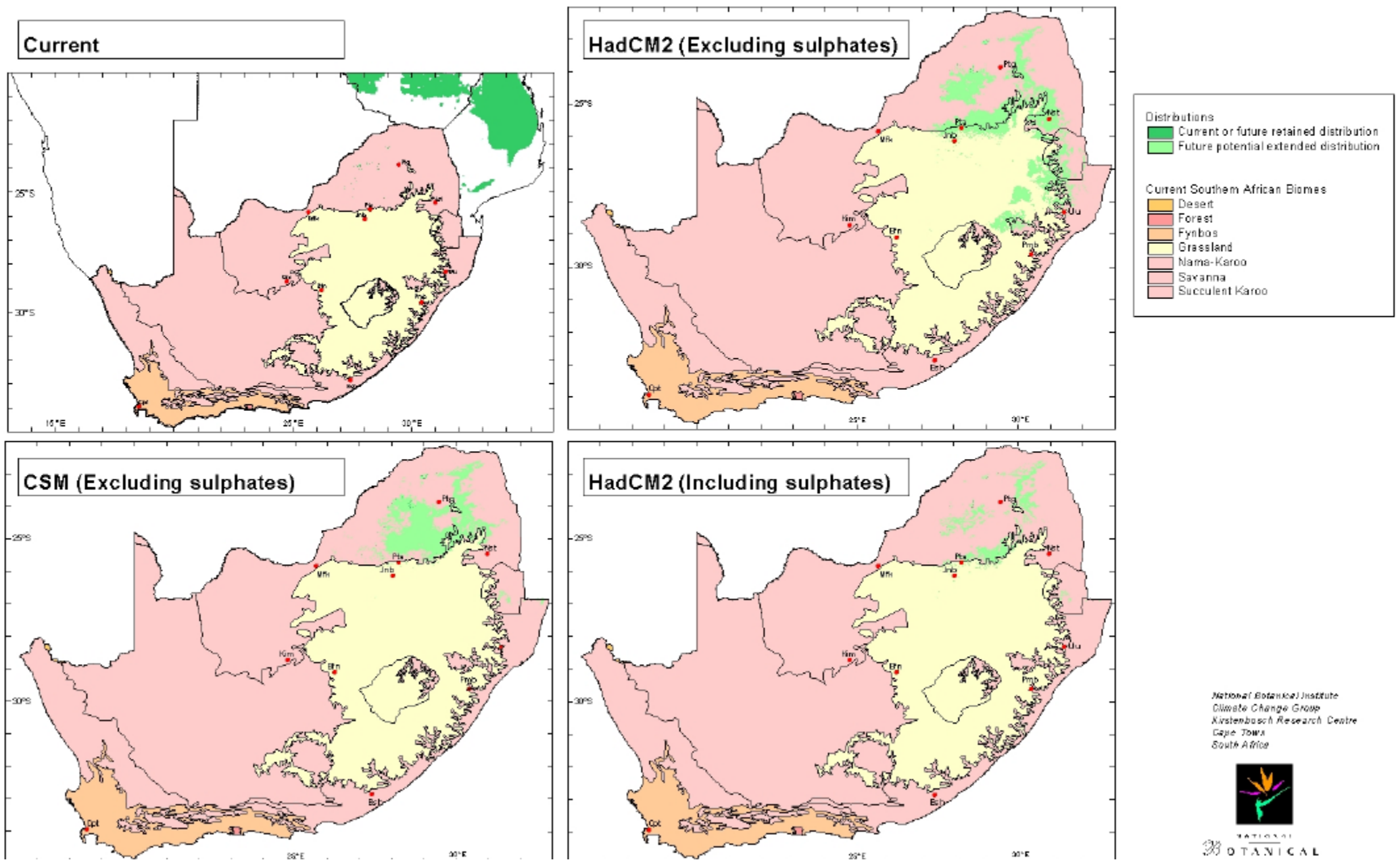
Colophospermum mopane distribution: current and future

Figure 4



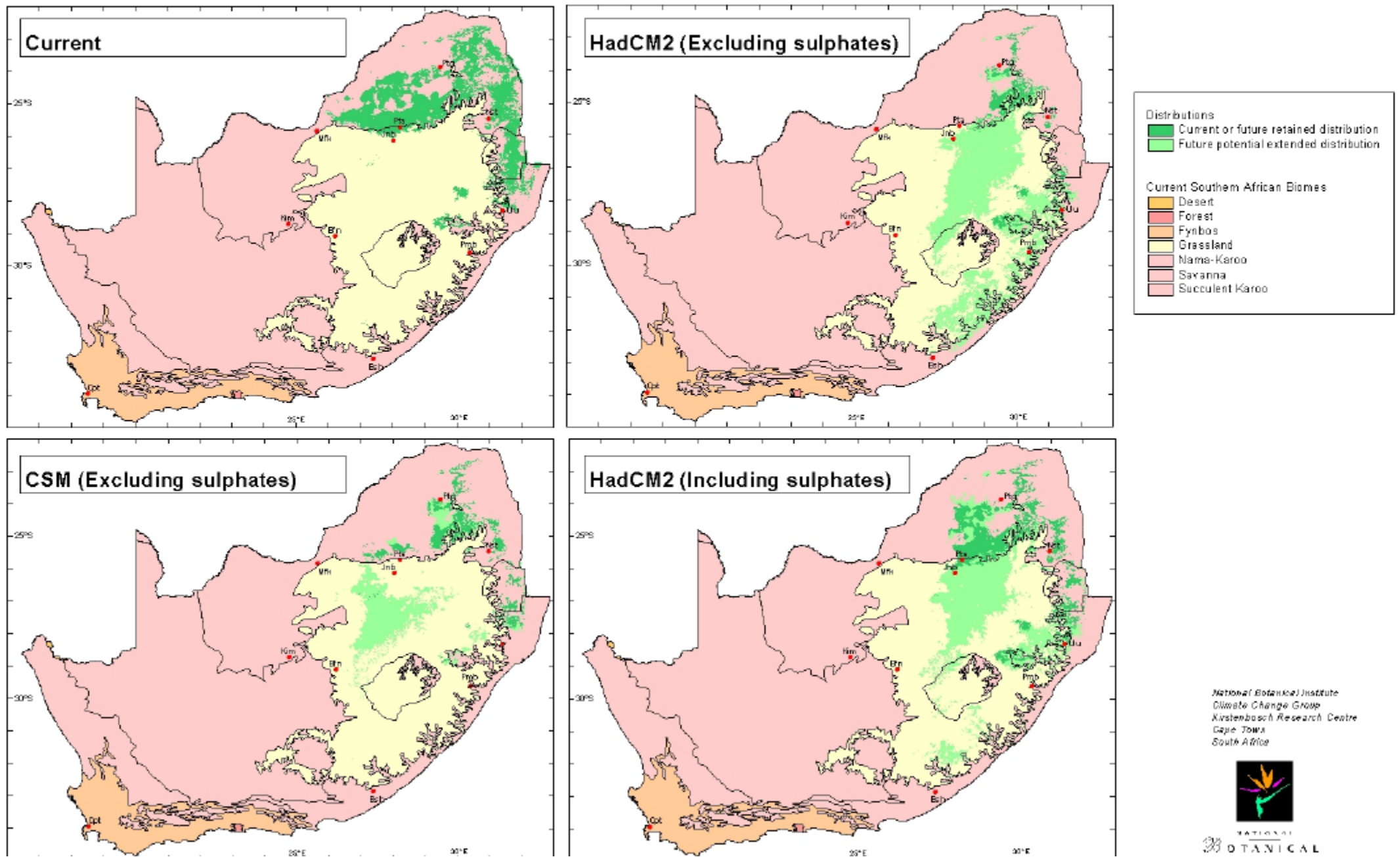
Brachystegia spiciformis distribution: current and future

Figure 5



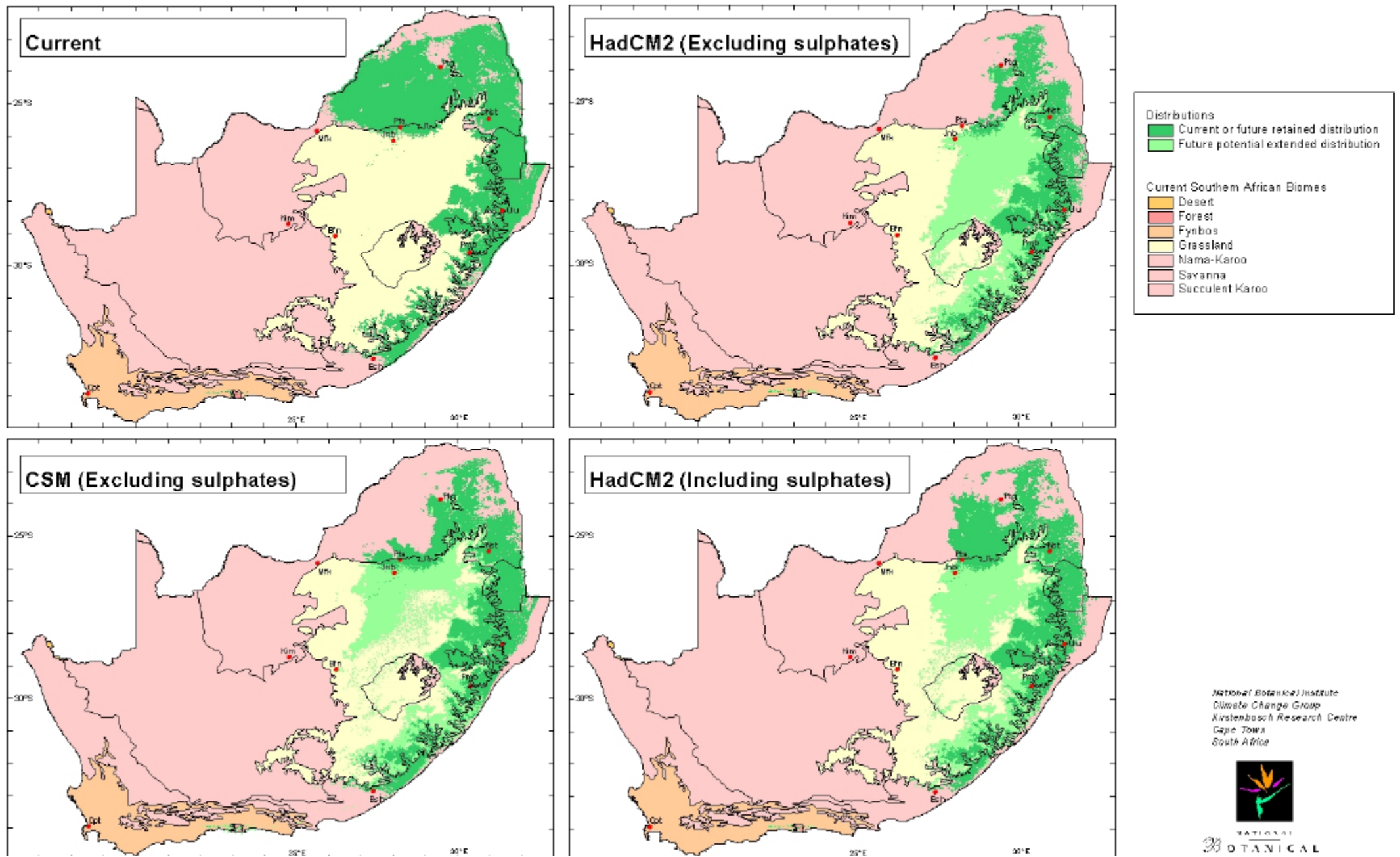
Aloe marlothii subsp. *marlothii* distribution: current and future

Figure 6



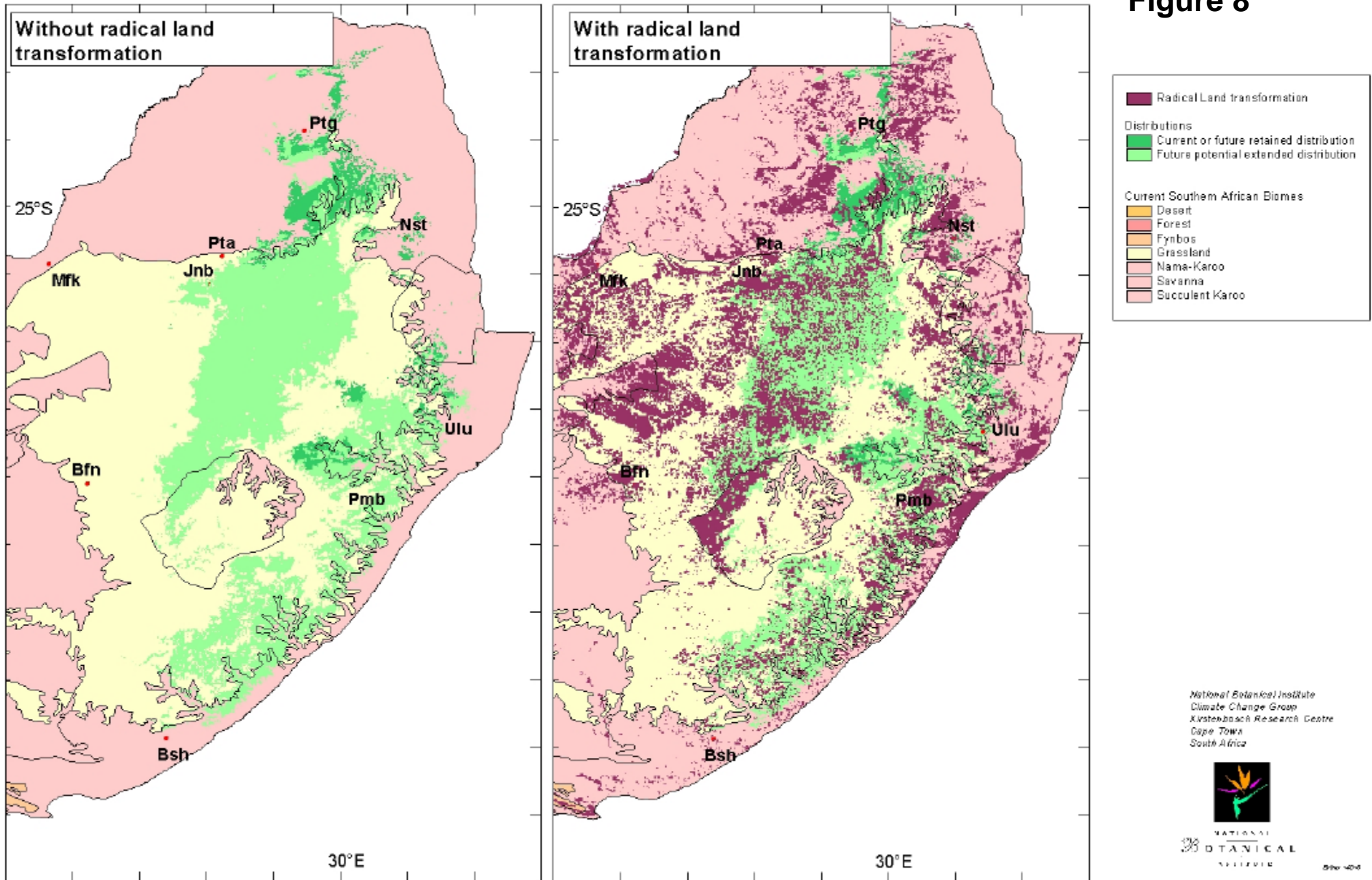
Erythrina lysistemon distribution: current and future

Figure 7



Impact of radical land transformation on potential future distribution of *Aloe marlothii* (HadCM2 Excluding sulphates)

Figure 8

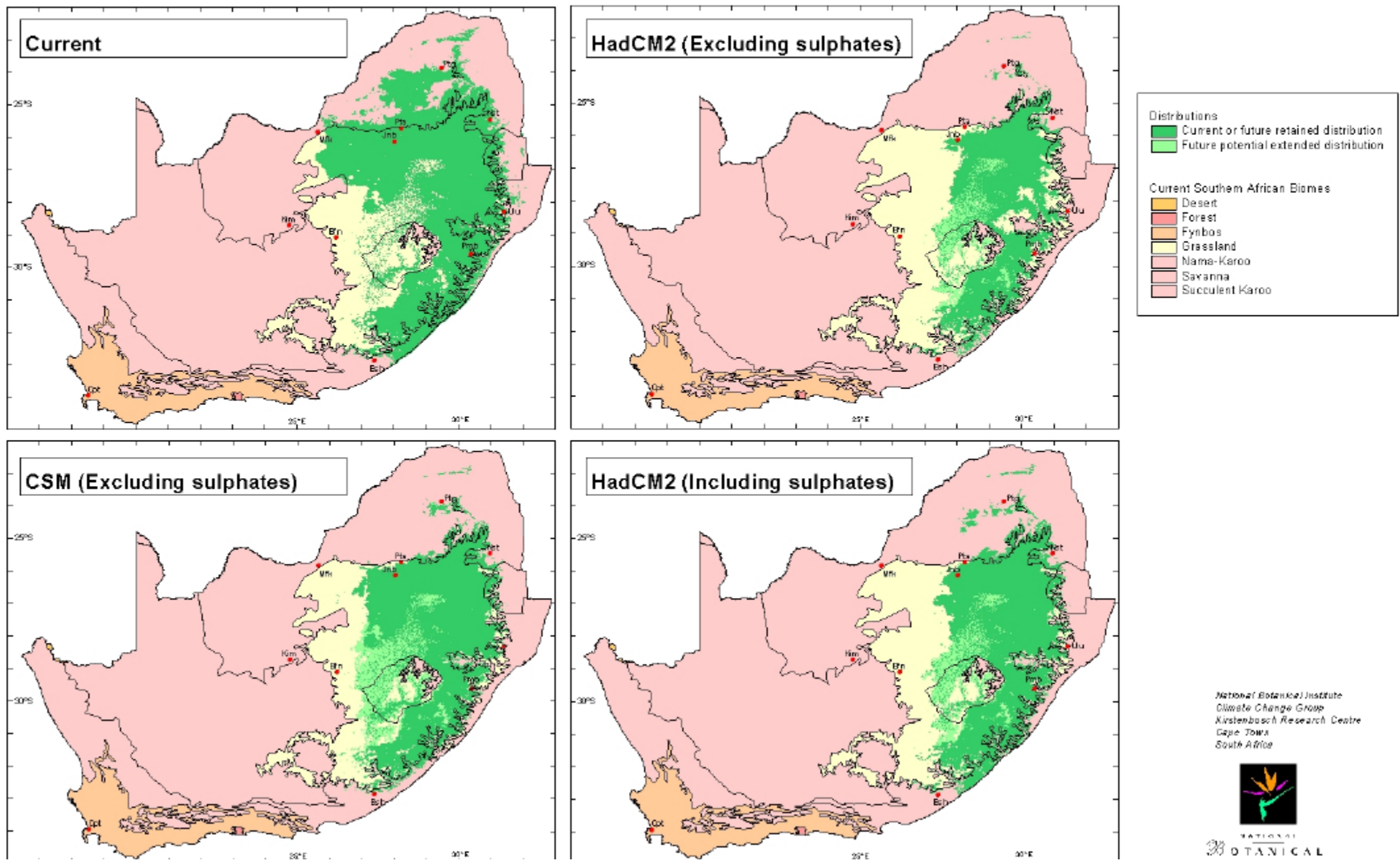


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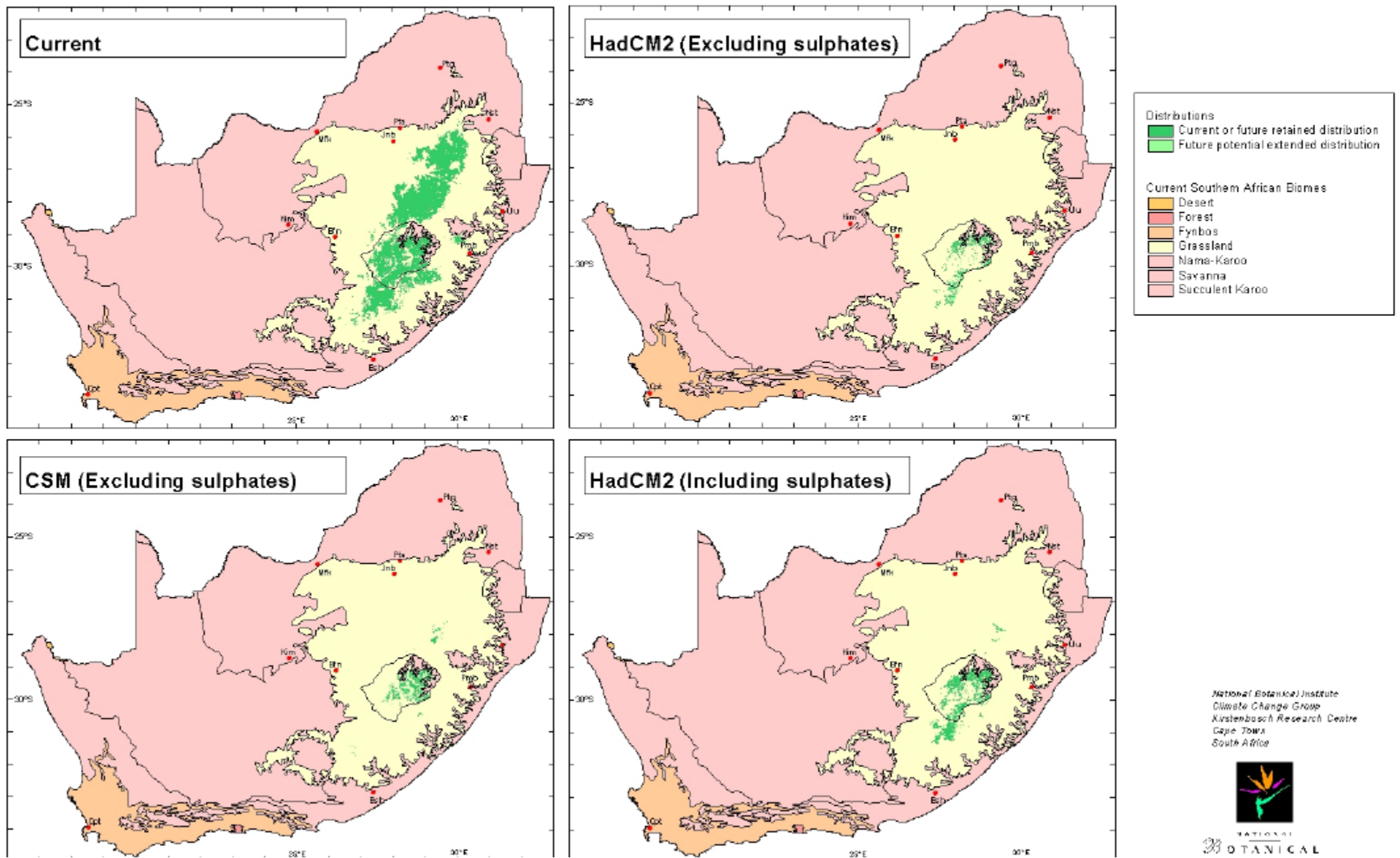
Protea caffra subsp. *caffra* distribution: current and future

Figure 9



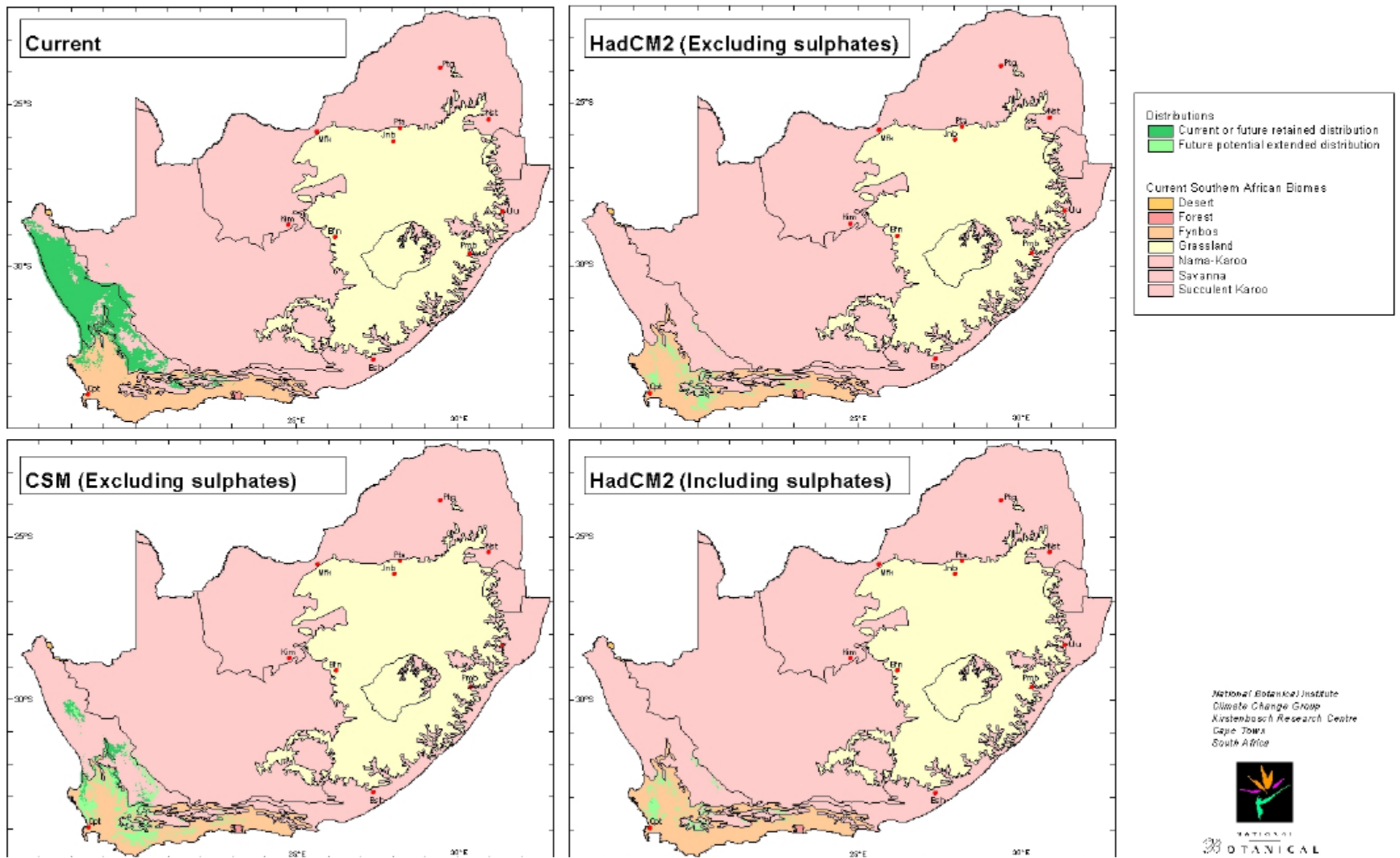
Catalepis gracilis distribution: current and future

Figure 10



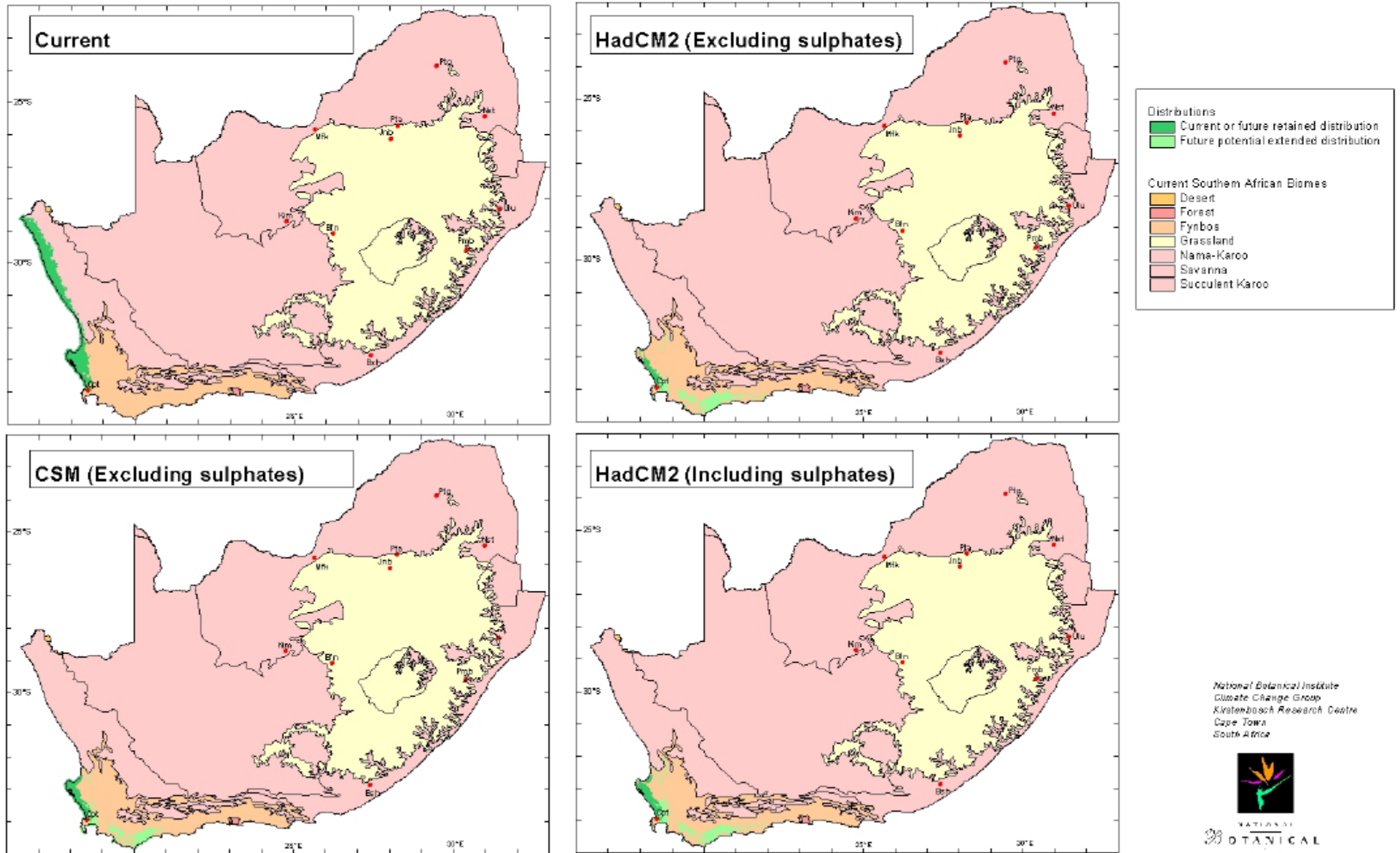
Didelta spinosa distribution: current and future

Figure 11



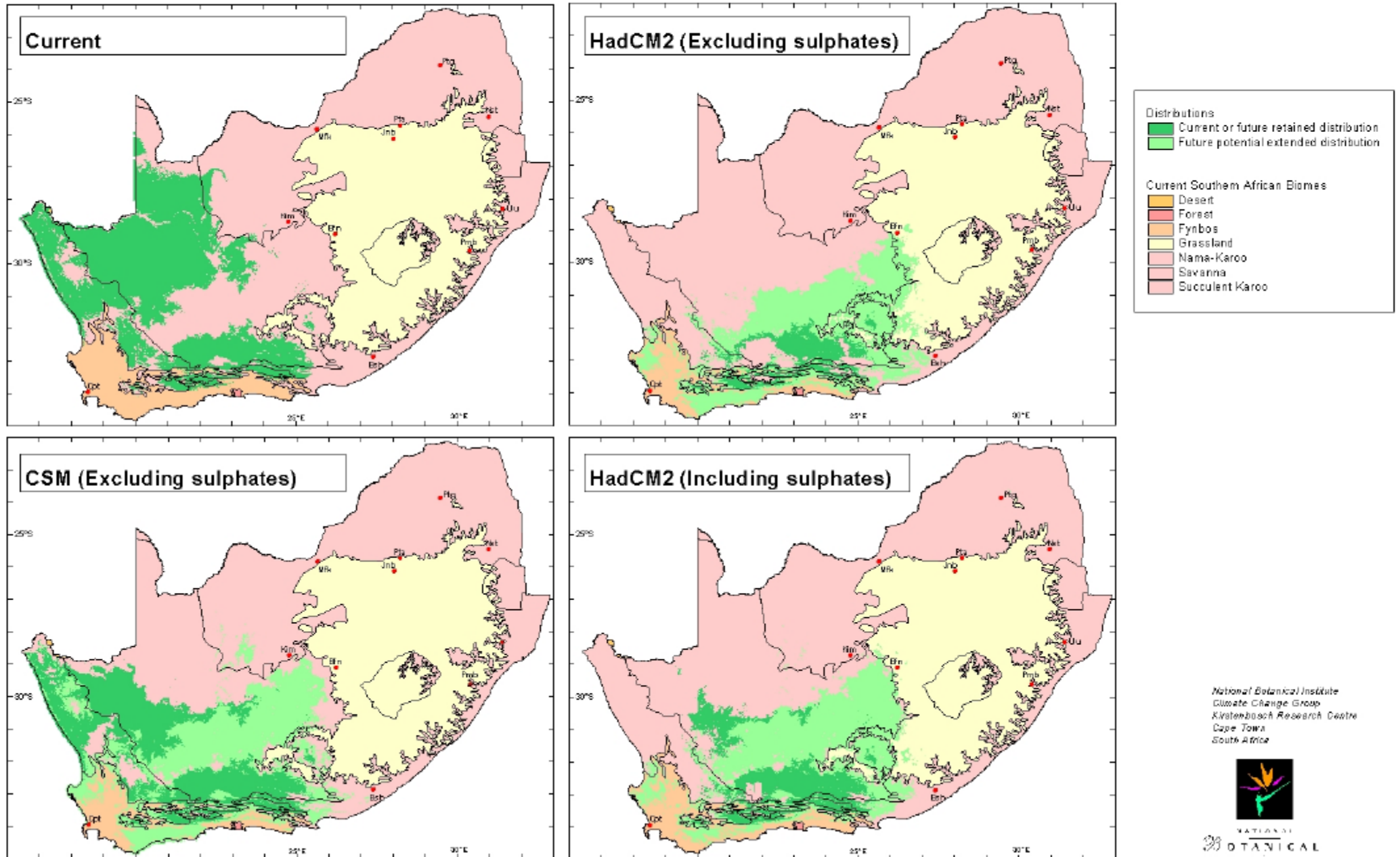
Cladoraphis cyperoides distribution: current and future

Figure 12



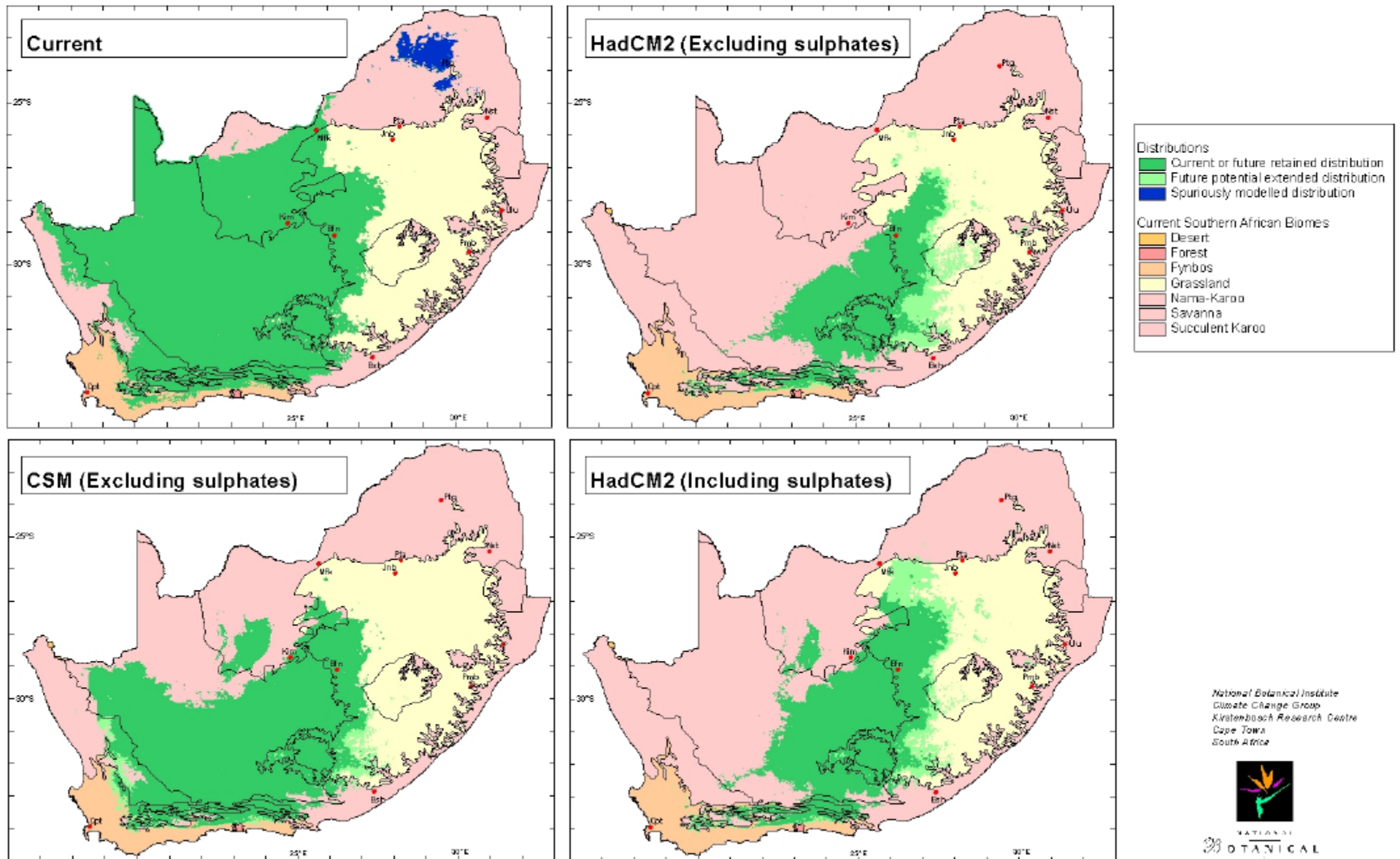
Augea capensis distribution: current and future

Figure 13



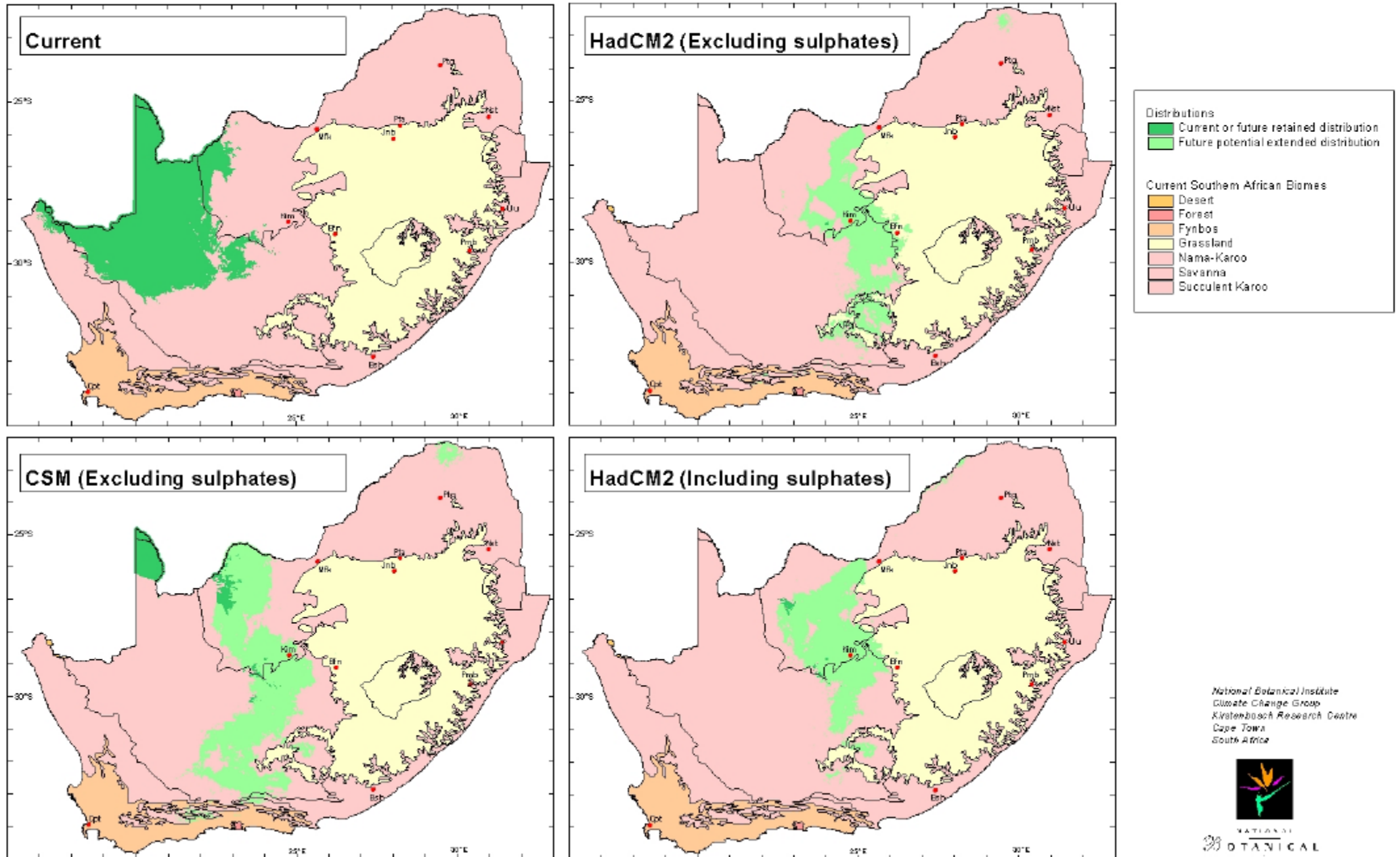
Pentzia incana distribution: current and future

Figure 14



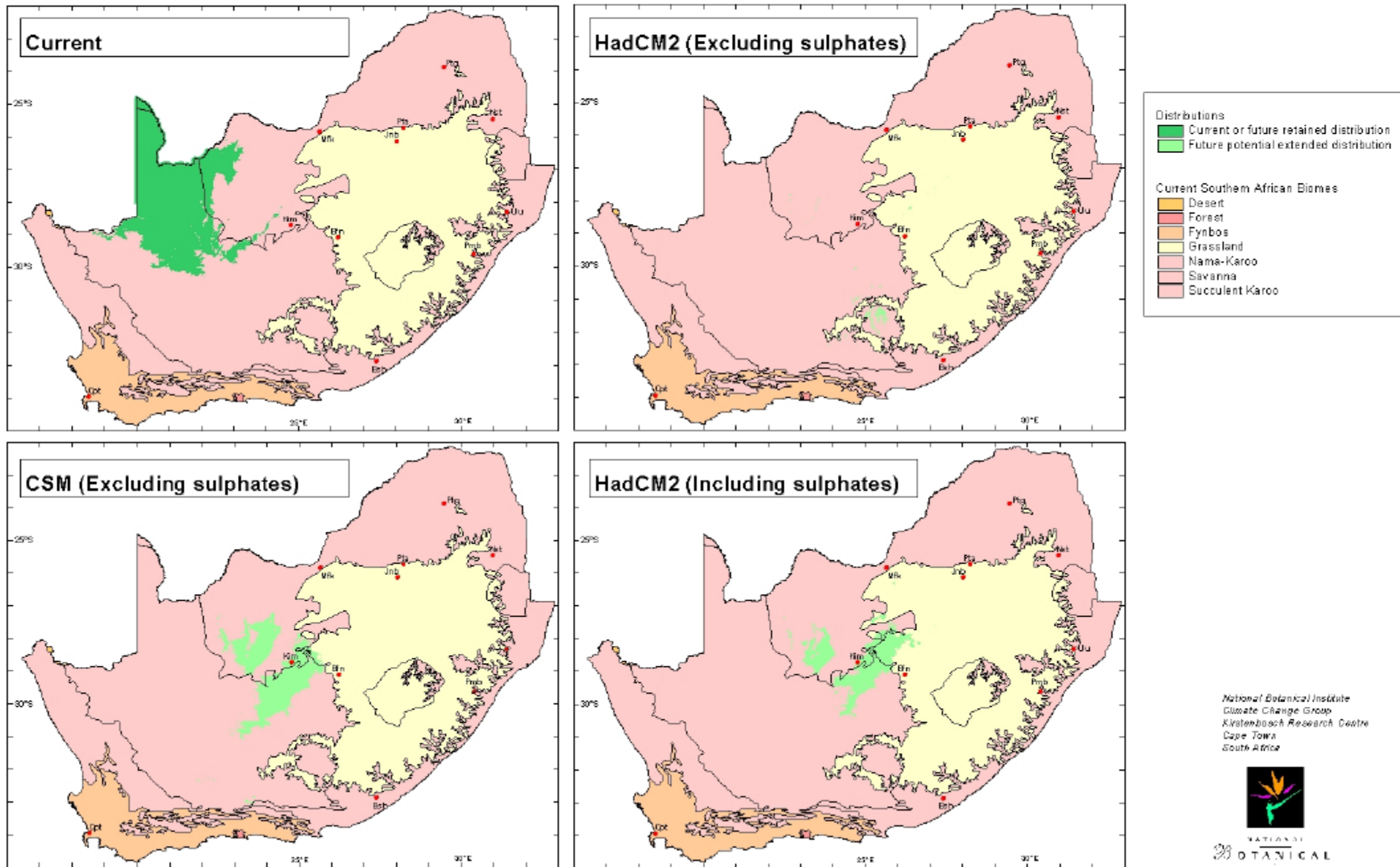
Parkinsonia africana distribution: current and future

Figure 15



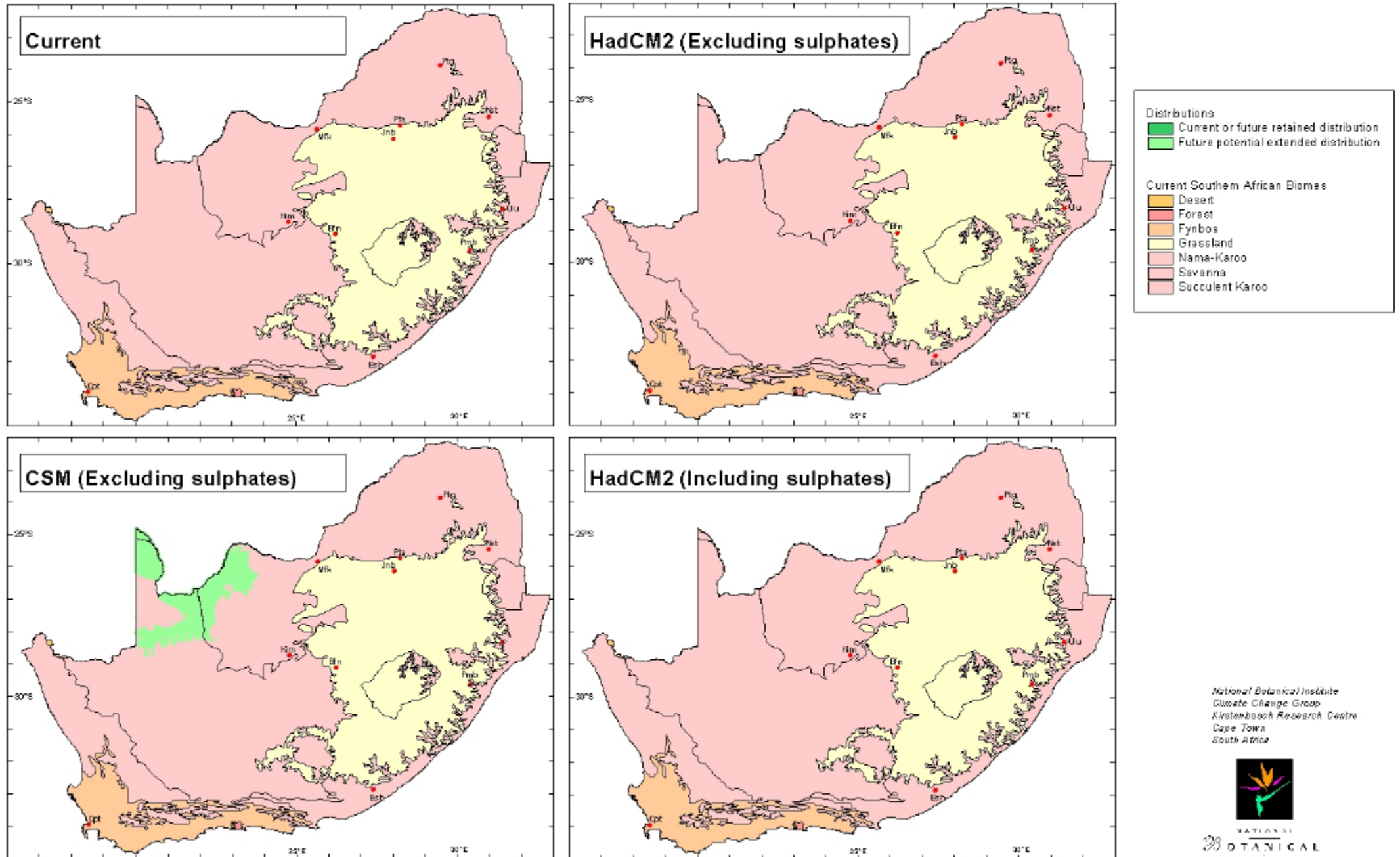
Stipagrostis amabilis distribution: current and future

Figure 16



Crassula ausensis distribution: current and future

Figure 17



Protea repens distribution: current and future

Figure 18

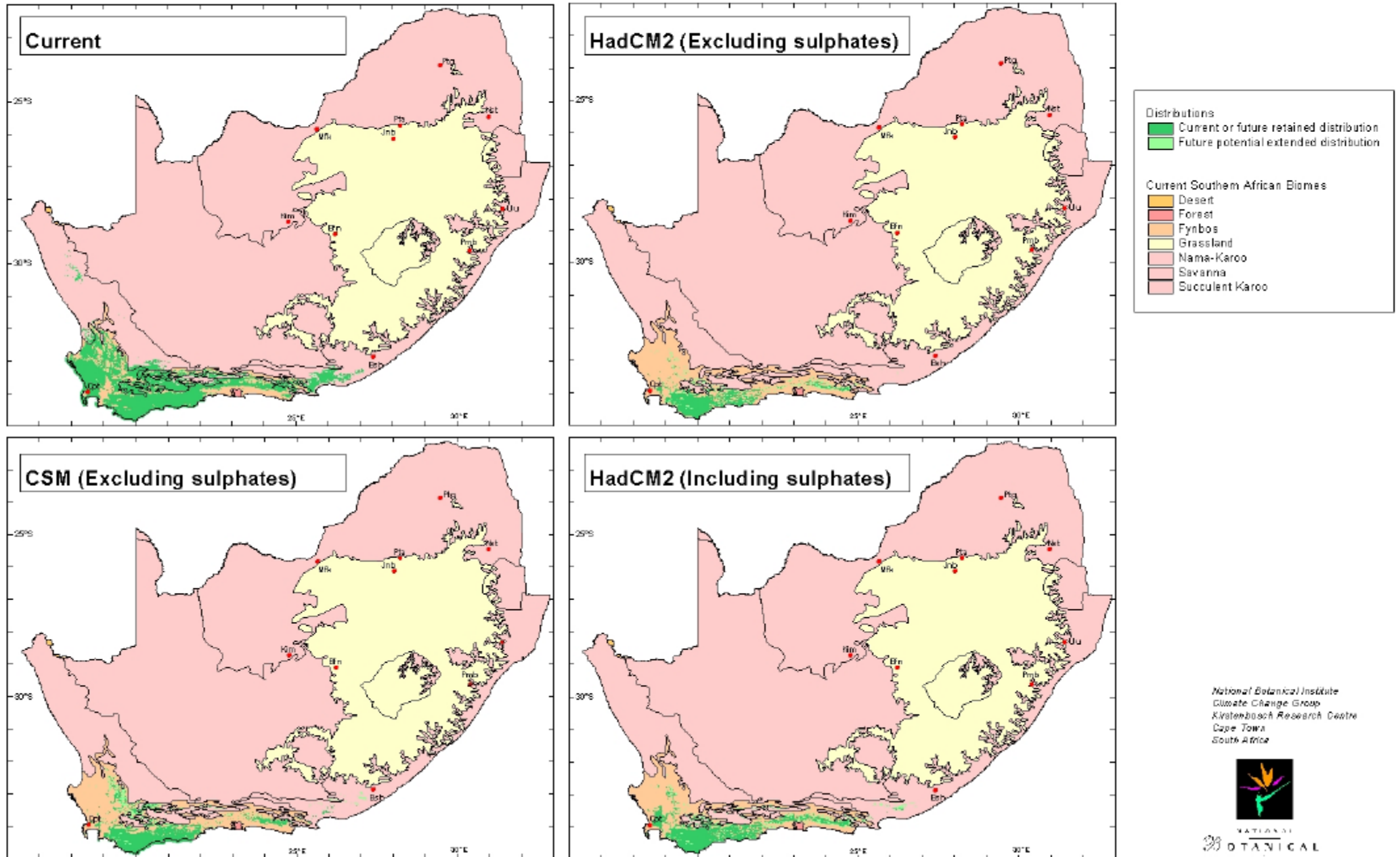


Figure 19a

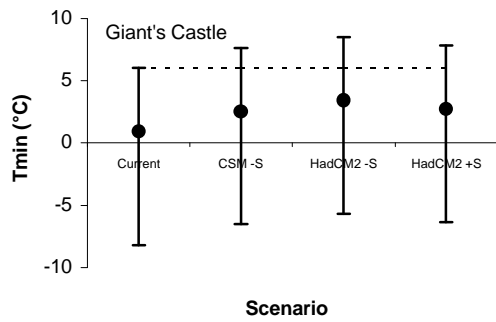
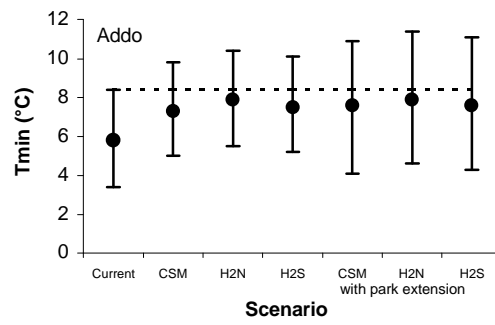
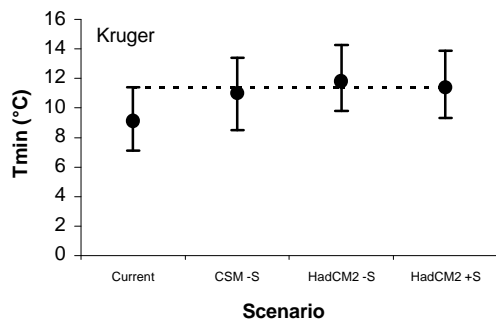
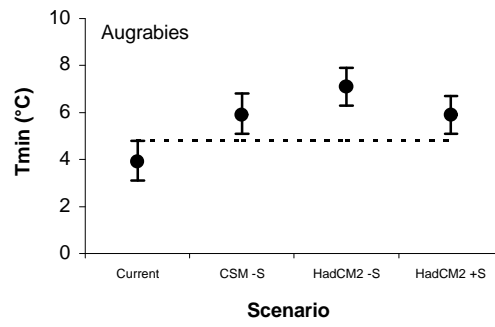
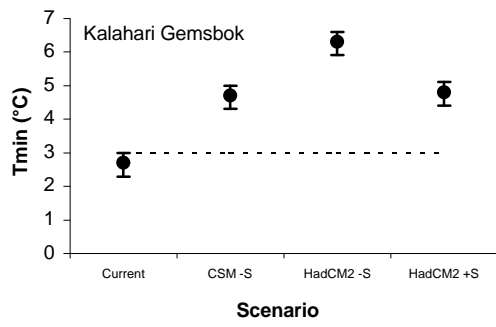


Figure 19b

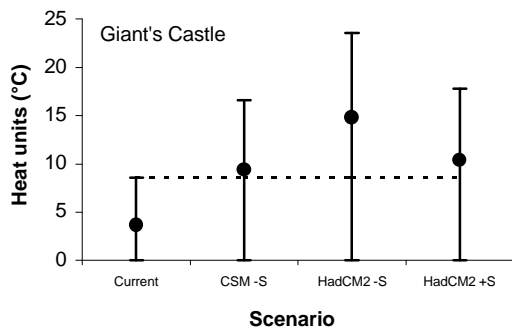
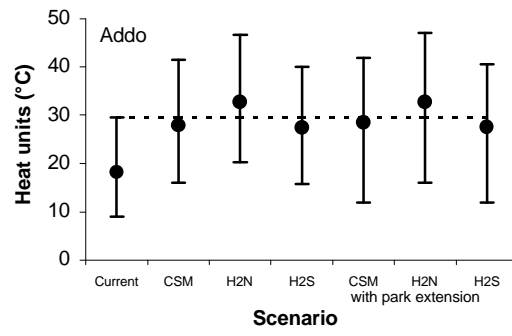
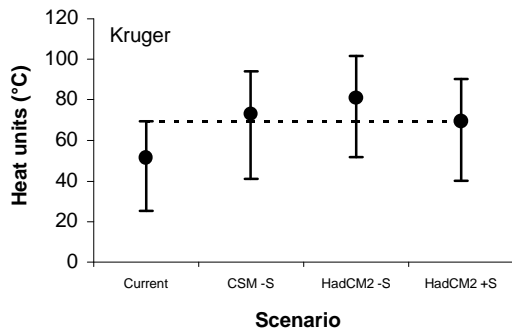
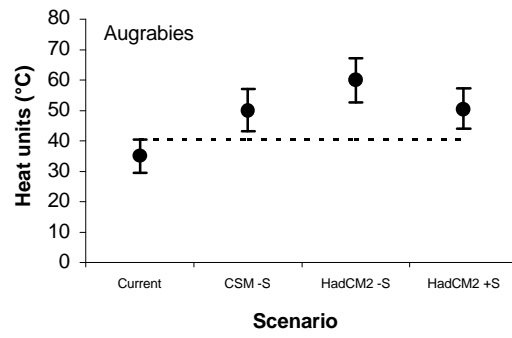
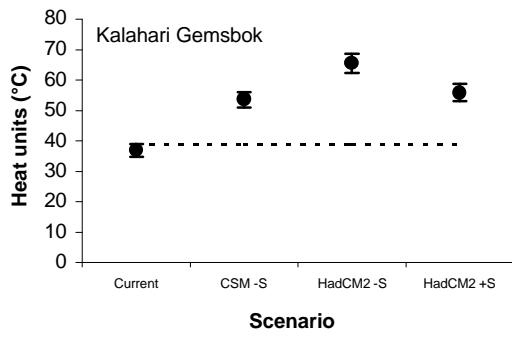


Figure 19c

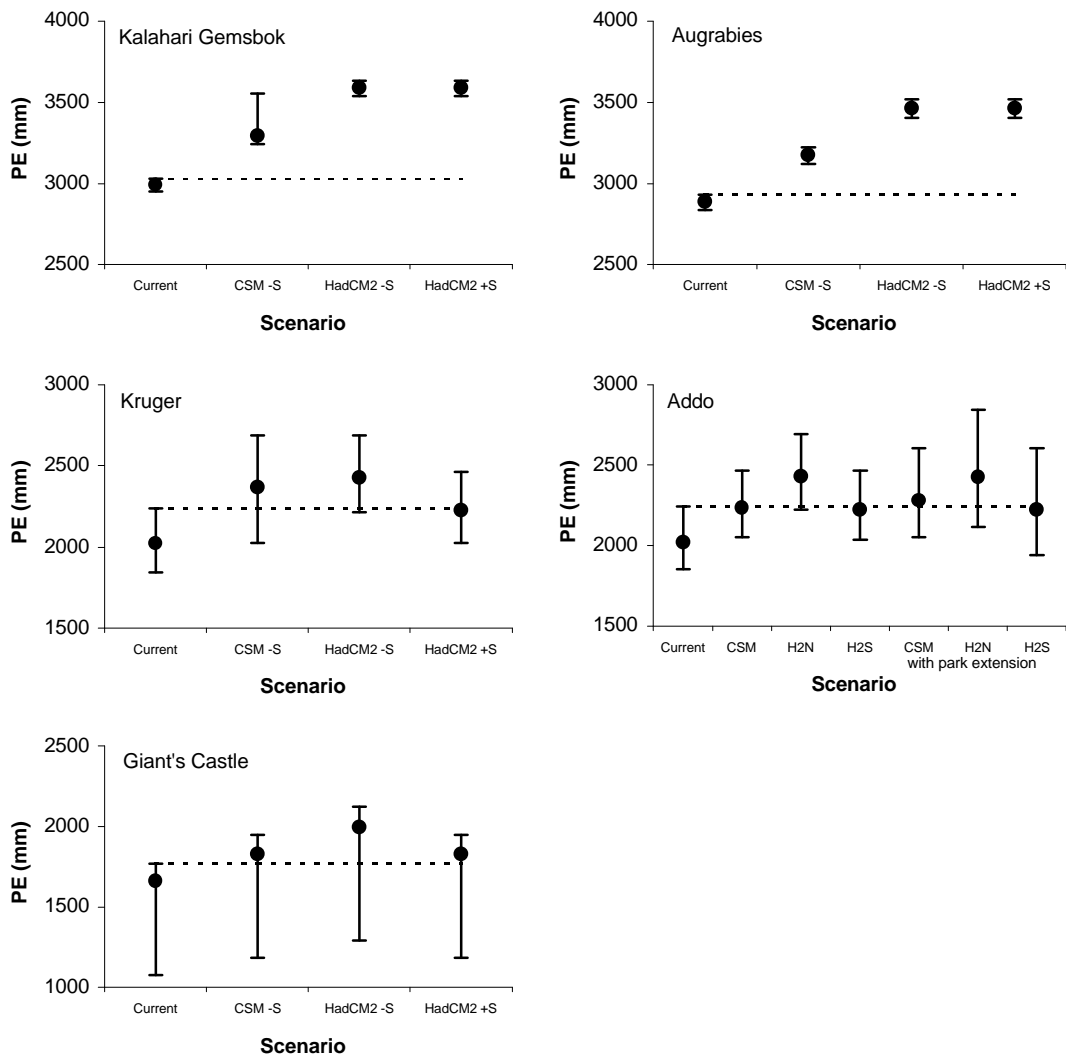


Figure 19d

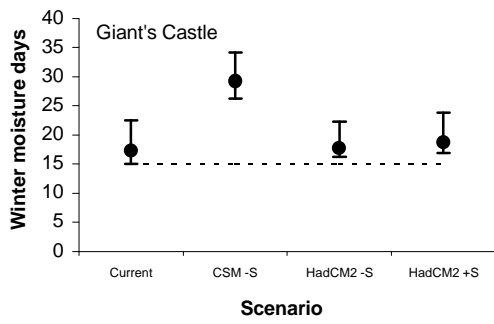
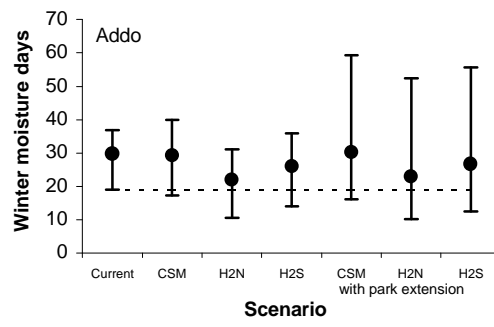
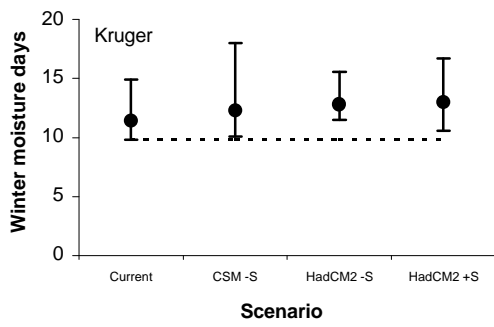
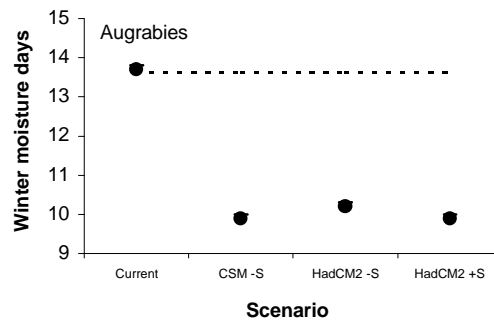
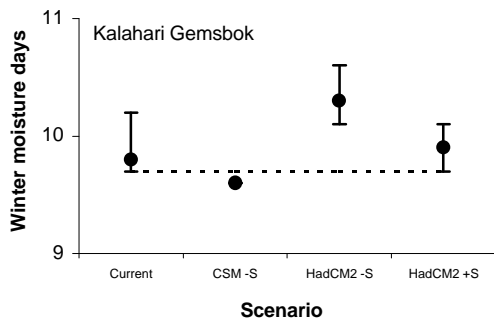


Figure 19e

