EUROPEAN AND MEDITERRANEAN PLANT PROTECTION ORGANIZATION
ORGANISATION EUROPEENNE ET MEDITERRANEENNE POUR LA PROTECTION DES PLANTES

Pest Risk Analysis for

Solanum viarum

Guillaume Fried EPPO Global Database (EPPO Code: SOLVI)

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The risk assessment follows EPPO standard PM 5/5(1) *Decision-Support Scheme for an Express Pest Risk Analysis* (available at http://archives.eppo.int/EPPOStandards/pra.htm), as recommended by the Panel on Phytosanitary Measures. Pest risk management (detailed in Section 3) was conducted according to the EPPO Decision-support scheme for quarantine pests PM 5/3(5). The risk assessment uses the terminology defined in ISPM 5 *Glossary of Phytosanitary Terms* (available at https://www.ippc.int/index.php).

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Based on this PRA, *Solanum viarum* was added to the EPPO Observation List (Invasive Alien Plants).

Pest Risk Analysis for *Solanum viarum* Dunal

PRA area: EPPO region
Prepared by: EWG on ***Solanum viarum***

Date: 14-18 February 2022
Further reviewed and amended by EPPO core members and Panel on Invasive Alien Plants.

Composition of the Expert Working Group (EWG)

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The first draft of the PRA was prepared by the EPPO Secretariat.

Ratings of likelihoods and levels of uncertainties were made during the meeting. These ratings are based on evidence provided in the PRA and on discussions in the group. Each EWG member provided a rating and a level of uncertainty anonymously and proposals were then discussed together in order to reach a final decision. Such a procedure is known as the Delphi technique (Schrader et al., 2010).

The PRA was reviewed and amended by the EPPO Panel on Invasive Alien Plants on 2022-05. The Panel on Invasive Alien Plants agreed with the recommendation of the EWG to list *Solanum viarum* on the EPPO Observation List. The Working Party on Phytosanitary Regulations was informed of the recommendation.

Contents

Summary of the Express Pest Risk Analysis for *Solanum viarum*			
PRA area: EPPO region (Albania, Algeria, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Guernsey, Hungary, Ireland, Israel, Italy, Jersey, Jordan, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Luxembourg, The Republic of North Macedonia, Malta, Moldova, Montenegro, Morocco, Netherlands, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Tunisia, Turkey, Ukraine, United Kingdom, Uzbekistan).			
Describe the endangered area: The EWG consider the endangered area to be the coastal areas of the Mediterranean and south Atlantic biogeographical regions. According to the modelling, frost may limit establishment in the inland parts of the EPPO region. Habitats at risk in the endangered area include pastures and agricultural systems, river systems and ruderal habitats. Appendix 2 gives the percentage of suitable areas in each country. The EWG considered the species distribution modelling conducted as part of this PRA (see Appendix 2) to be a realistic projection of the potential occurrence of *S. viarum* in the EPPO region.			
Main conclusions ***Solanum viarum* presents a moderate phytosanitary risk for the endangered area with high uncertainty.** The overall likelihood of *S. viarum* entering the EPPO region is very low with a moderate uncertainty. Several pathways were assessed in the PRA but there was no strong association with any pathways. The likelihood of further establishment outdoors is high with high uncertainty. The high uncertainty reflects the small area of potential establishment in the EPPO region. The only population in the EPPO region is in France and it is on the limits of climatic suitability and unclear if the population is established or transient. Establishment in protected conditions is very low with low uncertainty. Temperature within protected conditions would be suitable for the establishment however, other conditions, e.g., the intense management of the system are likely to reduce the likelihood of establishment. The potential for spread within the EPPO region is high with a high uncertainty. *S. viarum* can spread both naturally and via human assisted spread. The species is shown to spread via human assisted mechanisms which would potentially move the species over long distances. However, all spread data is taken from North America which is speculative, hence the high uncertainty score. The magnitude of impact in the current area of distribution (North America) is moderate with a moderate uncertainty. The species has had an impact on pasture production and cattle in North America in the late 1990s and early 2000s, but improved management (biological and chemical control) has reduced the impact. The EWG considered the potential socio-economic impacts in the EPPO region will be low with a high uncertainty. The high uncertainty reflects the unknowns relating to the plasticity of *S. viarum* and its ability to adapt to climatic and environmental parameters in the EPPO region. This in turn gives uncertainty to the level and type of impacts the species may have in the EPPO region. **The EWG recommend that *S. viarum* is included on the EPPO Observation List.**			
Phytosanitary risk for the *endangered area* (*Individual ratings for likelihood of entry and establishment, and for magnitude of spread and impact are provided in the document*)	High ☐	Moderate X	Low ☐
Level of uncertainty of assessment (see Section 17 for the justification of the rating. Individual ratings of uncertainty of entry, establishment, spread and impact are provided in the document)	High X	Moderate ☐	Low ☐
Other recommendations: • Whenever the species is maintained in germplasm collection, or used for breeding purposes, adequate biosecurity measures should be applied to avoid any risk of escape from cultivation			

EPPO Pest Risk Analysis:

Solanum viarum Dunal

Prepared by: EPPO Expert Working Group
Date: 2022-02-14/18

Stage 1. Initiation

Reason for performing the PRA:
Solanum viarum was first observed in the EPPO region in the 2000s (Verloove, 2003, 2006) as a transient alien species (port area in Belgium) and it has recently been recorded in the natural environment in France (Christians and Maglio, 2020). In the USA, *S. viarum* was first introduced in the late 1980s and has spread rapidly to become invasive in a number of southern States where it has negative impacts on agricultural crops and livestock farming. The species occurs in pastures, croplands (citrus plantations, sugar cane and vegetable fields), fields, roadsides and in a variety of natural habitats (scrub, flatwoods, swamps, floodplain forests). It has been reported as an alternative host for a number of crop pathogens and insect pests. In 2021, the EPPO Panel on Invasive Alien Plants considered the report of the first finding of *S. viarum* in France and prioritised *S. viarum* for an EPPO pest risk analysis (PRA). The Panel considered that *S. viarum* has the potential for further spread within the EPPO region, and therefore there is potential for impacts on agriculture, biodiversity and ecosystem services.

PRA area:
EPPO region: (Albania, Algeria, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Guernsey, Hungary, Ireland, Israel, Italy, Jersey, Jordan, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Luxembourg, The Republic of North Macedonia, Malta, Moldova, Montenegro, Morocco, Netherlands, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Tunisia, Turkey, Ukraine, United Kingdom, Uzbekistan).

(see https://www.eppo.int/ABOUT_EPPO/eppo_members)

Stage 2. Pest risk assessment

1. Taxonomy:

Kingdom: *Plantae,* Division: *Magnoliophyta,* Class: *Angiospermae,* Order: *Solanales,* Family: *Solanaceae,* Genus *Solanum,* Species *Solanum viarum* Dunal, Prodr. [A. P. de Candolle] 13(1): 240 (1852).

EPPO code: SOLVI

Main synonyms:

Solanum chloranthum DC., Pl. Rar. Jard. Genève 47, t. 13. (1826), *non* Sprengel (1824) [heterotypic synonym]
Solanum ambrosiacum Vell., Fl. Flumin. 90 (1829) ("1825"), [nom. rej. propos.];
Solanum viridiflorum Schltdl., Linnaea 19(3): 292 (1847), Ruiz López & Pavón (1799);
Solanum khasianum C.B.Clarke, var. *chatterjeeanum* Sengupta, Bull. Bot. Surv. India 3: 413 (1961).

[http://www.worldfloraonline.org/taxon/wfo-0001032367] & Atlas of Florida Plants (https://florida.plantatlas.usf.edu/plant.aspx?id=65)

Common name:

English; tropical soda apple (TSA), Portuguese (BR): arrebenta-cavalo, joa-bravo.

Plant type: Perennial herbaceous shrub

Related species in the EPPO region:
The genus *Solanum* is the largest in the family Solanaceae, containing about 2000 species which are predominantly distributed in the subtropical and tropical regions of Africa, Australia and parts of Asia (e.g. China, India and Japan) (Kaunda and Zhang, 2019). The genus includes a number of economically important species, in particular *S. lycopersicum*, *S. melongena* and *S. tuberosum*.

Approximately 60 species of the genus *Solanum* have been recorded in Europe and the Mediterranean basin (Valdés, 2012). Except for a few species such as *Solanum dulcamara*, *S. nigrum* or *S. villosum,* most of them are exotic species, several of which are weedy and/or invasive (*S. chenopodioides*, *S. elaeagnifolium*).

Coile (1993) gives a list of seven prickly nightshade species *S. viarum* can be confused with: *Solanum capsicoides*, *Solanum carolinense*, *Solanum dimidiatum*, *Solanum tampicense, Solanum rostratum*, *Solanum sisymbriifolium*, *Solanum torvum.*

2. Pest overview

2.1 Introduction
Solanum viarum is a perennial herbaceous shrub native to South America (Flora do Brazil, 2021). The species has become a major weed of pastureland and other disturbed habitats in parts of North America. *S. viarum* has several weedy attributes (e.g., rapid growth, prolific seed production, grows in a variety of biotic and abiotic conditions). *Solanum viarum* is a recent introduction into the EPPO region (Christians and Maglio, 2020; Verloove, 2006).

2.2 Identification

The following description of *Solanum viarum* is from Flora do Brasil (2021):

Shrubs 0.5–2 m tall and 1.5m wide, erect but with many spreading branches, armed.

S**tems** densely and uniformly glandular-puberulent with simple gland-tipped trichomes 0.4–0.5 mm long, moderately prickly with broad-based recurved prickles, variable in length and the largest to 8 mm long, the smaller prickles ca. 1 mm long, slender, straight and spreading. Leaves unequal, paired.

Leaves simple, the blades 7–10 (–15) cm long, 6-8 (–15) cm wide, about as long as wide, ovate to suborbicular in outline, membranous, concolorous, sparsely prickly adaxially and abaxially with straight spreading acicular prickles similar to the largest prickles on the petiole, with much smaller prickles on smaller veins; densely puberulent; base cordate to truncate; margins lobed, usually with 3-5 pairs of shallow obtuse or acute lobes, these entire or with small secondary lobes or teeth; apex acute or obtuse; petiole of the major leaves 3–6 cm, with pubescence similar to that of the stem.

Inflorescences lateral, sessile or nearly so, unbranched, with 3–5 flowers; axes densely pubescent with simple gland-tipped hairs 0.4–0.6 mm long, with some longer simple hyaline hairs up to 1.2 mm long, unarmed or with a few straight spreading prickles up to 2 mm long; peduncle 0-0.3 cm; pedicels 0.7-1.1 cm long.

Flowers 5-merous, heterostylous, usually only the lowermost (rarely 2) flowers long-styled and fertile, the rest short-styled and staminate. Calyx 2-4 mm long, unarmed or with a few prickles to 2 mm long, the lobes 0.8–2 mm long, 0.6–0.8 mm wide, triangular, acute at the tips. Corolla ca. 2 cm in diameter, pale greenish white or white, stellate, lobed nearly to the base, the lobes 7–10 mm long, 2.5–3 mm wide.

Fruit a globose berry, 1-2(-3) per infructescence, 2.2–2.5 cm in diameter, light green mottled with dark green when immature, yellow and glabrous at maturity; fruiting pedicels 1-2.1 cm long, ca. 2 mm thick, curved around the inflorescence axis; fruiting calyx somewhat accrescent

Seeds 100-300 per berry, 2.2–2.8 mm long, 2–2.5 mm wide, flattened-reniform, light red-brown.

Chromosome number: 2n=2x=24.

Images of *S. viarum* can be retrieved from the EPPO Global Database (EPPO, 2022).

2.2.2 Molecular identification

Solanum viarum can be identified by PCR DNA barcoding using two chloroplast regions (psbA-trnH and matK) and a nuclear region [internal transcribed spacer (ITS)] (Rosario *et al*., 2019). GenBank contains 56 accessions for *S. viarum* (https://www.ncbi.nlm.nih.gov/nuccore/?term=solanum+viarum).

2.4 Life cycle

This section utilises information provided in Waggy (2009).

Solanum viarum reproduces mainly from seed, though it can also regenerate from the shallow root system (up to 30 cm vertically and 1-2 m horizontally) and from the root crown (Mullahey *et al*. 1994). In North America, the growing season of *S. viarum* varies depending on the location. In Florida, seedlings or new sprouts developing from perennial roots emerge from August to March (the dry season), though in southern Florida, seedlings can emerge all year round.

In Florida, *S. viarum* produces flowers and fruits throughout the year (Mullahey *et al*., 1993 Mullahey et al., 2009). However, the timing and intensity can vary. For example, Mullahey *et al.* (1996) detail that in Florida, most flowering occurs from September to May with low fruit production in the summer months. However, again for Florida, Akanda *et al*. (1996) showed that flowering and fruit production occurred from February to August. Bryson and Byrd (2007) and Bryson et al. (2012) detail for Mississippi, *S. viarum* flowers and fruits from June until the first frost, with peak production occurring in August. In other regions outside of North America, *S. viarum* flowers from September to April. In Northeast India, *S. viarum* generally flowers all year round with peak flowering occurring during March to April. Mature fruits are present from May to June (Saha and Datta, 2014).

In the EPPO region, *S. viarum* has been observed in France flowering and fruiting in August and October with fruits remaining up until February. Further details on its life cycle under Mediterranean and European climatic conditions would be useful information to collect.

Solanum viarum is a prolific seed producer though seed production may vary between populations. Fresh seed is viable and the seed does not require treatment or a period of dormancy to germinate. Seed germination rates are high: 70 to 90% (Mullahey *et al*., 1998). In Florida, an individual plant can produce, on average, 125 fruits containing 413 seeds equating to more than >50,000 seeds annually. Cooke (1997 cited in Waggy, 2009) suggest that seed production may be greater in Mississippi than in Florida. Eight to 10 *S. viarum* plants in Mississippi have the potential to produce 1 million seeds annually. The amount of seed produced per individual may be less in other parts of the world.

Ripe fruits may stay attached to the plant or fall to the ground and animals may act to spread the seed. It appears cattle consume fruits and disperse viable seeds in manure as seedling tropical soda apple plants have been observed in livestock manure patties. In the US, detection of tropical soda apple plants adjacent infested pastures, but outside perimeter fences, is also strong evidence other animals likely consume fruits and disperse viable seeds. Emerged tropical soda apple plants have also been documented from bags of livestock manure retailed for flower bed and garden fertilization.

In controlled conditions, Patterson *et al.* (1997) showed that time from seedling emergence to appearance of the 1st flower ranged from 43 days with a 32/26 °C day-night temperature regime to 60 days with a 23/17 °C regime. In the USA, *S. viarum* has rapid growth rates and can flower and develop fruit at day 75 after germination. From a study conducted in Florida, seedlings in a pasture were shown to grow 20 cm in height with eight leaves per plant in 60-80 days. These plants flowered at 120 days. Other studies have shown plants attain rapid growth during the first 125 days of growth with some plants developing fruit between 75-100 days. In other regions, growth rates may be different dependent on local conditions. For example, in India, *S. viarum* plants have been shown to mature within five months of germination with 4-6 leaves within 45 days of emergence. In parts of India where it is hot, tropical soda apple can be an annual that produces flowers 3 months after germination and mature berries in another 2 months (Waggy, 2009).

In North America, *S. viarum* can form a seed bank but the longevity of the seed bank is not clear. One review suggested that seeds may survive for 2 or more years if soil is relatively dry (Cuda *et al.*, 2004). Other studies, e.g. Mullahey *et al*. (1998) highlight a seed longevity in the soil of up to only 1 year (transient seed bank).

Outside of North America, in Northeast India, *S. viarum* generally flowers all year round with peak flowering occurring during March to April. Mature fruits are present from May to June (Saha and Datta, 2014). An individual plant was shown to produce 30 fruits which can contained 190 to 385 seeds (Saha and Datta, 2014).

2.5 Environmental requirements

2.5.1 Temperature
Solanum viarum prefers tropical to sub-tropical environments (Csurhes, 2012). Mullahey *et al*. (1998) details that in North America frost and freeze events will kill the top growth of the plant, but with essentially no mortality to the roots. Within 2-3 weeks following a frost or freeze event, regrowth is initiated from the plant crown. It is interesting to note that in the EPPO region, Christians and Maglio (2020) note that winter frosts did not appear to affect plants in France, though no information was provided on the severity of the frost event. Frosts are not uncommon in winter, but usually just at night, with daytime temperatures rising to 10-12 °C in winter: in short, the intensity and duration of frosts are generally low (pers. comm. G. Fried, 2022).

Akanda *et al*. (1996) showed that seed germination of *S. viarum* increased from 4 to 64% between 10 and 30 °C, and then declined to 0 at 40 °C, with maximum germination found at 30 °C. The ability to germinate over a wide temperature range (10-35 °C) allows year-round germination in much of the southeastern USA (Akanda *et al*., 1996) and therefore also in climatically-similar other parts of the world (including part of the EPPO Mediterranean area).

Patterson *et al*. (1997) conducted experiments to determine the temperature and photoperiod requirements of *S. viarum* by growing plants in growth chambers in 16 day/night temperature regimes ranging from 18/8 to 36/26 °C. After 100 d of growth, maximum height and leaf area occurred at 36/26 °C day/night, and maximum shoot weight occurred at 24/26 to 36/20 or 36/26 °C. Plants survived in 8 °C nights with day temperatures of 18 to 36 °C, but biomass and leaf area were only 3 to 10% of maximum.

2.5.2 Precipitation
According to CABI (2021) growth and development is enhanced with annual average annual rainfall from 700 mm to 2000 mm. *S. viarum* does not tolerate waterlogged soils.

2.5.2 Soil
Solanum viarum can tolerate a broad range of soil types and textures but it prefers well drained sandy loam soils with high organic matter (CABI, 2021). In North America *S. viarum* has been shown to occur in poorly drained, sandy soils. It can occur in soils with a high percentage of sand (96% to 99%) and a small percentage of silt and clay. In other sites it has been shown to grow in sandy loam soils. In bahiagrass pastures (*Paspalum notatum*), where *S. viarum* can be abundant, soil pH is maintained from 5 to 7. Akanda *et al*. (1996) showed that germination under a variety of soil pH conditions (2-14, with an optimum between 4 and 8) indicating that *S. viarum* could invade many diverse habitats. Alkaline conditions may favour germination. Tropical soda apple may flourish in soils rich in phosphate.

2.5.3 *Shading*
In North America, *S. viarum* can grow in open and shaded sites. Seeds can germinate without light (Akanda *et al*., 1996). Sellers *et al*. (2009) suggest that *S. viarum* prefers open to semi-shaded sites suggesting it may be intolerant of deep shade.

2.6 Habitats
In the native range, *S. viarum* occurs in scattered populations, growing in grasslands, thickets, and disturbed areas (Bianco *et al*. 1997). In Brazil, *S. viarum* is occasional reported as a weed of field crops (Costa *et al*. 1985).

See section 7 for further details on habitats in the EPPO region.

2.9 Existing PRAs
No known risk assessments have been conducted on the species for the EPPO region, or countries within the EPPO region.

A risk assessment has been conducted for the USA (USDA, APHIS, 1994). The result of the risk assessment was high. The calculation was based on the high rating for spread potential, and the high rating for economic and environmental consequences of establishment.

A risk assessment was conducted for Florida where the species scored a total of 24 points resulting in the species being rejected (Gordon *et al*., 2008). This risk assessment used the Australia/New Zealand Weed Risk Assessment Scheme which was adapted for Florida.

A risk assessment was conducted by the Department of Agriculture and Fisheries Biosecurity Queensland (Csurhes, 2012). The outcome of the risk assessment was 'considering the history of the species as a significant weed in Florida and elsewhere, it is highly likely to have similar impacts in Queensland'. Climate modelling suggests it is well suited to most of coastal Queensland. Habitats most at risk are predicted to include a range of disturbed sites, especially overgrazed cattle paddocks.

3. Is the pest a vector? **Yes** ☐ **No** X

Although *S. viarum* is not a vector, it has been reported as a weed reservoir for plant viruses in the USA (McGovern *et al*., 1994a; 1994b, 1996). The viruses detected included cucumber mosaic virus (CMV), potato leaf roll virus (PLRV), potato virus Y (PVY), tobacco etch virus (TEV), tomato mosaic virus (ToMV), and tomato mottle virus (TMoV). Additionally, the Tropical soda apple mosaic virus (TSAMV0), a Tobamovirus was isolated from *S. viarum* in Florida (USA). Additionally, in the USA, *S. viarum* supports the reproduction and feeding of *Leptinotarsa decemlineata* (Colorado potato beetle, EPPO A2), *Myzus persicae* (green peach aphid), *Liriomyza brassicae* (serpentine leafminer), *Manduca sexta* (tobacco horn worm), and *Bemisia tabaci* (sweetpotato whitefly, EPPO A2) (Medal *et al*., 2012). EPPO (2022) list additional pests.

4. Is a vector needed for pest entry or spread? **Yes** ☐ **No** X

5. Regulatory status of the pest
In Chile, *S. viarum* is an A1 pest since 2019 and in Mexico it is listed as a quarantine pest since 2018 (EPPO, 2022).

In the USA, *S. viarum* is listed on both the Federal Noxious Weed List (1995) maintained by the United States Department of Agriculture (USDA) and both Florida Noxious Weed List (1994) maintained by the Florida Department of Agriculture and Consumer Services (FDACS) and Mississippi Noxious Weed List (2004) regulated by the Mississippi Department of Agriculture and Commerce Bureau of Plant Industry. It is unlawful to introduce, possess, move or release *Solanum viarum* except under a permit by the USDA, FDACS or MDAC. *S. viarum* can also be found on many other state noxious weed lists: Alabama, California, North Carolina, South Carolina, Tennessee, Texas, and Virginia.

6. Distribution

Solanum viarum is native to South America where the native range is often described as Brazil, Paraguay, and Argentina (e.g. Mullahey, 1996). However, PoWO (2021) considers the native range includes all countries where the species is recorded in South America.

The species has been introduced into the United States, Mexico, Africa, Asia, Australia, Central America and the Caribbean (Table 1, Figure 1).

Waggy (2009) details for the United States, *S. viarum* is most common in Florida where it has been first collected between 1987 and 1988. It spread to other southeastern and mid-Atlantic states soon after. It has also been reported in Texas, Arkansas, Louisiana, Mississippi, Alabama, Georgia, South Carolina, North Carolina, Texas, Pennsylvania and Puerto Rico. It is reported as invasive in Alabama, Florida, Mississippi and Georgia. By 2002, researchers had reported that the species may have been eradicated from Louisiana, Tennessee, and Pennsylvania, so its occurrence in these states is uncertain. By 2007, many of the small infestations of tropical soda apple had been eliminated in Mississippi. In addition to the above records, EDD Maps (2021) detail an occurrence in California, though it is not possible to confirm this record.

Solanum viarum was first detected in Australia in northern New South Wales (Kempsey 2022) in 2010. In late November 2010, *S. viarum* was detected for the first time in Queensland in cattle yards near Coominya, South-East Queensland (State of Queensland, 2016). It is now present in numerous locations in Queensland and New South Wales (Atlas of Living Australia, 2022).

The most recent country where *S. viarum* was discovered was Iran, where it was reported from around Qadikola in Mazandaran province north of Iran (Eskandari and Fouladkolaei, 2020).

Fig. 1. The global distribution of *Solanum viarum*

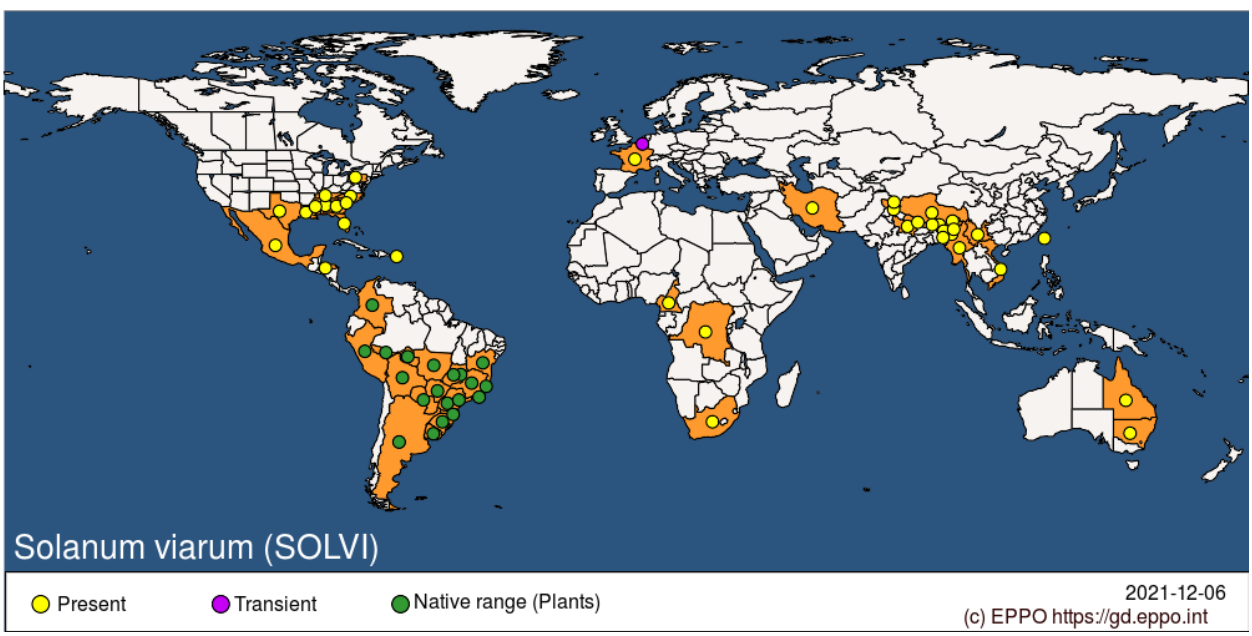


Table 1 Global distribution of *Solanum viarum*

Region	Distribution	Status	Reference
Africa	Cameroon	Introduced	Welman (2003)
	Democratic republic of Congo	Introduced	Welman (2003)
	Eswatini	Introduced	Welman (2003)
	South Africa	Introduced	Welman (2003)
North America	Mexico	Introduced	USDA-NRCS (2008)
USA	Alabama	Introduced	USDA-NRCS (2008)
	Florida	Introduced	USDA-NRCS (2008); Byrd *et al*. (2009)
	Georgia	Introduced	USDA-NRCS (2012); Byrd *et al*. (2009)
	Louisiana	Introduced	USDA-NRCS (2008)
	Mainland USA	Introduced	USDA-NRCS (2008)
	Mississippi	Introduced	Byrd *et al*. (2009); EDD Maps (2021)
	North Carolina	Introduced	USDA-NRCS (2008)
	Oklahoma	Introduced	EDD Maps (2021)
	Pennsylvania	Introduced	USDA-NRCS (2008)
	South Carolina	Introduced	USDA-NRCS (2008)
	Texas	Introduced	USDA-NRCS (2008)
Central America and the Caribbean	Honduras	Introduced	Díaz *et al*. (2008)
	Puerto Rico	Introduced	Kairo *et al*. (2003)
South America	Argentina	Native	PoWO (2021)
	Bolivia	Native	PoWO (2021)
	Brazil	Native	Flora do Brazil (2021)
	Colombia	Native	PoWO (2021)
	Paraguay	Native	PoWO (2021)
	Peru	Native	PoWO (2021)
	Uruguay	Native	PoWO (2021)
Asia	Bhutan	Introduced	Mill (2001)
	China (Xizhang, Yunnan)	Introduced	Flora of China (2008)
	India	Introduced	Chandra (2012)
	Iran	Introduced	Eskandari and Fouladkolaei (2020)
	Myanmar	Introduced	Mill (2001)
	Nepal	Introduced	Welman (2003)
	Taiwan	Introduced	Talekar *et al*. (1999)
	Vietnam	Introduced	Katz (2019)

EPPO region	Belgium	Transient	Verloove (2003)
	France	Present	Christians and Maglio (2020)
Oceania	Australia (NSW, Queensland)	Introduced	Atlas of Living Australia (2020)

Specific details about the distribution in selected EPPO countries (where available)

In **Belgium**, *S. viarum* was recorded as an ephemeral alien, introduced as a soyabean contaminant in the port of Gent (Vamo Mills at Rodenhuizedok) in 2000 (Verloove 2003).

In **France**, the first detection was made in September 2018 by an amateur botanist and then independently in 2019. *S. viarum* was discovered in the Gorges du Gardon a little way downstream from the regional nature reserve (Gard department). In this area, the species was found on the bank of a river in a clearing of a riparian thicket close to a hiking trail. In February 2019, approximately 21 individual plants covering 20 m^2 were recorded in semi-shade, at the edge of a holm oak (*Quercus ilex*) forest dominated by the flowering vine *Smilax aspera*. Christians and Maglio (2020) suggest that the species has been present at this site since 2016.

7. Habitats at risk and their distribution in the PRA area (habitat classification based on EUNIS habitat types)

The table provides information on habitats the species may establish in and habitats which the species is currently established in the EPPO region.

Habitats	**Presence**	**Status of habitat**	**Is the pest present in the habitat in the PRA area (Yes/No)**	**Comments (e.g. *major/minor habitats* in the PRA area)**	***Reference***
C: Inland surface waters	Banks of major waterways, littoral zone of inland surface waterbodies	Protected in part	Yes	Major	Christians and Maglio (2020); Medal *et al*. (2012); Waggy (2009)
E: Grasslands and lands dominated by forbs, mosses or lichens*	E2.1. Permanent mesotrophic pastures and aftermath-grazed meadows; Ruderal environments: road networks (J4-2), rail networks (J4-3)	Protected in part	No	Major	Medal *et al*. (2012); Waggy (2009)
F: Heathland, scrub and tundra	Mediterranean shrublands, shrub-steppes and semi-steppe shrublands	Protected in part	No	Localised	Medal *et al*. (2012); Waggy (2009)
G: Woodland, forest and other wooded land		Protected in part	No	Major	Medal *et al*. (2012); Waggy (2009)
I: Regularly or recently cultivated agricultural, horticultural and domestic habitats	Cultivated fields, bare tilled, fallow or recently abandoned arable land (I1-5),	None	No?	Major	Medal *et al*. (2012); Waggy (2009)
X: Habitat complexes	Gardens of city and town centres (X22 – X25),	None	No*	Major	Medal *et al*. (2012); Waggy (2009)

* But evidence from eBay suggests that the species is grown in gardens within the EPPO region (for example France and Poland).

In the USA, *S. viarum* invades sites associated with anthropogenic disturbance and native plant communities (Waggy,, 2009 ; Medal *et al*., 2012).

In Florida, *S. varium* has been observed in many agricultural lands including perennial grass pastures, primarily pastures planted with Bahia grass (*Paspalum notatum*), citrus (*Citrus* spp.) groves, sugar cane (*Saccharum officinarum* L.) fields, vegetable fields It is also observed on ditch banks. Occurrences of *S. viarum* in native plant communities include hammocks (forest clump or a narrow band of vegetation often dominated by evergreen tree species), hammock edges, cabbage palmetto (*Sabal palmetto*) hammocks, cypress (*Taxodium distichum*) heads or domes (Cypress heads are shallow, forested, usually circular depressions) (Waggy, 2009), oak stands (*Quercu*s spp.), pine forests, riparian habitats and native grassland (Medal *et al*., 2012).

In other southeastern states, *S. viarum* similarly occurs in pastures but also in croplands and native plant communities. It invades wooded areas in Mississippi. In Texas, it occurs in native grasslands and forested areas (Medal *et al*., 2012).

Suitable habitats for the establishment of *S. viarum* occur in the PRA area. The habitats detailed in the table above are widespread within the EPPO region.

In France, *S. viarum* occurs in semi-shade, at the edge of a holm oak (*Quercus ilex*) forest dominated by the flowering vine *Smilax aspera* (Christians & Maglio, 2020).

8. Pathways for entry

Seed and grain should be understood in this PRA as defined in ISPM 5 (FAO, 2019):

- Seeds: seeds (in the botanical sense) for planting [ISPM, 1990; revised ICPM, 2001; CPM, 2016]
- Grain: Seeds (in the botanical sense) for processing or consumption, but not for planting

The following pathways for entry of *S. viarum* are discussed in this PRA. Pathways in bold are studied in section 8.1; other pathways were considered as a very low likelihood of entry and are detailed in section 8.2.

- **Plants for planting (horticulture)**
- **Plants for planting (scientific purposes)**
- *Paspalum notatum* seed
- Grain
- Turf
- Used machinery and equipment
- Travellers and their equipment
- Hay
- Natural spread
- Manure
- Soil and other growing media
- Livestock

8.1 Pathways studied

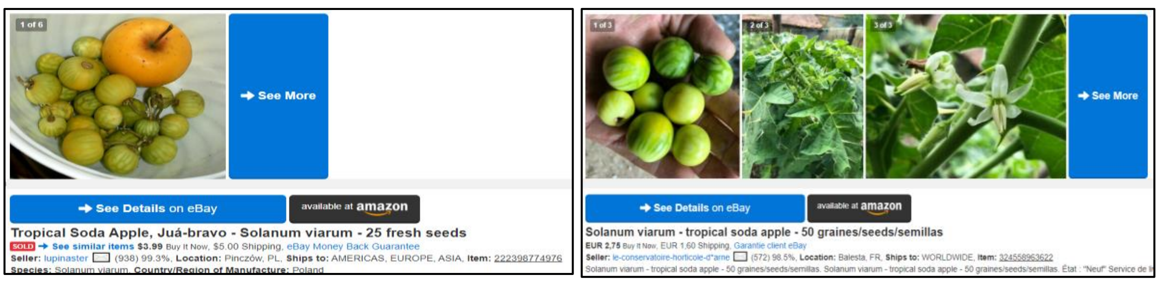
All the pathways are considered from areas where the pest has been reported to be present, into the EPPO region. Examples of prohibition or inspection are given only for some EPPO countries (in this express PRA the regulations of all EPPO countries was not fully analysed). Similarly, the current phytosanitary requirements of EPPO countries in place on the different pathways are not detailed in this PRA (although some were taken into account when looking at management options). EPPO countries would have to check whether their current requirements are appropriate to help preventing the introduction of the pest.

The EWG acknowledged that there is a lack of information for all pathways of entry and therefore considered a detailed analysis was not possible for pathways detailed in section 8.1. The EWG did however, score the rating and uncertainty of the pathways in section 8.1 as a group.

Plants for planting (horticulture)
There is limited evidence that *S. viarum* is sold within the EPPO region. However, only a very limited number of suppliers have been identified (suppliers can be found via e-commerce: see figures 2 and 3). The most likely stage associated with the pathway would be seed though live plants could also be imported. The volume and frequency of movement along this pathway are unknown and likely to be very low. *S. viarum* could transfer from this pathway to a suitable habitat as propagules would be planted outside in a garden. Misidentification of *Solanum* species may result in inadvertent introductions.

Very low likelihood of entry with a moderate uncertainty (not a classical ornamental species, very few suppliers, uncertainty with e-commerce, misidentification).

s



Figures 2 and 3. Examples of suppliers of *Solanum viarum* seed from Poland and France.

Plants for planting (scientific purposes)
Solanum viarum has been imported into the EPPO region for scientific studies on grafting of eggplants and scientific/agronomic experimental trials. Eggplant (*Solanum melongena* L.), an important crop in the world and in the EPPO region, is susceptible to soil borne pathogens in temperate areas (*Verticillium* sp.) and root knot nematodes (*Meloidogyne* spp.). Grafting on resistant rootstock is an alternative method to soil disinfection and has been used also to reduce cadmium content in fruits. In France, the generalised use of grafting spread over the 2000's. After several years of utilization of resistant tomato rootstocks for eggplant production, and to a lesser extent, of *Solanum torvum* rootstocks, damaging wilt-like-symptoms were often observed by growers. It was therefore necessary to identify alternative rootstocks. However, graft affinity between potential rootstocks and eggplant (scion) is the first step to investigate. Screening of a wide set of genetic resources was carried out at the *Centre Technique Interprofessionnel des Fruits et Légumes* – Ctifl - (Lanxade and Balandran center) in collaboration with INRAE. Experiments were carried out during a five-year period (2011-2015) with several *Solanum* species including *Solanum viarum* (seed source INRA-GAFL, without spines). Further studies with the MM 01602 accession of *Solanum viarum* on root phenotypic diversity were conducted at the INRAE Centre for Vegetable Germplasm, Avignon, France in 2019. Even earlier, during the EU EGGNET Project (2000-2005) 56 different accessions of *Solanum* (including *S. viarum*) were tested for rootstock resistant to *Verticillum dahliae* (Bletsos and Olympios, 2008) were tested in Europe. There is no evidence that *S. varium* is used commercially for grafting in the EPPO region. The most likely stage associated with the pathway would be seed though live plants could

also be imported. The volume and frequency of movement along this pathway are unknown and likely to be very low.

Very low likelihood of entry with a low uncertainty (trials will be conducted under strict regulation with little opportunity to escape).

8.2 Pathways with a very low likelihood of entry

***Paspalum notatum* seed.** *S. viarum* has been reported as a contaminant of *Paspalum notatum* (bahiagrass) seed in North America where contamination has likely occurred from farm to farm seed sales of non-certified seed (Bryson *et al.* 1994; Mullahey, 1996). *Paspalum notatum* is widely planted as a drought resistant grass (known commonly as bahiagrass) in the southernmost regions of the EPPO region, and readily escapes. It is established at least in southwestern and Mediterranean France (Tison & de Foucault, 2014), including Corsica (Tison, 2012), Spain (incl. Canary Islands), Greece, and doubtlessly occurs elsewhere in the Mediterranean area, at least as planted turf. Registered varieties exist in Florida which are produced by commercial seed companies, and they can be exported to the EPPO region (bahiagrass is used in trade France and Italy:
https://www.ingegnoli.it/ita/paspalum-notatum-erba-bahia.html
https://www.padanasementi.com/prodotto/paspalum-notatum/
However, the likelihood of *S. viarum* as a contaminant in bahiagrass seed can be considered very low in view of the quality standard of seed (plants for planting). (The EWG assessed this pathway with a low uncertainty)

Grain. Verloove (2006) details that *S. viarum* is recorded as a soybean alien in the port of Gent with the means of introduction as 'grain'. As the species is native to South America (in particular Brazil) where soybean is produced and exported to the EPPO region, there is the potential of *S. viarum* to be a contaminant of soybean, however, there is no further evidence that the species has been found as a contaminant of soybean. (EWG assessed this pathway with a moderate uncertainty)

Turf. A number of sources detail that *S. viarum* seed can be transported through the movement of turf (e.g. Florida Department of Agriculture (2021). As turf will contain a large amount of growing media (mainly soil) it is likely that such material will be prohibited for entry into many countries in the EPPO region. (The EWG assessed this pathway with a low uncertainty)

Used machinery and equipment. Seed of *S. viarum* may become a contaminant of soil and other growing medium attached to used machinery and equipment. However, there is probably very little movement of used machinery from the countries where the pest occurs into the EPPO region and if there is, it is probable that such equipment would undergo phytosanitary procedures such as decontamination (e.g. In the EU, machinery and vehicles imported from third countries other than Switzerland and which have been operated for agricultural or forestry purposes should be cleaned and free from soil and plant debris (Regulation (EU) 2019/2072)). In addition, this pathway is now covered by an International Standard for Phytosanitary Measures (ISPM 41) (FAO, 2017a). (The EWG assessed this pathway with a low uncertainty)

Travellers and their equipment. *S. viarum* seed may be a contaminant of travellers and their equipment (e.g. shoes, clothes and leisure equipment (tents, bags, etc.)). The site where the species is recorded from France is close to a hiking trail and Christians and Maglio (2020) note that this may be a potential pathway. (The EWG assessed this pathway with a low uncertainty)

Hay. Medal *et al*. (2012) detail the potential of *S. viarum* seed as a contaminant of hay material in the USA. Thus, this pathway is possible in principle, but contamination with seeds seems unlikely. FAO (2022 provides limited data on the export of hay from the USA to the EPPO region, where Austria, Finland, Norway, Sweden and Tunisia are reported to have received imports between 2012 -2017 under the item code 859 Hay (unspecified). (The EWG assessed this pathway with a moderate uncertainty)

Natural spread. Taking into consideration the current area of distribution (see section 6), it is unlikely that *S. viarum* can naturally spread from outside into the PRA area. (The EWG assessed this pathway with a low uncertainty)

Manure. A number of sources in the USA (e.g., Mullahey *et al*., 1998), detail the spread of *S. viarum* through the movement of manure from livestock. In Florida, cow manure has been shown to contain 35 000 to 75 000 seeds per ton of dry manure (Waggy, 2009). The movement of manure from the USA to the EPPO region is likely to be extremely low. Unprocessed manure is prohibited from entering the European Union (Regulation 142/2011). (The EWG assessed this pathway with a low uncertainty)

Soil and other growing media (on its own or associated with plants for planting of non-hosts). (from countries where the pest occurs) (see ISPM 40; FAO, 2017b): import of growing media is prohibited in most EPPO countries (e.g. importation of soil and growing medium as such is prohibited in the EU, and is regulated when associated with plants (Regulation (EU) 2019/2072)). (The EWG assessed this pathway with a low uncertainty)

Livestock. Medal *et al*. (2012) highlights the role of livestock in spreading *S. viarum* within the USA**.** Additionally, it is suggested that *S. varium* seeds may have been accidentally introduced with cattle carrying undigested seeds that were imported from Brazil (Waggy, 2009). Seed can remain in the digestive tract for up to 18 days after consumption (Mullahey *et al*., 1998). (The EWG assessed this pathway with a low uncertainty)

The EWG note that from the pathway assessment, there is no one pathway that is more likely than others. Overall rating of the likelihood of entry combining the assessments from the individual pathways considered:

Rating overall	Very low X	Low ☐	Moderate ☐	High ☐	Very high ☐
Rating of uncertainty			Low ☐	Moderate X	High ☐

9. Likelihood of establishment outdoors in the PRA area

Suitable habitats for the establishment of *S. viarum* are detailed in section 7, and are widespread within the EPPO region. Thus further establishment is likely in regions where climatic conditions are conducive for establishment.

Solanum viarum can tolerate a wide range of environmental parameters from temperature, precipitation, soil type, pH, and shading (see section 2.5). Although the literature suggests that frost will kill the above ground plant parts, Christians and Maglio (2020) note that winter frosts did not kill the plants in France.

9.1 Natural habitats

Solanum viarum is present in one location in the natural environment in the EPPO region (see section 7). The potential for further establishment in a wider area is likely.

Within the EPPO region, natural habitats which may be suitable for the establishment of the species (e.g. riverbanks, wooded habitats or disturbed sites) are widespread. It is likely that *S. viarum* will be able to establish further in the natural environment within the EPPO region, in particular in disturbed habitats. In stable intact natural habitats, interspecies competition patterns may limit the establishment of *S. viarum*.

Small animals may feed on the fruit and spread seeds may promote the spread and establishment potential of *S. viarum* in the natural environment.

9.2 Managed habitats

Solanum viarum is currently absent from managed environments in the EPPO region.

It is very likely that *S. viarum* can establish in the managed environment. This is the main habitat type that the species has invaded in the USA (see Habitats detailed in section 7). It invades pastures, vegetable fields, and perennial crops such a citrus (*Citrus* spp.) and sugar cane (*Saccharum officinale* L.) (Mullahey & Cornell 1994). It is capable of rapidly invading pastures due to its prolific seed production and dispersal by livestock.

Further complications may arise from the reduction in the number of herbicide compounds (in particular compounds with systemic activity against perennial weeds) and the decrease in the number of herbicides treatments associated with the reduction in the use of plant protection products. In particular, to control perennial weeds, such as *S. viarum*, multiple annual application may be required for adequate control. All of these factors potentially foster the establishment of *S. viarum* in the EPPO region

In areas where the climatic conditions are suitable for the establishment of the species, establishment can occur along roadsides, railway networks, nearby processing facilities etc. These habitats may act to promote the spread of the species into other managed habitats in close proximity (e.g. agricultural fields).

9.3 Other factors affecting establishment

Natural enemies
Within the EPPO region, there are no host specific natural enemies of *S. viarum.* Generalist natural enemies will potentially attack the plant, but these are unlikely to inflect enough damage at the population level to influence establishment.

Climatic conditions
The most important climatic variables were precipitation (bio12) and winter temperature (bio6), with a lesser effect of summer temperature (bio10). Optimal locations had annual precipitation above approx. 650 kgm^{-2}, frost-free winters and warm summers above approx. 20 °C. The model also represented weaker negative effects of strong diurnal temperature variation (bio2) and highly seasonal precipitation regimes (bio15).

In the EPPO region, the model predicts climatically suitable areas in relatively humid, warm and frost-free areas such as the southern Atlantic coast of France and Iberia, humid parts of the Mediterranean coast west-facing Mediterranean coasts and the southern coasts of the Black and Caspian Seas (Figure 5). The location in southern France where *S. viarum* is established is predicted suitable.

Outside these suitable areas, the model suggests the main limiting factors are low winter temperature in most of inland Europe other than the Atlantic fringe where summers are too cool. Low precipitation is

predicted to limit occurrence in much of Iberia, the Mediterranean, North Africa, the Middle East and steppic areas towards central Asia (Figure 6).
Predictions of the model for 2041-2070 under both climate change scenarios suggest little loss of current suitability but expansion of the suitable area into western Europe and Italy in particular, driven by warmer summers and milder winters (Figure 7 and 8). Note that these projections assume no land use change.

These results are reflected in the suitability of different European Biogeographical Regions (Bundesamt fur Naturschutz (BfN), 2003) (Figure 9). Regions highly suitable for establishment in the current climate are Macaronesia and Mediterranean though there are also significant suitable areas in southern parts of the Atlantic and Black Sea. By 2041-2070, the model projects Macaronesia to remain highly suitable while there are increases in suitability in the Mediterranean, Atlantic and Black Sea regions.

Soil conditions
Soil conditions are suitable for the species in the EPPO region. *Solanum viarum* can tolerate a broad range of soil types and textures but it prefers well drained sandy loam soils with high organic matter (CABI, 2021).

The EWG scored the likelihood of establishment outdoors in the PRA area as high with a high uncertainty. The EWG based this score on the worst-case scenario, as there are areas where the species can establish based on its sub-tropical origin, and the model output, and taking into consideration the availability of suitable habitats. The high uncertainty reflects that the model shows only a small area of potential establishment for the EPPO region. The only population in the EPPO region is in France and it is on the limits of climatic suitability and unclear if the population is established or transient. The EWG also note that little is known about the adaptability of the species to the different climatic conditions in the EPPO region.

Rating of the likelihood of establishment outdoors in the PRA area	Very low ☐	Low ☐	Moderate ☐	High X	Very high ☐
Rating of uncertainty			Low ☐	Moderate ☐	High X

10. Likelihood of establishment in protected conditions in the PRA area

No evidence was found of the presence of *S. viarum* under protected conditions (other than research facilities) in North America or other areas of its invaded range.

The management of temperatures under protection (e.g. polytunnels, glasshouses) maintains average temperatures between 20 and 35 °C which would be more favourable for the development of the species.

Protected conditions, such as in nurseries and polytunnels, may offer appropriate conditions for the development of *S. viarum*. However, these crops are often produced in highly managed production systems (with possible rotation e.g. for polytunnels) that would limit the likelihood of establishment due to short intervals between consecutive management practices.

The EWG consider that the likelihood of *S. viarum* establishment in protected conditions in the EPPO region is very low with a low uncertainty. Climate in these conditions would be suitable for establishment however, other conditions e.g., the intense management of the system are likely to reduce the likelihood of establishment, no evidence of establishment under protected conditions in the USA.

Rating of the likelihood of establishment in protected conditions	Very low X	Low ☐	Moderate ☐	High ☐	Very high ☐
Rating of uncertainty			Low X	Moderate ☐	High

11. Spread in the PRA area

This section is mostly based on information coming from outside of the PRA area, mainly North America and where relevant, it is related to the EPPO region.

Within the EPPO region, *S. viarum* has not shown to spread from its current limited distribution in France.

In North America, *S. viarum* has shown a rapid rate of spread. In Florida alone Mullahey *et al*., (1998) estimated that the area of land infested by *S. viarum* in 1990 was 10 000 ha, in 1993 162 000 ha and in 1995 0.5 million ha. Spread is mainly facilitated by human assisted spread including used machinery, movement of livestock, and other agricultural/habitat material.

Solanum viarum produces many seeds averaging 50,000/plant/year (Mullahey *et al*., 1998), which facilitates the spread of the species.

Natural spread

Natural spread in North America is primarily via the spread of small seed which may be dispersed by small mammals. Deer, birds, rodents, feral pigs and racoons have all been suggested as animals that will digest the fruit and spread the seed (Cuda *et al*., 2002). Reptiles (tegu lizard (*Tupinambis merianae*) have also been detailed as feeding on the fruits and dispersing the seed (Castro and Galetti, 2004 cited in CABI, 2021).

Seeds which are not dispersed by animals are likely to fall close to the parent plant (Waggy, 2009).

Spread by natural dispersal mechanisms, in particular small mammals is likely to occur in the EPPO region though to-date, this has not been studied and there is some uncertainty if small mammals within the region will consume the berries and spread seed. In the EPPO region, natural spread is likely to spread the species locally.

The one population in the EPPO region is within a flood plain of a river (Christians and Maglio, 2020) and therefore there is the potential that fruit or seed can be spread via water. This may act to spread seed over long distances. In New South Wales (Australia), *S. viarum* seed has been shown to spread via flood waters where mass germination of *S. viarum* seed was observed downstream following flooding events (Kempsey Shire Council, 2022),

Natural spread pathways are likely to be similar in the EPPO region to those of North America, where animals may feed on the fruit and spread seeds.

Human assisted spread

In the USA (Florida), *S. viarum* has spread rapidly following its first introduction and within five years it had infested half a million hectares. Its estimated annual rate of spread between 1990 and 1995 was 117% in Florida and 35% in other southeastern states (Duncan *et al*., 2004).
Movement of hay, grass seed, grain, turf, machinery and vehicles, and livestock have all been suggested as interstate and intrastate spread pathways for *S. viarum* in the USA. Cattle has also been reported as spreading the seed in Australia (Bio-Security Queensland, 2009). Cuda *et al*. (2002) detail potential local intra-farm spread from disking a field, cattle congregating around a feeder, cleaning of ditch banks.

Although the plant is unpalatable to livestock, they will feed on the fruits (Bryson and Byrd 1994). Cattle are likely to have been the major vector for the intra- and inter-state movement of *S. viarum* in the United States (Bryson and Byrd 1994). The number of infested acres in Georgia, Mississippi, and Alabama was directly related to the number of cattle imported from Florida (Bryson and Byrd, 1994).

Wunderlin *et al*. (1993) also attribute the rapid spread from pasture to pasture to the transport of hay and farm machinery.

Online sales of the fruit/seeds (see section 8.1. Plants for planting: horticulture) may also contribute to human assisted spread. The species may be accidental or deliberate spread into the natural environment.

The vectors for spread from North America and Australia, e.g. spread via cattle and movement of equipment and used machinery, also occur in the EPPO region. However, these mechanisms may not be in the same volumes and frequencies as in North America.

With climate change, and the potential increase in established populations, spread may increase within the EPPO region. If climate change promotes establishment, populations may produce higher propagule pressure and the frequency of spread may be higher.

High magnitude of spread. Spread via flooding events can act to spread *S. viarum* over long distances. The species is shown to spread via human assisted mechanisms which would potentially move the species over long distances. However, the EWG considered this score should have a high uncertainty as the majority of information on spread is taken from North America. Additionally, spread mechanisms such as via cattle may be more restricted (in terms of movement, frequency and volume) in the EPPO region which may lead to lower spread compared to North America.

Rating of the magnitude of spread in the PRA area	Very low ☐	Low ☐	Moderate ☐	High X	Very high ☐
Rating of uncertainty			Low ☐	Moderate ☐	High X

12. Impact in the current area of distribution (excluding the EPPO region)

For management options see section See section 16.2

It should be noted that the negative impacts of the species are predominantly associated with economic impacts of crop yield reductions where the species invades agricultural habitats and economic impacts on cattle production and management (Thomas, 2007).

12.1 Impacts on biodiversity

There are only limited scientific studies that have assessed the impact of *S. viarum* on biological diversity in the current area of distribution. Some researchers have concluded *S. viarum* can form dense monospecific stands where it invades (Waggy, 2009; Medal *et al*., 2012) although this has not been frequently observed. Waggy (2009, citing Mullahey, 1996) states '[*Solanum viarum*] also reduces biodiversity in natural forests because plants are able to dominate large areas in the understory affecting the germination and establishment of native species. In the southeastern USA it infests natural areas including state parks, nature reserves and hammocks (raised woodland above swamp land) (Mullahey, 1996)'. Plant prickles can also restrict wildlife grazing and create a physical barrier to animals, preventing movement through infested areas (USDA-FS, 2005). In Vietnam, Katz (2019) conducted a study assessing the impact of *S. viarum* on native plant species in natural pastures and forest areas. The study showed that neither species richness nor total vegetation cover was affected by the occurrence of *S. viarum.*

12.2 Impacts on ecosystem services

Solanum viarum has an impact on ecosystem services within the current area of distribution (see table below).

Ecosystem service	**Does the pest impact on this Ecosystem service?** Yes/No	**Short description of impact**	**Reference**
Provisioning	Yes	Reduces yields in pastures and can have a negative impact on cattle production	Waggy (2009)
Regulating	No	No studies have investigated regulating impacts	
Supporting	No	No studies have investigated supporting impacts	
Cultural	No recorded impact	No studies have investigated cultural impacts though the species could restrict access due to the formation on monospecific stands and the sharp spines.	EWG opinion

12.3 Socio-economic impacts

Information on socio-economic impacts is mainly available from North America. The economic consequences associated with the presence of *S. viarum* are considered important from an agricultural point of view:

(1) it is a common weed in pastures,
(2) it is considered toxic to livestock,
(3) displaces grass species,
(4) it is a host to many crop diseases and pests.

In the USA (Florida) *S. viarum* has had high socio-economic impacts on agriculture, in particular the cattle industry. *S. viarum* invades improved pastures and can have a negative impact on the livestock carry capacity. However, Mullahey and Cornell (1994) stated most pastures in Florida did not have *S. viarum* populations of sufficient density to justify pasture renovation. Dense stands have been shown to prevent access of cattle to shaded areas which cattle require to shelter from the sun. This can inflict heat stress on cattle, and it has been estimated that this alone can result in economic losses of $2 million annually (1 771 200 Euro) (Mullahey *et al*. 1998). *Solanum viarum* was reported to cause an estimated $11 million annually in production losses to Florida cattle ranchers (Mullahey *et al*. 1994 in Duncan *et al*. 2004). In another study about the economic impact of *S. viarum*, Salaudeen *et al*. (2013) concluded that "The total annual economic impact to the state of Florida was $14.99 million" and that "With state-wide direct losses at $8.11 million annually (2006 dollars) TSA is a major concern for cattle producers in Florida and other southeastern states" In Florida, management practices (mowing and herbicide application) have been estimated to cost between US $61 (54 Euros) and $47 (41.6 Euros) per ha. It should be noted that all of the aforementioned costs are from the late 1990s and early 2000s before the implementation of a biological control programme. It is estimated that biological control has reduced the management costs of *S. viarum* in Florida by 50 % (Diaz *et al*., 2014).

Solanum viarum contains solasodine which is toxic to humans and animals (Waggy, 2009). There is a higher concentration of solasodine in the fruit, especially in the mucilaginous layer surrounding the seed and the concentration increases as the fruit matures.

There is evidence that *S. viarum* reduces pasture grass. *S. viarum* has been shown to reduce the production of bahiagrass (*Paspalum notatum*) in pastures (Mullahey *et al*., 1999). Akanda *et al*. (1996) also stressed that due to its vigorous growth in pastures, *S. viarum* can easily shade grasses after 3 months. Call *et al*. (2000) showed that *S. viarum* was more competitive than tall fescue (*Festuca arundinacea*) and yield losses of tall fescue ranged from 1-31% for 8-64 *S. viarum* plants/700 cm^2. After 10 week of competition, *S. viarum* monopolized the canopy with a coverage of 92 and 94% while tall fescue coverage was limited to only 7 and 5%. Waggy (2009) highlight displacing shade intolerant grasses as one of the biggest impacts of the species in Florida.

It is speculated that *S. viarum* can be a threat to the vegetable crop industry as it is an alternate host to a number of viruses and pathogens. *Solanum viarum* has been reported as a weed reservoir for plant viruses in the USA (McGovern *et al*., 1994b). The viruses detected included cucumber mosaic virus (CMV), potato leaf roll virus (PLRV), potato virus Y (PVY), tobacco etch virus (TEV), tomato mosaic virus (ToMV), and tomato mottle virus (TMoV). Additionally, the Tropical soda apple mosaic virus (TSAMV0), a Tobamovirus was isolated from *S. viarum* in Florida (USA). In addition, bidens mottle virus (BIMOVO) was identified in *S. viarum* in the USA (Baker *et al*., 2007). This virus has a wide host range including agricultural crop species. Also, in the USA, *S. viarum* supports the reproduction and feeding of *Leptinotarsa decemlineata* (Colorado potato beetle, EPPO A2), *Myzus persicae* (green peach aphid), *Liriomyza brassicae* (serpentine leafminer), *Manduca sexta* (tobacco horn worm), and *Bemisia tabaci* (sweetpotato whitefly, EPPO A2) (Medal *et al*., 2012). All of the aforementioned pests have the potential to cause economic damage.

A moderate rating of magnitude was scored by the EWG along with a moderate rating of uncertainty. The EWG agreed this scoring based on the fact that the economic impacts that are detailed are all from the late 1990s and early 2000's, and are not currently being realised in North America. This could potentially be due to the reduced cost of control products and better control options. In addition, a biological control programme was initiated against the species in North America which may have decreased its impact in rangeland.

Rating of the magnitude of impact in the current area of distribution	Very low ☐	Low ☐	Moderate X	High ☐	Very high ☐
Rating of uncertainty			Low ☐	Moderate X	High ☐

13. Potential impact in the PRA area

At present, there are no negative impacts recorded for the EPPO region. The species is present in the natural environment (in France) in one location. *S. viarum* has the potential to establish in a limited area of the EPPO region (see section 9) and a variety of habitats, both natural and agricultural (see section 7).

13.1 Potential impacts on biodiversity in the PRA area

In areas that are climatically suitable for the optimal growth and reproduction of *S. viarum*, there is the potential for impacts on biological diversity. The species has the potential to compete with native species for resources (space, light and nutrients). This may lead to a displacement of native biodiversity in areas where *S. viarum* invades. The invasion of the species in natural areas may also have a negative impact on higher trophic levels. No information can be inferred from the situation in France.

13.2 Potential impact on ecosystem services in the PRA area

There is the potential for impacts on ecosystem services where *S. viarum* invades in the EPPO region. The species can potentially impact on cultural ecosystem services by invading riverbanks and wooded habitats and reducing access to sites. Additionally, the sharp spines can injure people who come in close contact with the plant. Accidentally consuming the fruit can lead to illness (Waggy, 2009).

Impacts on provisioning ecosystem services are dealt with under 'socio-economic impacts' (see section12.3).

13.3 Potential socio-economic impact in the PRA area

Economic impacts could be realised if the species spreads and establishes in grassland and pasture areas in the EPPO region.

However, there is a limited area of pastureland under the climatic conditions suitable for the establishment of *S. viarum* and therefore it is unlikely that economic impacts as seen in the USA will be replicated in the EPPO region.

Any action targeting control of this species will generate additional production costs (cost of weeding practices, establishment of less profitable crops). However, these costs are unlikely to be on the scale seen in the US in the early 2000s as new management practices and biosecurity measures are likely to reduce the impact.

Will impacts be largely the same as in the current area of distribution? **No**

The EWG scored the magnitude of impact in the PRA area as low with a high uncertainty. Impacts are rated as low in view of the limited climatically suitable areas and habitats in the PRA area. The suitability of habitat is based on the observed presence in North America. However, it is not known if the species will behave the same in the PRA area, especially considering the first record in the EPPO region being recorded along a major river. The high rating of uncertainty also reflects that the genus *Solanum* contains a lot of invasive or weedy species in the EPPO region and worldwide and there is the potential that the species may become invasive in the future. Climate change may also promote the expansion of the species into new areas and habitats.

Rating of the magnitude of impact in the PRA area	Very low ☐	Low X	Moderate ☐	High ☐	Very high ☐
Rating of uncertainty			Low ☐	Moderate ☐	High X

14. Identification of the endangered area

The EWG consider the endangered area to be the coastal areas of the Mediterranean and south Atlantic biogeographical regions. According to the modelling, frost may limit establishment in the inland parts of the EPPO region. Habitats at risk in the endangered area include pastures and agricultural systems, river systems and ruderal habitats. Appendix 2 gives the percentage of suitable areas in each country. The EWG considered the species distribution modelling conducted as part of this PRA (see Appendix 2) to be a realistic projection of the potential occurrence of *S. viarum* in the EPPO region.

15. Overall assessment of risk

	Likelihood	**Uncertainty**
Entry	**V. Low**	**Moderate**
Plants for planting (horticulture).	V. Low	Moderate
Plants for planting (scientific purposes)	V. Low	Low
Establishment outdoors in the PRA area	High	High
Establishment in protected conditions in the PRA area	V. Low	Low
Spread	High	High
Impact in the current area of distribution	Moderate	Moderate
Potential impact in the PRA area	Low	High

The overall likelihood of new introductions entering the EPPO region is very low with a moderate uncertainty. Several pathways were assessed in the PRA but there was no strong association with any pathways. The likelihood of further establishment outdoors is high with high uncertainty. The high uncertainty reflects the small area of potential establishment in the EPPO region. The only population in the EPPO region is in France and it is on the limits of climatic suitability and unclear if the population is established or transient. Establishment in protected conditions is very low with low uncertainty. Temperature within protected conditions would be suitable for the establishment however, other conditions, e.g., the intense management of the system are likely to reduce the likelihood of establishment. The potential for spread within the EPPO region is high with a high uncertainty. *S. viarum* can spread both naturally and via human assisted spread. The species is shown to spread via human assisted mechanisms which would potentially move the species over long distances. However, all spread data is taken from North America which is speculative, hence the high uncertainty score.

The magnitude of impact in the current area of distribution (North America) is moderate with a moderate uncertainty. The species has had an impact on pasture production and cattle in North America in the late 1990s and early 2000s, but improved management (biological and chemical control) has reduced the impact. The EWG considered the potential socio-economic impacts in the EPPO region will be low with a high uncertainty. The high uncertainty reflects the unknowns relating to the plasticity of *S. viarum* and its ability to adapt to climatic and environmental parameters in the EPPO region. This in turn gives uncertainty to the level and type of impacts the species may have in the EPPO region.

Stage 3. Pest risk management

16. Phytosanitary measures

The results of the risk assessment show that *Solanum viarum* has a moderate phytosanitary risk to the endangered area with a high uncertainty.

The EWG does not recommend any phytosanitary measures for individual pathways. Several pathways were assessed in the PRA but there was no strong association with any pathways.

The EWG recommend that *S. viarum* is included on the EPPO Observation List.

As the species may be easily confused with other non-native *Solanum* species, listing on the EPPO Observation List may facilitate correct identification of weedy populations and its rapid intervention. At present only one population exists in the EPPO region in France.

The Expert Working Group recommends that the PRA is reviewed every ten years and/or when significant new information (e.g. establishment in the endangered area or occurrence of further interceptions along pathways) becomes available.

National measures
Early detection is important to identify new occurrences of the species. *S. viarum* should be monitored and eradicated, contained or controlled where it occurs in the endangered area. In addition, public awareness campaigns may be adopted to prevent spread from existing populations and to raise awareness.

16.2 Eradication and containment

Management of *Solanum viarum*

Eradication
Eradication measures provided in this section should be promoted where feasible with a planned strategy to include surveillance, containment (see following paragraph), treatment and follow-up measures to assess the success of such actions. Regional cooperation is essential to promote phytosanitary measures and information exchange in identification and management methods. NPPOs should facilitate collaboration with all sectors to enable early identification including education measures to promote citizen science and linking with universities, land managers and government departments.

Eradication is only considered to be possible for *S. viarum* in case of early detection (newly established populations) of a small population in agricultural productions, or when detected in the natural environment, cargo areas, roadsides and other transportation networks etc.

Eradication may be feasible in some EPPO countries where this species is at an early stage of invasion. It is recommended that member countries eradicate this species where feasible to prevent further spread and impact.

Containment
A pro-active and integrated weed management strategy will be required to effectively manage *S. viarum*. General considerations are listed below. It should be noted that in natural environments, management practices should be tailored to the habitat invaded. NPPOs should provide land managers, farmers and

stakeholders with identification guides including information on preventive measures and control techniques.

Prevention

The most appropriate method for prevention is a ban on the possession and movement of the species. In the USA, *S. viarum* is listed on the USA Federal Noxious Weed List, and hence its movement across state lines is prohibited in the USA (USDA-NRCS, 2008).

When moving livestock from areas where *S. viarum* is present, spread can be minimised by holding livestock in restricted areas for 6 days. By this time any seeds ingested should have either moved through the system or killed by the natural digestion process of the cattle.

Unintentional transport of *S. viarum* seeds through the movement of agricultural products and equipment should be avoided. Equipment and machinery should be cleaned to remove the weed seeds before moving to an uninfested area (see ISPM 41: *International movement of used vehicles, machinery and equipment*; FAO, 2017a).

Control

Solanum viarum is a difficult invasive species to control due to its prolific seed production, seedbank dynamics and perennial growth habit (it hasn't really formed monocultures in US). The most effective method to control the species is to prevent fruit and subsequent seed set.

Depending on the size of the population, different management actions can be employed. Individual plants, or very small populations can be managed by manual removal of the plants and safe disposal of all plant parts. *Solanum viarum* plants with fruit < 1.0 cm. in diameter can be hand-removed or mowed without special treatment to destroy fruits or seeds as Bryson & Byrd (2007) showed that under this fruit size, does not contain viable seed. Disposal may include burning of the plants. Below ground parts are more difficult. However, it is shallowly rooted thus easily removed by hand. All roots should be removed as the plant can regenerate from fragments. When controlling larger populations, repeated applications (chemical control or manual control) may be required and the seed bank should be exhausted to ensure no regeneration.

Chemical control

A number of active ingredients are available to control *S. viarum* and these include aminopyralid, glyphosate, imazapyr or triclopyr. Chemical application is effective against all plant parts except for the fruits, which should be collected and disposed either by cooking in an oven or microwave Other recommended herbicides include aminopyralid (Akanda *et al*., 1997; Ferrell *et al*., 2006), hexazinone (Mislevy and Martin, 1999), glufosinate-ammonium, picloram, clopyralid, fluroxypyr and dicamba (Dowler, 1995).

Effectiveness of triclopyr and hexazinone was enhanced when they were applied 60 days after frost had damaged the foliage (Mislevy and Martin, 1999). However, aminopyralid can be applied at any time of year and will control existing plants and germinating seedlings for over 6 months after application (Hogue *et al*., 2006).

Treatments containing picloram or triclopyr controlled eight-leaf, 16-leaf, and 1-yr-old *S. viarum* greater than 90%, 8 weeks after treatment (Call *et al*., 2000). Acifluorfen, clopyralid, dicamba, fluroxypyr, picloram, triclopyr, glyphosate and imazapyr all resulted in >90% weed control after 145 days, though the latter two also caused >90% damage to *Paspalum notatum* (Akanda *et al*., 1997).

Mechanical control

Cultural practices such as discing, that fragment *S. viarum* roots, will help spread the weed because of regeneration from roots (Mullahey & Cornell, 1994). Mowing alone can achieve a high level of control if repeated. *S. viarum* control increased from 10% 60 d after a single mowing to 92% after three consecutive mowing at 60-d intervals (Mislevy *et al*., 1999).

Biological control

CABI (2021) reviews the biological control of *S. viarum* as below:

A petition for release of *Gratiana boliviana* in the USA was approved in 2002 (Medal *et al*., 2007; USDA/TAG, 2008). The beetle was introduced from Argentina and Paraguay: releases began in Florida in 2003 and more than 100,000 beetles have been released in Florida, Georgia, Alabama, South Carolina and Texas. Establishment has been good, with spread of 1-10 miles (1.5-16.0 km) per year from the release sites, with 20-100% defoliation and no non-target damage has been observed (Medal *et al*., 2006; 2007; Medal, 2008). Studies have shown that *G. boliviana* is better suited for control of small infestations of *S. viarum* than large or remote infestations (Waggy, 2009).

Field tests in Brazil and Argentina confirmed the specificity of *Metriona elatior* to *S. viarum* and lack of attack on related solanaceous crops (Bredow *et al*., 2007; Gandolfo *et al*., 2007), and "these data suggest that a host range expansion of *M. elatior* to include eggplant, potato, tomato, or bell-pepper is highly unlikely" (Bredow *et al*., 2007). However, other laboratory tests had shown some feeding on eggplant (Medal *et al*., 2002) and the release of *M. elatior* in the USA was rejected in 2008 (USDA/TAG, 2008). Release of *Gratiana graminea* was also refused at this time. A petition to release *Anthonomus tenebrosus* was submitted in 2007 (USDA/TAG, 2008), and work with the flower-bud weevil, *Platyphora* sp. is apparently still in progress.

A bioherbicide containing tobacco mild green mosaic virus strain U2 has been recently registered for use against *S. viarum* in the USA (Charudattan and Hiebert, 2007; Charudattan, 2015).

Integrated management

Integrated weed management strategies include prevention (avoidance of contaminated hay or grass seed, control of movement of cattle), control (mechanical, chemical, biological) and monitoring (Mullahey *et al*., 1998). Integrated control combining bioherbicides with chemical herbicides have been shown to be more effective than the chemical treatments alone (Roberts *et al*., 2002; Ferrell *et al*., 2008).

Mechanical control (mowing) combined with chemical application can also achieve a high level of control. Mislevy *et al.* (1999) conducted field studies to evaluate mowing followed by herbicide at several application rates. Mature *S. viarum* plants were mowed one, two, or three times to a 7.5-cm stubble with a 60-d interval between mowings. Triclopyr was applied at 0, 0.6, and 1.1 kg ai/ha at 375 L/ha at 207 kPa 60 d after each mowing treatment. Mowing *S. viarum* twice before an application of 0.6 kg ai/ha triclopyr resulted in 100% control.

Effectiveness of triclopyr was similarly enhanced when applied after one or two prior mowings (Miselvy *et al*., 1999).

17. Uncertainty

Main sources of uncertainties in this risk assessment are linked to:

- The pathway that resulted in the occurrence of *S. varium* in France,
- The plasticity of *S. viarum* and its ability to adapt to climatic and environmental parameters in the EPPO region,

- If spread mechanisms will be the same in the EPPO region as seen outside of the EPPO region,
- If animals will spread the fruit in the EPPO region,
- Level and type of impact in the EPPO region.

18. Remarks

Whenever the species is maintained in germplasm collection, or used for breeding purposes, adequate biosecurity measures should be applied to avoid any risk of escape from cultivation.

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Appendix 1. Relevant illustrative pictures of *Solanum viarum* (for information)

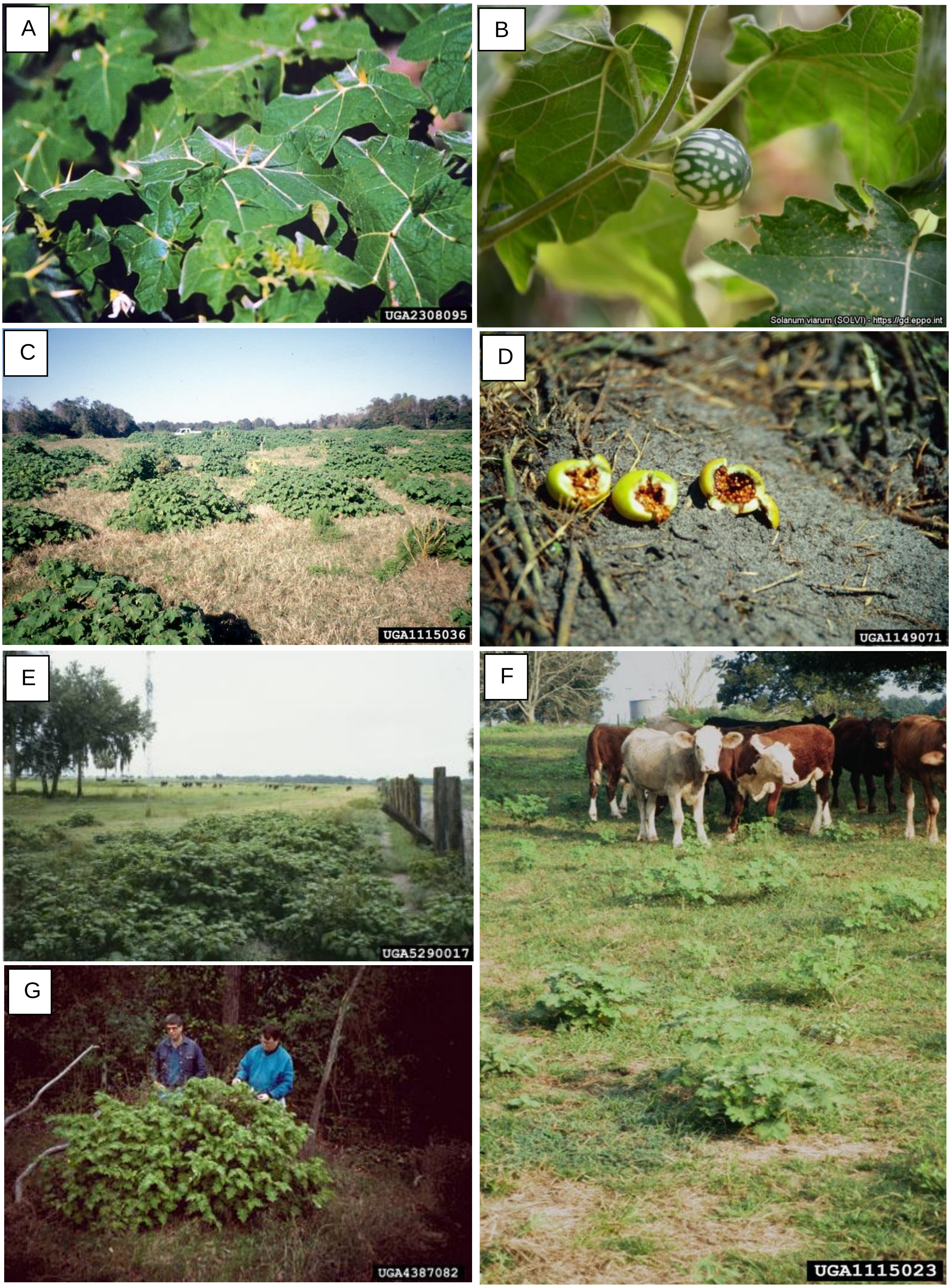


Fig. A. Leaves and spines (Image James Rollins, Bugwood); **Fig. B**. Fruit (Collias France) (EPPO Global Database Image courtesy Guillaume Fried; **Fig. C**. infestation North America (Image Charles T. Bryson, Bugwood); **Fig. D**. Fruit (Image USDA APHIS PPQ – Oxford North Carolina, Bugwood); **Fig. E**. Infestation North America (Image, Peggy Greb, Bugwood) **Fig. F**. infestation cattle pasture (Image Charles T. Bryson, Bugwood); **Fig. G.** Tropical soda apple plant (Image Arthur E Miller, USDA APHIS PPQ, Bugwood);

Appendix 2. Projection of climate suitability for *S. viarum* establishment in the EPPO region

Climatic suitability modelling for *Solanum viarum* establishment in the EPPO region

Aim
To project the climatic suitability for potential establishment of *Solanum viarum* in Europe and the Mediterranean region, under current and predicted future climatic conditions.

Data for modelling
Species occurrence data were obtained from the Global Biodiversity Information Facility (Gbif.Org, 2022), iNaturalist, Integrated Digitized Biocollections (iDigBio), USGS Biodiversity Information Serving Our Nation (BISON), EDDMapS and Atlas of Living Australia. The records were scrutinised to remove any considered of dubious quality (e.g. suspected casual or cultivated occurrence, imprecise or bad coordinates, no date or older than 1970).

On the advice of the EWG, only records from the native range in South America and the invaded ranges in North America, South Africa and Australia were used in the modelling. This excluded many records from Asia, including in the Himalayan region. The EWG considered these records potentially unreliable for modelling climatic suitability for the species. *S. viarum* is reported as being cultivated medicinally widely in Asia and so may be planted outside its climate niche. Furthermore, information on cultivation was unclear and there may be taxonomic confusion with other native *Solanum* species that are difficult to separate reliably. Additionally extreme topographic heterogeneity in the Himalayas may yield presence in locations that are overall climatically unsuitable (e.g. presence in a sheltered valley floor in an otherwise very cold grid cell) which could confuse the model.

The records were gridded at a 0.125 x 0.125 degree resolution for modelling (approximately 8 x 13 km in central Europe) (Figure 1a). This resulted in 793 grid cells containing valid records of *S. viarum* (Figure 1a), which is a sufficient number for distribution modelling.

Predictor variables were selected based on the life history and habitat requirements of *S. viarum* and likely limiting factors for establishment in Europe. Predictors included climate from 1981-2010 from the Chelsa database V2.1 (Karger et al., 2017), and preferred land cover types in 2013 from the FAO Global Land Cover - SHARE database (Latham, Cumani, Rosati, & Bloise, 2014):

- Mean temperature of the warmest quarter (bio10 °C) as a measure of growing season heat. Growth of *S. viarum* is temperature dependent with optimal day/night temperatures around 36/20 °C and extremely limited growth at 18/14 and 18/8 °C (Patterson *et al*. 1997). If the warmest part of the year is too cold then *S. viarum* will likely be unable to sustain growth.
- Mean minimum temperature of the coldest month (bio6 °C) since frost kills above and below ground parts of the plants and may limit the northern distribution in USA (Bryson & Byrd, 2007). Overwinter survival of seeds, especially those in intact fruits, may allow the species to persist as an annual in frost-affected areas (Bryson & Byrd, 2007), but there is likely to be a limit to this strategy.
- Mean diurnal temperature variation (bio2 °C) since growth of *S. viarum* is severely limited by cold night temperatures (Patterson et al., 1997).
- Annual precipitation (bio12 kgm^{-2}), which was natural log transformed for modelling.
- Precipitation seasonality (bio15 kgm^{-2}) since highly seasonal precipitation regimes might involve periods of high drought stress.
- Artificial surfaces proportion cover as a preferred habitat listed in the PRA.
- Croplands proportion cover as a preferred habitat listed in the PRA.
- Grasslands proportion cover as a preferred habitat listed in the PRA.
- Forests proportion cover as a preferred habitat listed in the PRA.

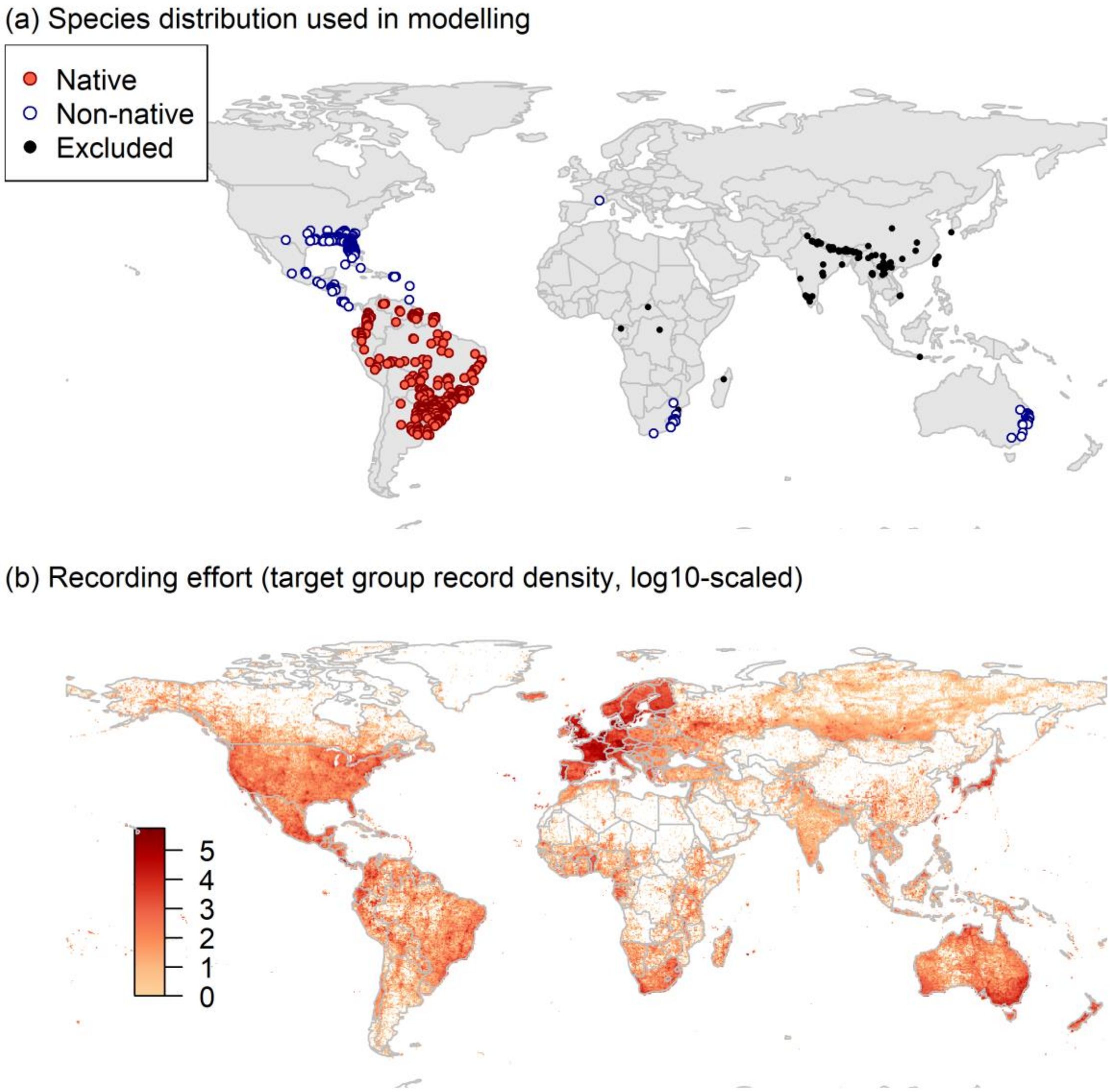
To estimate the effect of climate change on the potential distribution, equivalent modelled future climate conditions for 2041-2070 were obtained for two IPCC Coupled Model Intercomparison Project 6 (CMIP6) scenarios or Shared Socioeconomic Pathways (SSPs) (IPCC, 2021):

- SSP1-2.6 is an optimistic low-emissions scenario in which atmospheric CO_2 concentration peaks below 450 ppm in the mid-21st century and then falls slightly. The estimated warming by around 2050 is 1.7 °C.
- SSP3-7.0 is a high emissions scenario for a world that fails to act to limit warming. Atmospheric CO_2 concentrations rise to approximately 850 ppm by 2100. The estimated warming by around 2050 is 2.1 °C.

For both SSPs, the climate variables for modelling were obtained as averages of outputs of five Global Climate Models (NOAA's GFDL-ESM4, UK Met Office's UKESM1-0-LL, Max Planck Institute's MPI-ESM1-2-HR, Institut Pierre Simon Laplace's IPSL-CM6A-LR, and Meteorological Research Institute's MRI-ESM2-0), downscaled and calibrated against the Chelsa baseline.

Finally, the recording density of vascular plants (phylum Tracheophyta) on GBIF was obtained as a proxy for spatial recording effort bias (Figure 1b).

Figure 1. (a) Occurrence records obtained for *Solanum viarum*, showing the native (South America) and non-native records used in the modelling, as well as the records excluded from the modelling on the advice of the EWG. (b) A proxy for recording effort – the number of post-1970 vascular plant records held by the Global Biodiversity Information Facility, displayed on a $\log_{10}$ scale.



Species distribution model

The modelling followed a recent modification of standard presence-background (presence-only) ensemble distribution modelling for emerging invasive non-native species (Chapman, Pescott, Roy, & Tanner, 2019). This accounts for dispersal constraints on non-equilibrium invasive species' distributions (Elith, Kearney, & Phillips, 2010) by excluding locations suitable for the species but where it has not been able to disperse to.

To do this, background samples (pseudo-absences) were sampled from two distinct background regions:

- An accessible background includes places close to *S. viarum* populations, in which the species is likely to have had sufficient time to disperse and sample the range of environments. Based on potential for long-distance seed dispersal by animals, the accessible background was defined as a 200 km buffer around the native range (minimum convex polygon bounding native occurrences) and a 15 km buffer around non-native occurrences (capturing a 4-cell neighbourhood of the non-native occurrences). Sampling was more restrictive from the invaded range to account for stronger dispersal constraint over a shorter residence time. In previous testing of the model approach alternative buffer radii did not substantively affect the model projections (Chapman et al., 2019).

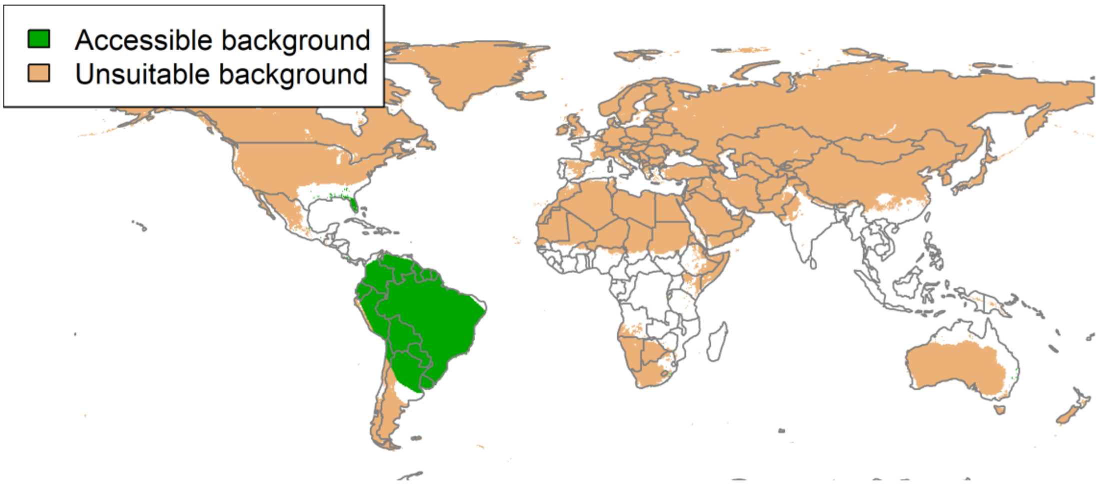
- An unsuitable background includes places expected to be physiologically unsuitable for the species, so that absence will be irrespective of dispersal constraints. Little specific ecophysiological information was available so other than where stated extreme values of the predictors at the species occurrences were used to define unsuitability as:

    - Temperature of the warmest quarter (bio10) < 16 °C, presumed too cold for growth based on experimental exposure to 18/14 °C temperature regimes (Patterson et al., 1997); OR
    - Mean minimum temperature of the coldest month (bio6) < 0.5 °C, presumed too cold for survival through winter; OR
    - Diurnal temperature variation (bio2) > 13 °C, presumed too variable for growth; OR
    - Annual precipitation accumulation (bio12) < 500 kgm^{-2}, presumed too dry; OR
    - Precipitation seasonality (bio15) > 150 kgm^{-2}, presumed to produce periods of severe drought stress

Of the 793 occurrences for modelling, 7 (0.9%) fell in the unsuitable background and were mainly high elevation tropical points in the native range where the species probably occupied warm microclimates relative to the grid cell average (e.g. in a valley bottom of a grid cell that is mainly high elevation).
For modelling, five random background samples were obtained as follows:

- From the accessible background 793 samples were drawn, which is the same number as the occurrences. Sampling was performed with realistic recording bias using the target group approach (S. J. Phillips, 2009) in which sampling was weighted by GBIF Tracheophyte recording density (Figure 1b). Taking the same number of background samples as occurrences ensured the background sample had the same level of bias as the data.
- From the unsuitable background 5000 simple random samples were taken. Sampling was not adjusted for recording biases as we are confident of absence from these regions.

Figure 2. The background regions from which 'pseudo-absences' were sampled for modelling. The accessible background is assumed to represent the range of environments the species has had chance to sample. The unsuitable background is assumed to be environmentally unsuitable for the species.



Using these data, a presence-background (presence-only) ensemble modelling strategy was employed using the BIOMOD2 R package v3.4.6 (Thuiller *et al.*, 2009, 2016). Each dataset (presences and the five individual background samples) was randomly split into 80% for model training and 20% for model evaluation. With each training dataset, seven statistical algorithms were fitted with the default BIOMOD2 settings (except where specified below) and rescaled using logistic regression:

- Generalised linear model (GLM) with linear and quadratic terms for each predictor
- Generalised boosting model (GBM)
- Generalised additive model (GAM) with a maximum of four degrees of freedom per predictor
- Multivariate adaptive regression splines (MARS)
- Artificial neural network (ANN)
- Random forest (RF)
- Maxent (Phillips *et al.*, 2008)

Prevalence weights were applied to give equal overall importance to the occurrences and the background. Normalised variable importance was assessed and variable response functions were produced using BIOMOD2's default procedure. Model predictive performance was assessed by calculating the Area Under the Receiver-Operator Curve (AUC) for model predictions on the evaluation data, which were reserved from model fitting. AUC is the probability that a randomly selected presence has a higher model-predicted suitability than a randomly selected pseudo-absence.

An ensemble model was created by rejecting poorly performing algorithms and then averaging the predictions of the remaining algorithms, weighted by their AUC. To identify poorly performing algorithms, AUC values were converted into modified z-scores based on their difference to the median and the median absolute deviation across all algorithms (Iglewicz & Hoaglin, 1993). Algorithms with $z < -2$ were rejected. In this way, ensemble projections were made for each dataset and then averaged to give an overall suitability.

Global model projections were made for the current climate and for the two climate change scenarios, avoiding model extrapolation beyond the ranges of the input variables. The optimal threshold for partitioning the ensemble predictions into suitable and unsuitable regions was determined using the maximum sum of sensitivity and specificity method, which performs well for presence-only models (Liu *et al.*, 2013).

Limiting factor maps were produced following Elith *et al.* (2010). Projections were made separately with each individual variable fixed at a near-optimal value (median values at the occurrence grid cells). Then, the most strongly limiting factors were identified as the one resulting in the highest increase in suitability in each grid cell.

Results and Discussion

The ensemble model suggested that suitability for *S. viarum* at the global scale and resolution of the model was most strongly limited by climate rather than habitat variables (Table 1). The most important climatic variables were precipitation (bio12) and winter temperature (bio6), with a lesser effect of summer temperature (bio10). Optimal locations had annual precipitation above approx. 650 kgm^{-2}, frost-free winters and warm summers above approx. 20 °C (Figure 3). The model also represented weaker negative effects of strong diurnal temperature variation (bio2) and highly seasonal precipitation regimes (bio15) (Figure 3).
Global projection of the ensemble model in current climatic conditions indicates that >99% of valid native and invaded records fell within regions predicted to have high suitability, i.e. above the threshold of 0.33 maximising the sum of sensitivity and specificity (Figure 4).

Outside of *S. viarum*'s native South American range, the model suggested the species had reached its northern limit of establishment in North America (Figure 4), and would be limited in further northwards range expansion by cold winters in the current climate. Some further invasion on the east coasts of Australia and South Africa is also predicted.

The model also gave a reasonable prediction of the occurrences in Asia and other parts of Africa excluded from the modelling, other than for the highest elevation locations (Figure 4). These were predicted to have too cold winters as a whole, though as noted above the records in such locations may have been in valley floors that are warmer than the overall grid cell.

In the EPPO region, the model predicts climatically suitable areas in relatively humid, warm and frost-free areas such as the southern Atlantic coast of France and Iberia, humid parts of the Mediterranean coast west-facing Mediterranean coasts and the southern coasts of the Black and Caspian Seas (Figure 5). The location in southern France where *S. viarum* is established is predicted suitable.

Outside these suitable areas, the model suggests the main limiting factors are low winter temperature in most of inland Europe other than the Atlantic fringe where summers are too cool. Low precipitation is predicted to limit occurrence in much of Iberia, the Mediterranean, North Africa, the Middle East and steppic areas towards central Asia (Figure 6).

Predictions of the model for 2041-2070 under both climate change scenarios suggest little loss of current suitability but expansion of the suitable area into western Europe and Italy in particular, driven by warmer summers and milder winters (Figure 7 and 8). Note that these projections assume no land use change.
These results are reflected in the suitability of different European Biogeographical Regions (Bundesamt fur Naturschutz (BfN), 2003) (Figure 9). Regions highly suitable for establishment in the current climate are Macaronesia and Mediterranean though there are also significant suitable areas in southern parts of the Atlantic and Black Sea. By 2041-2070, the model projects Macaronesia to remain highly suitable while there are increases in suitability in the Mediterranean, Atlantic and Black Sea regions.

Table 2 provides a similar breakdown by EPPO member state, identifying countries such as Portugal, Albania and Italy as having the most suitable areas currently.

Caveats and uncertainties

Modelling the potential distributions of range-expanding species is always difficult and uncertain. In this case study, uncertainty arises because:

- Exclusion of Asian and African records (except South Africa) from the model leads to some uncertainty in the modelling, but was a pragmatic approach given the questionable status of those records.
- The model aims to predict establishment, but high impact invasion may be more limited to totally frost-free areas within the overall suitable range (e.g. Florida), where the species can establish as a perennial weed.
- The models were constructed using convenient climate and habitat layers, which may not be the most appropriate for *S. viarum*. Specific predictors layers capturing requirements for different stages of the life cycle may have improved the predictions.
- The selection of the background sample was weighted by the density of vascular plant records on the Global Biodiversity Information Facility (GBIF) to reduce spatial recording bias. While this is preferable to not accounting for recording bias at all, a number of factors mean this may not be the perfect null model for species recording, especially because additional data sources to GBIF were used.

Table 1. Summary of the cross-validation predictive performance (AUC) and variable importances of the fitted model algorithms and the ensemble (AUC-weighted average of the best performing algorithms). Results are the average from models fitted to five different background samples of the data.

Algorithm	**AUC**	**In the ensemble**	**Variable importance**								
			Temperature of warmest quarter (bio10)	**Minimum temperature of coldest month (bio6)**	**Diurnal temperature variation (bio2)**	**Annual precipitation (bio12)**	**Precipitation seasonality (bio15)**	**Artificial cover**	**Croplands cover**	**Grassland cover**	**Forest cover**
MAXENT	0.9752	yes	18%	39%	3%	34%	3%	0%	0%	0%	2%
GBM	0.9750	yes	18%	35%	0%	45%	0%	1%	1%	0%	0%
GAM	0.9730	yes	19%	33%	1%	42%	4%	0%	0%	0%	0%
GLM	0.9728	yes	17%	32%	2%	44%	5%	0%	0%	0%	0%
MARS	0.9716	yes	21%	38%	0%	37%	2%	0%	1%	0%	0%
RF	0.9710	yes	8%	35%	3%	41%	2%	2%	4%	2%	2%
ANN	0.9672	no	15%	41%	9%	26%	4%	0%	1%	1%	2%
Ensemble	0.9748	-	17%	35%	2%	40%	3%	1%	1%	1%	1%

Figure 3. Partial response plots from the individual algorithms and ensemble model (thick black lines), ordered from most to least important. In each plot, other model variables are held at their median value in the training data. Variable codes are as in Table 1.

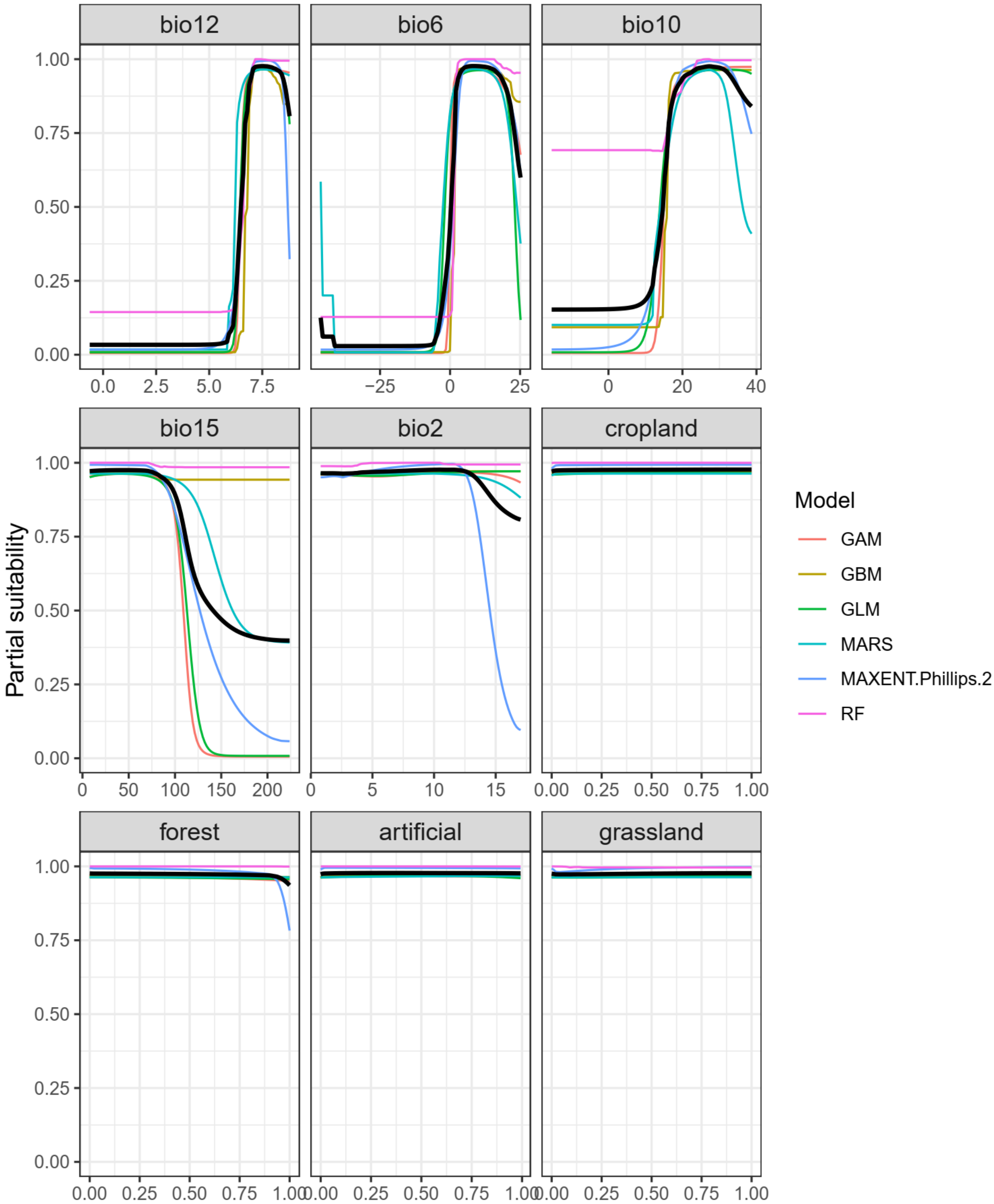


Figure 4. (a) Projected global suitability for *Solanum viarum* establishment in the current climate. For visualisation, the projection has been aggregated to a 0.5 x 0.5 degree resolution, by taking the maximum suitability of constituent higher resolution grid cells. Red shading indicates suitability, according to the selected threshold. (b) Uncertainty in the suitability projections, expressed as the standard deviation of projections from different algorithms in the ensemble model.

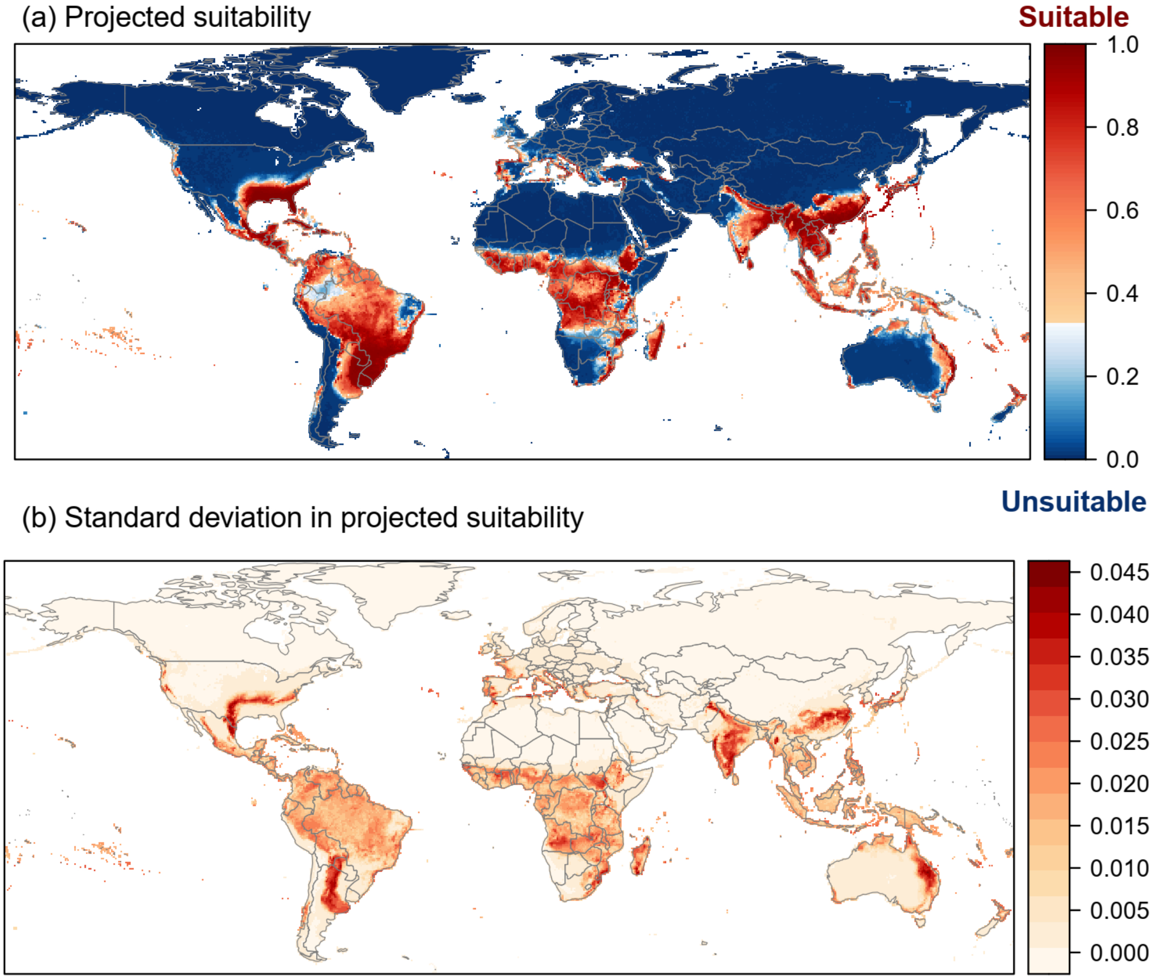


Figure 5. Projected current suitability for *Solanum viarum* establishment in Europe and the Mediterranean region.

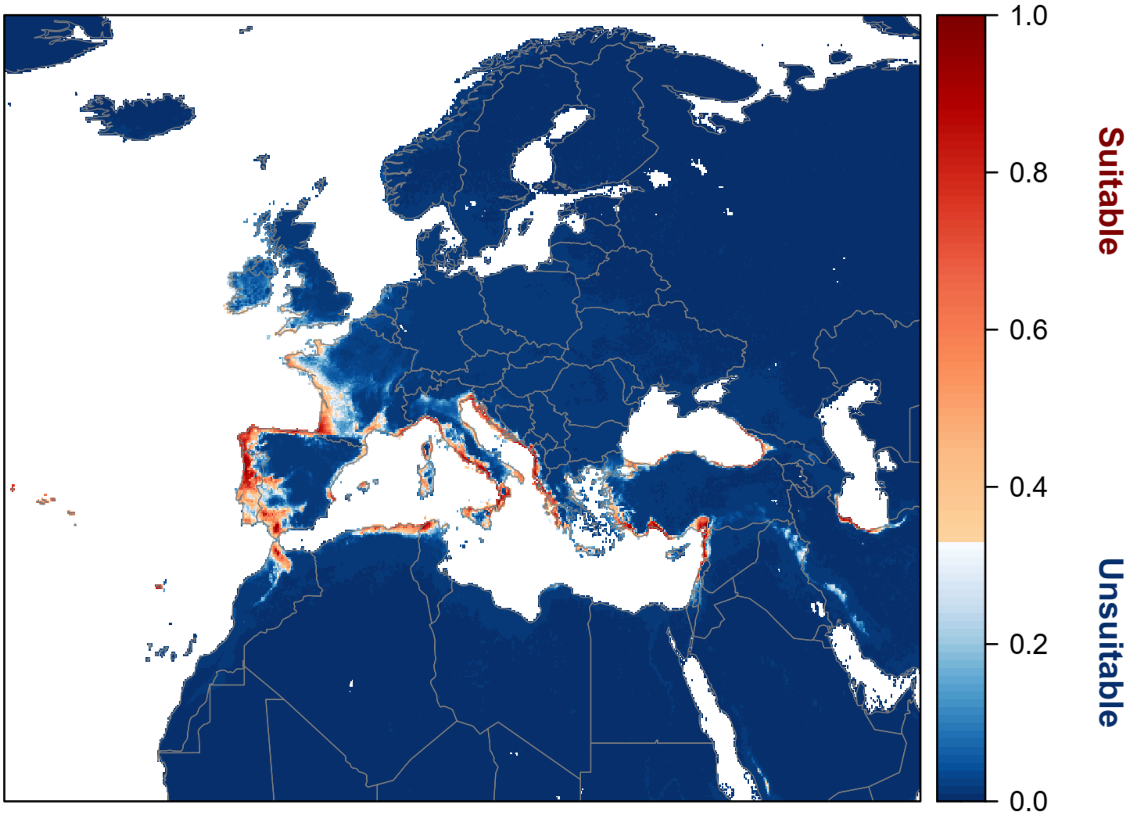
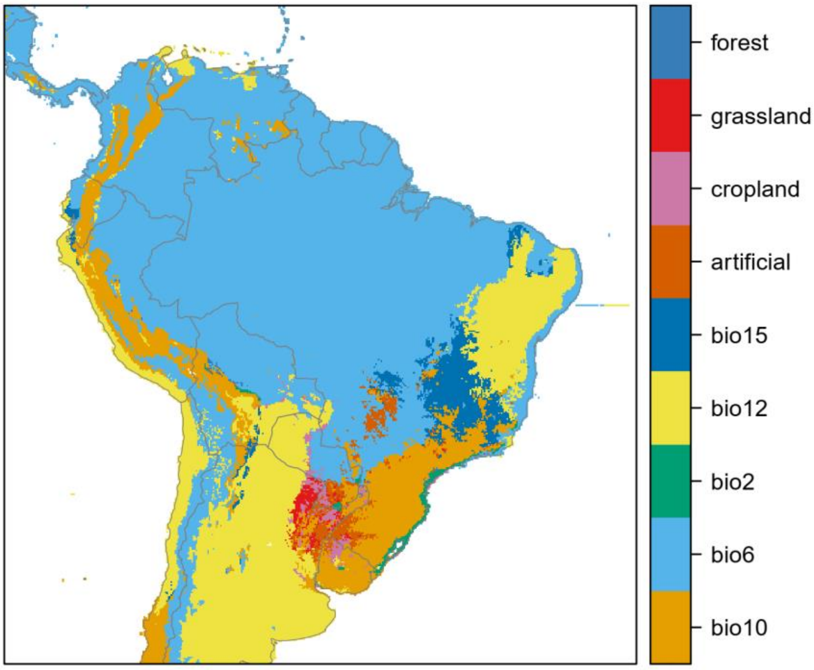


Figure 6. Limiting factor maps projected by the model for *Solanum viarum* in (a) the native North American region and (b) Europe and the Mediterranean region, under the current climate and land use. Colours show the variable most strongly limiting suitability.

(a)



(b)

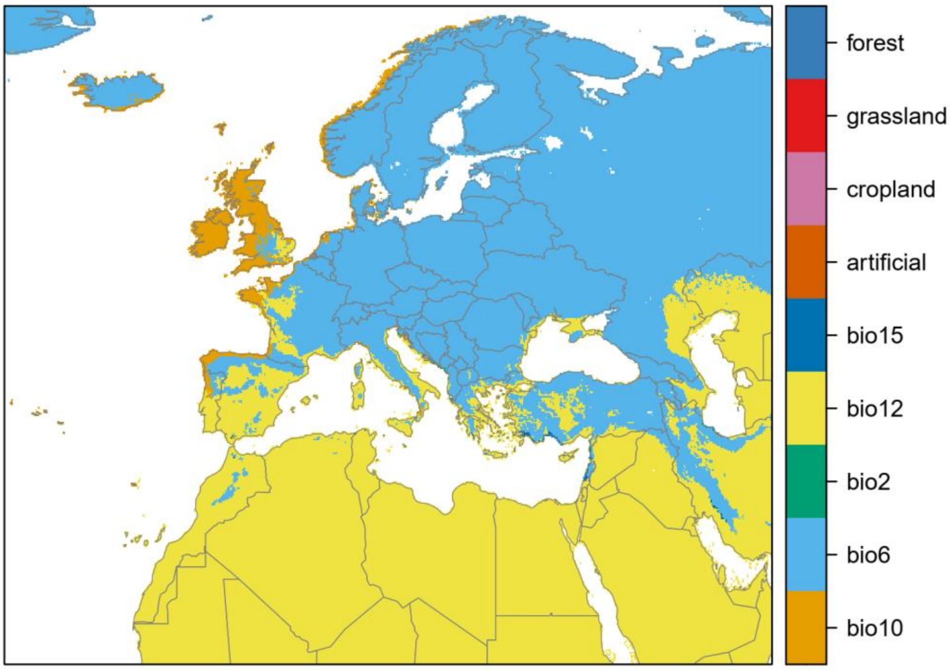


Figure 7. Projected suitability for *Solanum viarum* establishment in Europe and the Mediterranean region for 2041-2070 under climate change scenario SSP1-2.6.

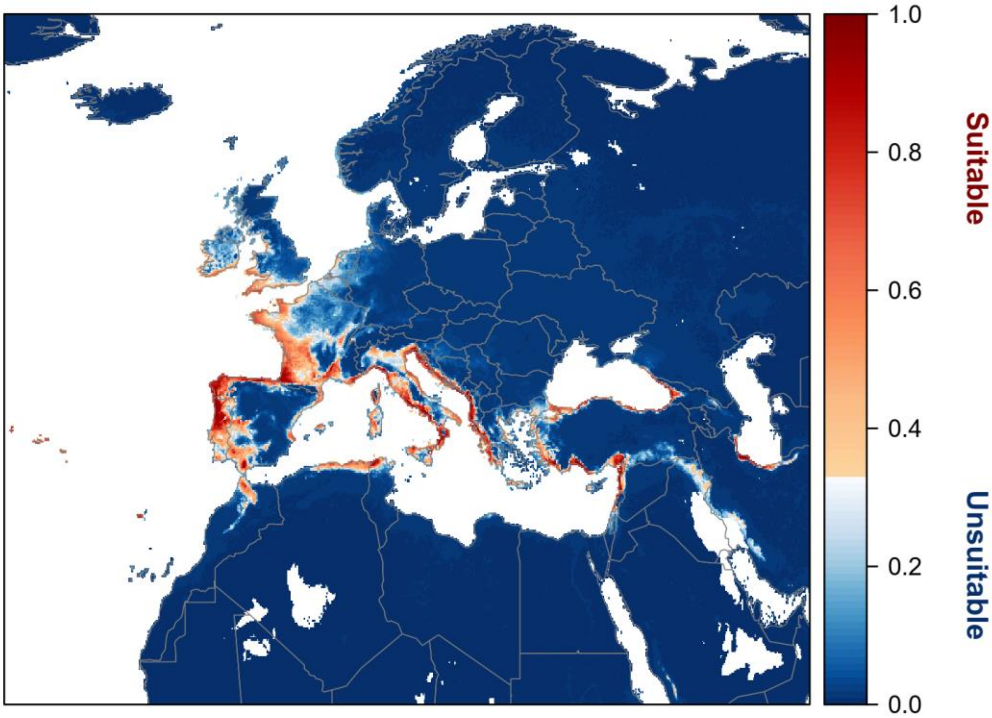


Figure 8. Projected suitability for *Solanum viarum* establishment in Europe and the Mediterranean region for 2041-2070 under climate change scenario SSP3-7.0.

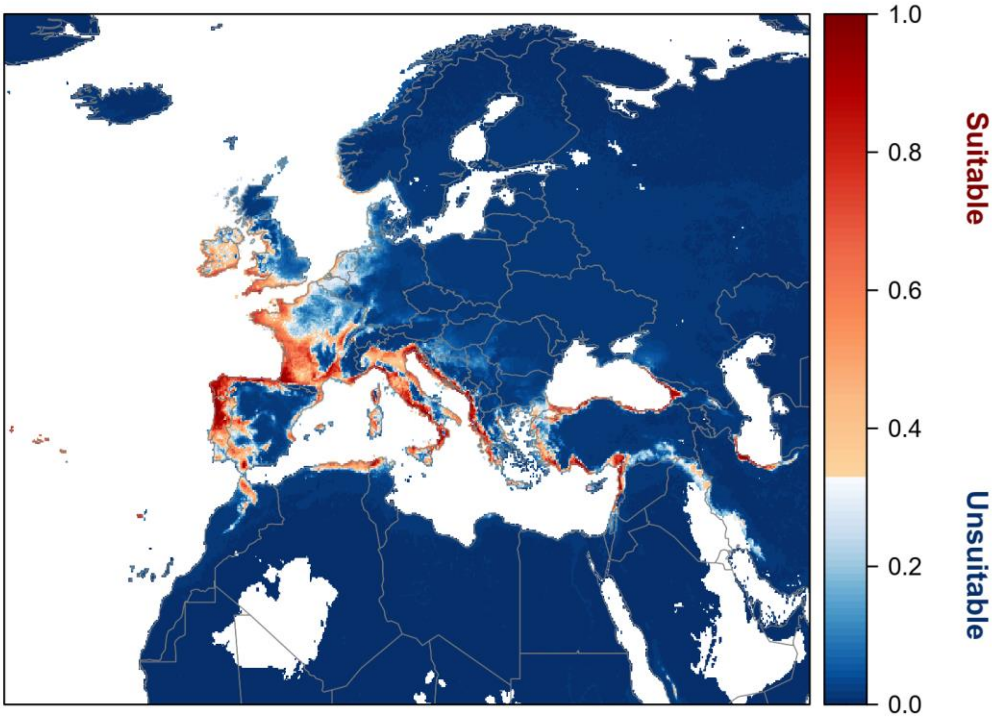
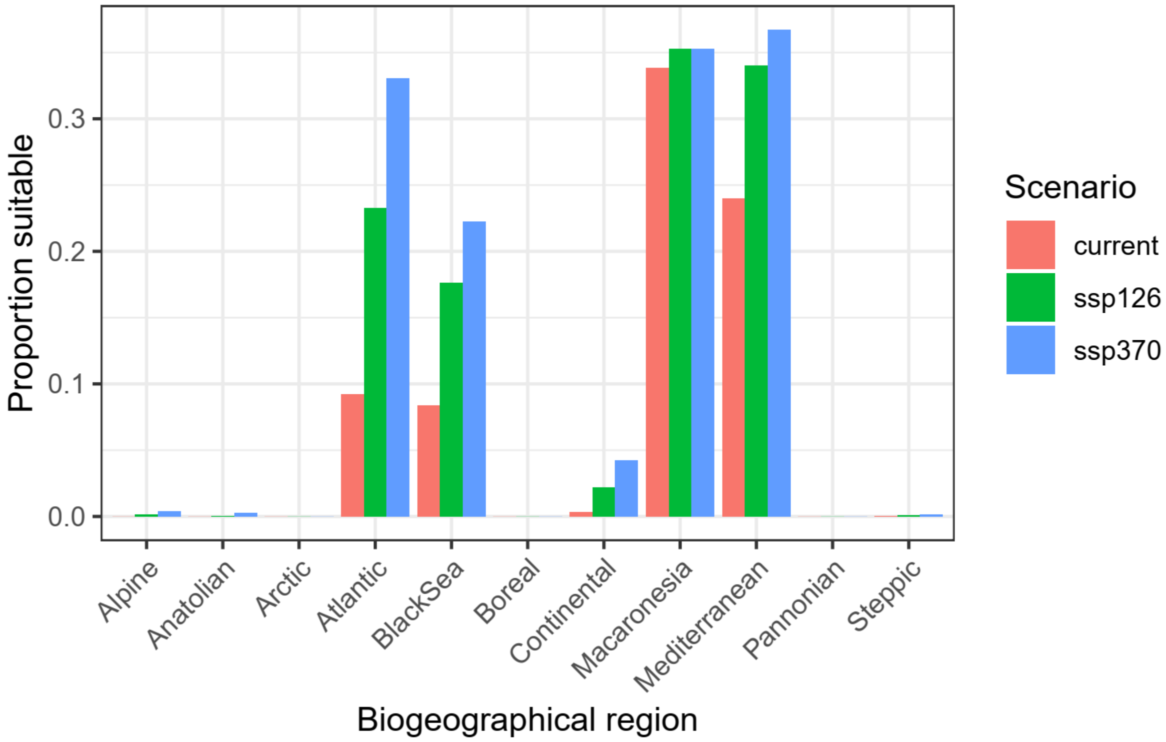


Figure 9. Variation in projected suitability among Biogeographical regions of Europe (Bundesamt fur Naturschutz (BfN), 2003). Bar plots show the proportion of grid cells in each region classified as suitable in the current climate (1981-2010) and projected climate for 2041-2070 under scenarios SSP1-2.6 and SSP3-7.0. The coverage of each region is shown in the map below.


Proportion suitable
0.0
0.1
0.2
0.3
Alpine
Anatolian
Arctic
Atlantic
BlackSea
Boreal
Continental
Macaronesia
Mediterranean
Pannonian
Steppic
Biogeographical region
Scenario
current
ssp126
ssp370

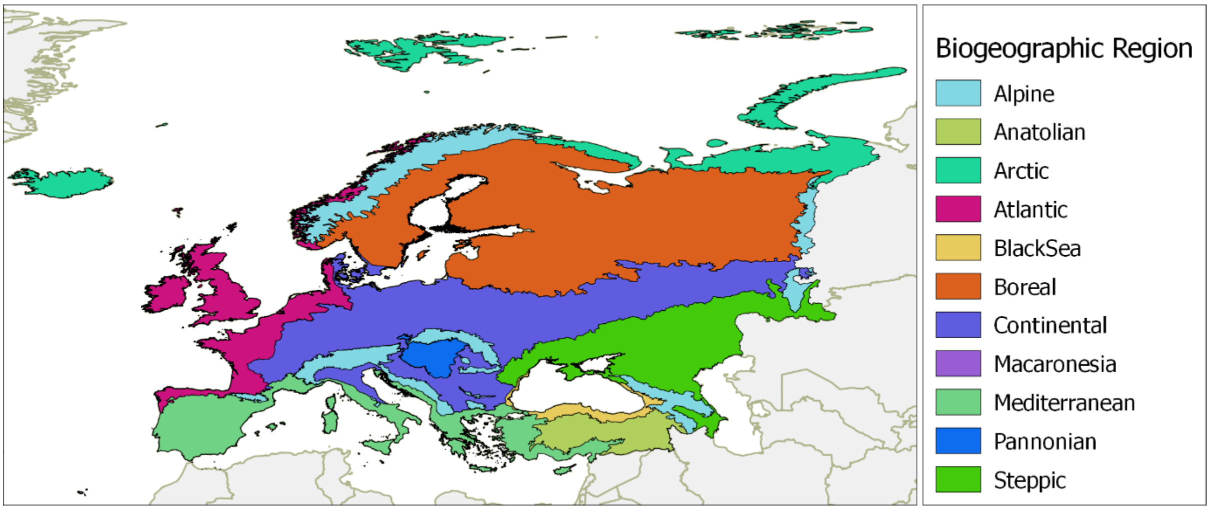

Biogeographic Region
Alpine
Anatolian
Arctic
Atlantic
BlackSea
Boreal
Continental
Macaronesia
Mediterranean
Pannonian
Steppic

Table 2. Projected % suitability among EPPO member countries, sorted from high to low in the current climate. Values are the % of grid cells in each country classified as suitable in the current climate (1981-2010) and projected climate for 2041-2070 under scenarios SSP1-2.6 and SSP3-7.0.

EPPO country (ISO3)	Current	SSP1-2.6	SSP3-7.0	EPPO country (ISO3)	Current	SSP1-2.6	SSP3-7.0
PRT	68%	80%	81%	CZE	0%	0%	0%
ALB	32%	44%	49%	DEU	0%	0%	0%
ITA	23%	42%	56%	DNK	0%	0%	1%
ESP	18%	24%	25%	EST	0%	0%	0%
GRC	16%	23%	25%	FIN	0%	0%	0%
HRV	15%	20%	24%	GGY	0%	100%	100%
FRA	13%	37%	47%	HUN	0%	0%	0%
MNE	13%	17%	19%	JEY	0%	100%	100%
CYP	12%	21%	15%	JOR	0%	0%	0%
GEO	7%	12%	14%	KAZ	0%	0%	0%
TUR	7%	11%	13%	KGZ	0%	0%	0%
TUN	6%	7%	6%	LTU	0%	0%	0%
MAR	4%	4%	3%	LUX	0%	0%	0%
BIH	2%	6%	8%	LVA	0%	0%	0%
GBR	1%	11%	19%	MDA	0%	0%	0%
ISR	1%	2%	2%	MKD	0%	0%	0%
SVN	1%	3%	6%	MLT	0%	0%	0%
AZE	1%	1%	2%	NLD	0%	8%	17%
IRL	1%	15%	65%	NOR	0%	0%	0%
DZA	1%	1%	1%	POL	0%	0%	0%
RUS	0%	0%	0%	ROU	0%	0%	0%
AUT	0%	0%	0%	SRB	0%	0%	0%
BEL	0%	2%	5%	SVK	0%	0%	0%
BGR	0%	0%	0%	SWE	0%	0%	0%
BLR	0%	0%	0%	UKR	0%	0%	0%
CHE	0%	2%	4%	UZB	0%	0%	0%

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