Alnus glutinosa (Betulaceae) in South Africa: invasive potential and management options

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Highlights

- Black Alder invades riparian ecosystems in the Western Cape province of South Africa.
- Large areas of South Africa are bio-climatically suitable for Black Alder.
- Black Alder scored "High" in a risk analysis.
- The vigorous resprouting of Black Alder presents large management challenges.
- We propose Black Alder be listed as Category 1a or 1b under NEMBA.

Abstract

Invasive alien plants cause major environmental and economic impacts and preventing the establishment and spread of emerging invaders is crucial. Black Alder (*Alnus glutinosa*) is well established as a widespread invader in a number of countries, notably the USA and New Zealand, and was recently detected invading riparian ecosystems in South Africa's Western Cape Province. We review the introduction history, current distribution and invasion potential (via species distribution and risk analysis) of Black Alder in South Africa, collate information on its biology, environmental impacts and options for management from its native and invaded range, assess its potential range and management attempts in South Africa, and provide guidelines for effective management. Furthermore, correlative modelling predicted areas of the southern and eastern part of South Africa to have suitable environments for Black Alder establishment. However, water availability will likely limit the species to riparian areas, and areas where the annual rainfall exceeds 500 mm per annum. We estimated control costs to be minimum R 82 000 per month, and the vigorous resprouting nature of Black Alder and its riparian zone preferences presents large management challenges. We propose that Black Alder should be listed as Category 1a under the National Environmental Management: Biodiversity Act (NEMBA) in South Africa. We advise that riparian areas in particular be monitored closely to prevent Black Alder from becoming a widespread invader.

Keywords: Biological invasions; Invasive alien plants; Species distribution modelling; Tree invasions

1. Introduction

Invasive alien plants (IAPs) pose significant threats to the ecosystems they invade; many IAPs have devastating impacts on agricultural and ecosystem services (Pyšek et al., 2020). In South Africa annual losses in ecosystem services due to IAPs have been estimated at 6.5 billion South African Rand (de Lange and van Wilgen, 2010). The rate at which new species are introduced into novel ranges shows no signs of abating, and is indeed increasing

(Seebens et al., 2017). Each new introduction is potentially a new invasive species. There are currently about 2033 alien plant species recorded outside of cultivation in South Africa (van Wilgen and Wilson, 2018), of which 759 are considered naturalized or invasive (Richardson et al., 2020). IAPs are often only detected once they become naturalized or invasive. It is crucial to stop such invasions early, since the costs of long-term management and mitigating impacts far outweigh costs of early eradication. South Africa has been greatly impacted by IAPs (Le Maitre et al., 2016; van Wilgen et al., 2011), especially invasive alien tree species (Richardson et al., 2020). Riparian ecosystems throughout the country have been heavily invaded by alien trees, creating major challenges for managers (Holmes et al., 2005). Thorough assessments of the potential of emerging invasive tree species to extend their ranges and to cause damage is warranted. In this regard, reports of local-scale invasions of an alien tree species (Black Alder; *Alnus glutinosa* (L.) Gaertn.; Betulaceae) that is known to be highly invasive in certain parts of the world is of concern. This study aimed to: 1) review the characteristics, uses, and environmental impacts of Black Alder in other parts of the world; 2) investigate the introduction history of the species in South Africa; 3) investigate its current distribution and invasion potential in South Africa (using species distribution modelling and risk analysis) and its global invasion history; 4) assess attempts to control invasions of the species in South Africa to date; and 5) provide guidelines for effective management.

2. Materials and methods

2.1. Literature review

Online literature searches were conducted to obtain information regarding Black Alder's invasiveness worldwide. Specifically, we made use of the Web of Science using the following keywords and combinations: “invasi*” OR “natural*” AND “alnus glutinosa”; “alnus glutinosa” AND “damage”; “alnus glutinosa” AND (“nitrogen pollution” OR “nitrogen elevation” OR “nitrogen”); “alnus glutinosa” AND “allerg*”; “alnus glutinosa” AND “safety”; “alnus glutinosa” AND (“water uptake” OR “water usage”); “alnus glutinosa” AND soil AND “microb*” AND “community”. To investigate the introduction history of Black Alder in South Africa we contacted all local herbaria to obtain records. We also contacted various land managers in the government and private sector in South Africa to collate data on localities.

2.2. Species distribution modelling

We collected distribution data for Black Alder from various databases such as iNaturalist, The Global Biodiversity Information Facility (GBIF), the South African Plant Invaders Atlas (SAPIA; Henderson and Wilson, 2017), and used data from our own field observations. Data cleaning, using the biogeo package (Robertson et al., 2016), involved removal of records without any co-ordinates, records that were obviously erroneous (e.g. in the sea), and those that appeared to be outliers. To reduce problems associated with unequal sampling effort, we removed duplicate records per 10 minute grid cell and spatially thinned the records in the native range and in North America using the spThin R package (Aiello-Lammens et al., 2015). After data cleaning, we had a total of 1411 unique global occurrences for Black Alder, including both the native (n = 1142) and non-native ranges (n = 269).

We downloaded 19 bioclimatic variables from the WorldClim database (Fick and Hijmans, 2017) and 16 variables from the Envirem database (Title and Bemmels, 2018) at 2.5-minute spatial resolution. We selected 12 candidate variables from this set based on our understanding of the biology of Black Alder, which was informed by available literature (Cao et al., 2020; Claessens et al., 2010; Kajba and Gračan, 2003; McVean, 1953). Briefly, the most important variables pertained to Black Alder's affinity to water availability (see section 3.2 for more details). From this set we removed variables that were highly correlated (Pearson's correlation coefficient > |0.75|), since high levels of multicollinearity can increase model errors (Cruz-Cárdenas et al., 2014). We were cognisant to retain the most biologically meaningful variables during the removal process. After removing highly correlated variables, the following eight were retained as predictors for the models: isothermality (BIO3), maximum temperature of warmest month (BIO5), temperature annual range (BIO7), mean temperature of wettest quarter (BIO8), precipitation of wettest month (BIO13), precipitation of driest month (BIO14), precipitation seasonality (BIO15), and potential evapotranspiration of the driest quarter (PETDriestQuarter).

Although numerous algorithms exist for species distribution modelling, each with its own strengths and weaknesses (Cabra-Rivas et al., 2016; Thuiller et al., 2004), no single technique is most effective (Pearson et al., 2006). We thus made use of ensemble forecasting (Araújo and New, 2007) to reduce uncertainty among models. This approach involves combining multiple species distribution models into a single consensus forecast (Araújo et al., 2005; Araújo and New, 2007). We used three algorithms to model the potential distribution of Black Alder, namely: A regression method — Generalized Linear Models (GLM) — and two machine-learning methods — Random forest (RF; Liaw and Wiener, 2002) and Generalized Boosted Models (GBM; Ridgeway, 1999). The algorithms were implemented from the biomod2 package (Thuiller et al., 2020) run in R version 3.6.3 (R Core Team, 2020). The algorithms require a set of presence-absence records for modelling (Elith and Leathwick, 2009), but since our dataset included only presence records, we sampled 10 000 pseudo-absence records for use in model construction and validation (Barbet-Massin et al., 2012). To prevent geographical biases due to species dispersal limitations, we restricted pseudo-absence selection to the native range map region (see section 3.6 for full description of the native range) (Barbet-Massin et al., 2012). A split-sample cross-validation procedure was used for model construction and validation: models were calibrated on a 70% randomly selected subset of occurrences, with the remaining 30% used for validation via the area under the ROC curve, or AUC (Cabra-Rivas et al., 2016; Fielding and Bell, 1997). Five cross validations were performed for each algorithm resulting in 15 different models. Only models with an AUC score > 0.8 were used to build the final committee-averaging ensemble model (Crossman and Bass, 2008).

2.3. Control costs

To estimate clearing costs of Black Alder in South Africa, we obtained data from WildTrust™, an NGO involved in managing the only dense invasive stands of Black Alder known to occur in the country, those on the banks of the Dwars River from Kylemore to Lanquedoc, near Stellenbosch in the Western Cape Province. The main aim of the clearing operation is the extirpation of Black Alder from this section of the river system. Data on clearing costs are for the period August 2018 to April 2019. Costs taken into account include salaries, herbicide and equipment costs, training costs, and miscellaneous expenses. We used total area (hectares) cleared over the period to derive an estimate of total monthly cost per hectare for initial clearing costs of dense Black Alder stands.

2.4. Risk analysis

To determine the invasion risk that Black Alder poses to South Africa we used currently available information, via extensive literature searches (as per Section 2.1), to conduct a risk analysis according to a newly developed framework for supporting alien species regulation, namely the Risk Analysis for Alien Taxa (RAAT) (Kumschick et al., 2020a, 2020b).

The RAAT framework pertains to the analysis of risks associated with alien taxa becoming invasive. Risk is assessed using a set structure for collating evidence, the end goal being the listing of alien species under the regulatory framework of the South African National Environmental Management: Biodiversity Act (NEMBA, Act 10 of 2004). Risk analysis in general comprises four components: 1) hazard identification; 2) risk assessment; 3) risk management; and 4) risk communication. The RAAT framework aligns with national and international agreements, policies, and best practices. Apart from serving as a scientifically repeatable procedure for the categorization of alien species in legislation, RAAT assessments also provide baseline evaluations for any emergent invasive taxon, against which its future spread and impacts can be monitored.

3. Study species

3.1. Morphological and physical characteristics

The genus *Alnus* Mill. in the family Betulaceae (Birch) comprises 36 species of deciduous trees that occur mainly in northern temperate regions of the world (Russel et al., 2007). One of the main characteristics of the family is their pendulous, egg-shaped cones which contain numerous tiny, winged fruits (Russel et al., 2007). *Alnus glutinosa* (synonyms *Alnus alnus* (L.) Britton, *Betula alnus* var. glutinosa L., *Betula glutinosa* (L.) Lam.), commonly called Black-, European-, or Common Alder, is a single or multi-stemmed, monoecious (sexes separate), deciduous tree that can live up to 100 years (Jaworski, 1995). It usually grows up to 25 m in height (rarely up to 40 m) with a trunk diameter of old trees of between 3.5 – 4 m (Kajba and Gračan, 2003), crown diameter of 6 to 12 m; the bark is fissured greyish and turns to a speckled greyish-brown (Kajba and Gračan, 2003; Russel et al., 2007). It has alternate, simple, dark green, glossy leaves that are doubly-toothed, with up to ten pairs of pronounced leaf veins and a central midrib, and are up to 10 cm long and 7.5 cm wide (Figure 1A) (Kajba and Gračan, 2003; Russel et al., 2007).

The flowers are small and inconspicuous, and are assembled in unisexual inflorescences (male – catkins; female – strobili), a characteristic feature of many of the members of the Birch family: male Black Alder catkins are pendulous, up to 10 cm long, and greenish-yellow in colour, while female strobili are much smaller and upright, and initially red in colour, eventually ripening into a characteristic blackish-brown cone after fertilization (Figure 1B) (Kajba and Gračan, 2003; Russel et al., 2007). Flowering is usually in spring, when inflorescences appear before leaves, and cone development occurs throughout summer (Russel et al., 2007). Black Alder is effectively self-sterile (McVean, 1955a).

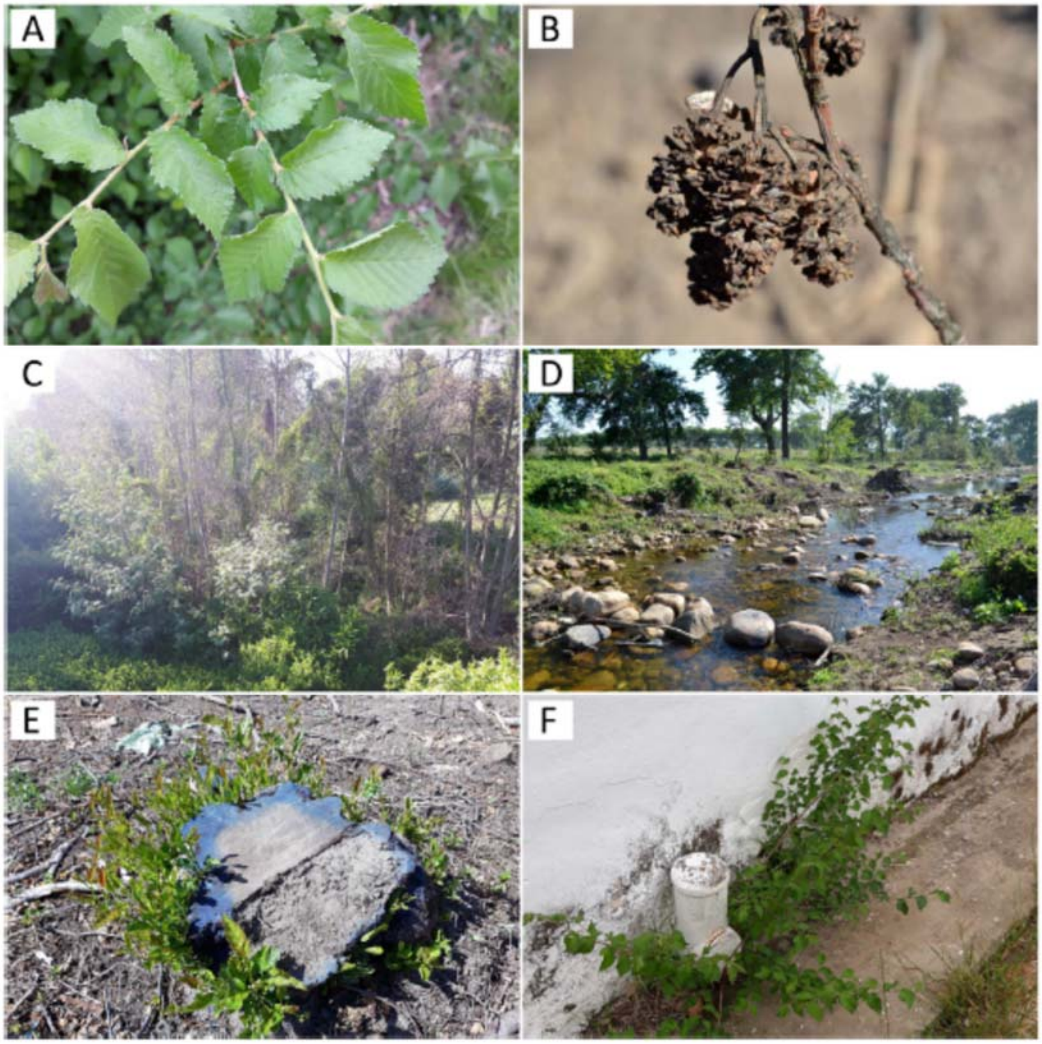

Fig. 1. Features of Black Alder (*Alnus glutinosa*) in South Africa: a) new foliage developing during spring when the tree exits dormancy after winter; b) the characteristic blackish-brown female strobili which have already released their fruits/seeds; c) invasive stand growing on the banks of the Dwars River near Kylemore (Western Cape) before clearing; d) the stand after initial clearing efforts (remaining trees are *Quercus* sp.); e) a cut stump resprouting vigorously even after being treated with herbicide, and f) Black Alder suckers penetrating paving around a drain outlet in search of moisture.

Fruits (tiny samaras) are released in autumn when the strobili turn from reddish-green to black. Although there might be considerable variability in seed set (0 – 80%), the seeds are tiny (± 700 000 seeds kg^{-1}) and can be released *en masse* (McVean, 1955b). The seeds are well adapted for dispersal in water due to the presence of two float chambers of corky tissue and an oily, water-resistant outer coat, enabling fruits to float for up to 12 months in still water (McVean, 1955b). Although fruits are also dispersed by wind (McVean, 1956a), this mode of dispersal is much less effective than would be assumed from the low fruit weight (McVean, 1955b), which is primarily due to the near absence of fruit wings (Funk, 1990). In fact, if water dispersal is excluded, saplings are rarely found further than 30 m from adult trees (McVean, 1955b), although in rare cases fruits can be blown some distance over crusted snow (Funk, 1990). Thus, when growing near surface water the main dispersal agents of Black Alder fruit are running water and wind drift over standing water (McVean, 1955b). Fruits are concentrated along shorelines as a result of wind and wave action, which enable them to germinate in areas with lower competition but with high moisture levels (McVean, 1955b). The only type of animal-mediated dispersal is by water-fowl which disperse fruits attached to their bodies; seed-eating birds do not disperse seeds as the seed embryos are extracted by such birds in the process of opening the seed coat (McVean, 1955b). Black Alder seedlings can survive flooded conditions, but usually do not thrive (McVean, 1956a).

3.2. Flowering and growing conditions

Black Alder can flower as early as the second growing season, and trees produce large quantities of seed by year six (Funk, 1990). A tree of a 6 – 9 m in height can have several hundred strobili, such that the mass of maturing fruit approximates the mass of foliage during fruit and seed development (Pizelle, 1984). Black Alder seeds do not seem to have a long life, and few seeds survive beyond the first germination season (McVean, 1955b). Furthermore, seeds of Black Alder require specific conditions to be met for successful germination. For example, seed germination is optimal at 24 – 26 °C (minimum of 17 °C and maximum of 36 °C) with high oxygen tension and humidity, and cold treatment of seeds reduces minimum germination temperature to 7 °C (McVean, 1955b, 1953). However, epigeal germination of viable seed is quick and usually begins 10 to 20 days after spring sowing, reaching completion in just two weeks (Funk, 1990). Interestingly, due to the high oxygen tension requirement, seeds will reportedly not germinate below the surface of waterlogged soils (i.e. low oxygen tension) (McVean, 1953). Seeds therefore germinate either on soil or vegetation surfaces, due to their buoyancy (McVean, 1953). Seedlings require abundant moisture and a high light intensity for at least 20 days after germination in order to establish successfully (McVean, 1953).

Black Alder readily hybridizes with other alders; notable hybrids include *A. cordata x A. glutinosa, A. glutinosa x A. incana, A. glutinosa x A. rubra*, and *A. glutinosa x A. orientalis* (Funk, 1990). Three intraspecific taxa of *Alnus glutinosa* are recognised: *Alnus glutinosa* subsp. *barbata* (C.A.Mey.) Yalt., *Alnus glutinosa* var. *incisa* (Willd.) Regel, and *Alnus glutinosa* var. *laciniata* (Willd.) Regel (The Plant List, 2013). Black Alder grows rapidly, such that one-year old seedlings intended for plantations are usually large enough for planting out (Funk, 1990). Seedlings intended for commercial plantations are usually inoculated with *Frankia* bacteria (symbiotic root bacteria, see Section 3.3 on “Mutualists”) to facilitate nodule development before planting out (Funk, 1990). Once established, either in its native or alien ranges, Black Alder can tolerate a wide variety of soil conditions (except soils with very low pH, but within the range of 4.2 – 7.5) (Claessens et al., 2010), in part due to its nitrogen-fixing ability (McVean, 1956b). It often forms dense monotypic stands, usually at elevations between 1500 and 1800 m (Kajba and Gračan, 2003). Black Alder has well developed surface- and deep root systems, and the trees are thus seldom blown over by wind (McVean, 1956b); the surface system is important for nutrition, with its associated nodules and mycorrhizae, while the deep system accesses water from the water table. Such a deep root system also allows Black Alder to survive periods of drought, since it can access water located well below the water table (McVean, 1956b). When the water table rises above the soil surface Black Alder generally reacts by producing adventitious roots from the bole (McVean, 1956b). Although Black Alder is highly tolerant of flooding and waterlogging, it is susceptible to drought (Cao et al., 2020). It can tolerate seasonal frost (Cao et al., 2020), and mature trees can withstand winter temperatures as low as -49 °C (McVean, 1953).

3.3. Mutualists

Due to its extreme chemical stability, atmospheric nitrogen gas (N_2) is unusable to plants. The amount of fixed (i.e. usable/available) nitrogen therefore limits the establishment and proliferation of plants in most environments (Franche et al., 2009). However, nitrogen-fixing bacteria convert atmospheric nitrogen into forms usable to plants, such as NH_4^+ (Stacey, 2007). The ability of plants to form associations with nitrogen-fixing bacteria can therefore facilitate colonization of novel environments, especially when such environments are nitrogen poor. Moreover, such associations (and mutualistic associations in general) are thought to confer a competitive advantage to invasive alien plants that are introduced into novel environments (which is clearly evident in legumes), especially when such regions are characterised by nitrogen poor soils (Le Roux et al., 2017; Parker, 2001; Rodríguez-Echeverría et al., 2011; Traveset and Richardson, 2014).

Black Alder, and the genus *Alnus* as a whole, forms mutualistic associations with the nitrogen-fixing bacterial genus *Frankia* (Franche et al., 2009); these bacteria reside in root nodules that can become as big as cricket balls (McVean, 1956b). Black Alder is part of the group referred to as "actinorhizal plants" (Franche et al., 2009; Wall, 2000). The genus *Frankia* is considered to be free-living and ubiquitous in soils, and occurs outside the boundaries of its associated hosts' ranges (Chaia et al., 2010). More specifically, the *F. alni* complex, potentially consisting of up to 70 operational taxonomic units (OTU's: equivalent to species) (Põlme et al., 2014), associates exclusively with the genus *Alnus* (Põlme et al., 2014). The actinorhizal symbioses of Black Alder are not obligate, however (Chaia et al., 2010).

Black Alder's association with nitrogen-fixing bacteria is important for its establishment success in low-nitrogen soils (McVean, 1956b), which often includes water-logged areas. No information is available on the strains of *Frankia* that nodulate Black Alder in South Africa, but elsewhere outside of its native range Black Alder associates with "typical" strains of *Frankia* (Clawson et al., 1997). However, the composition of *Frankia* communities that associate with *Alnus* seem to be driven predominantly by host identity, and not edaphic or climatic factors (Põlme et al., 2014); this is surprising given how strongly edaphic factors (e.g. pH) influence the soil microbial communities with which plants associate (Lauber et al., 2009). This means that Black Alder could well be very specific in terms of the strains of *Frankia* with which it associates (Põlme et al., 2014), an idea that merits investigation in South Africa.

Nitrogen fixation requires large amounts of phosphorous, which is supplied to alders and *Frankia* by arbuscular mycorrhizal- (AM) and ectomycorrhizal (EcM) fungi in what is termed a tetrapartite root symbiosis (Chatarpaul et al., 1989). Thus, the mineral nutrition of alders and their associated actinorhizal symbionts are thought to be highly dependent on EcM fungi (Baar et al., 2000; Yamanaka et al., 2003), since these EcM fungi dominate root systems of mature alder trees (Becerra et al., 2005, Becerra et al., 2005). Specifically, Black Alder is known to associate with the EcM fungal genera *Alnicola, Cortinarius, Geopyxis, Hebeloma, Helvella, Inocybe, Lactarius, Paxillus, Peziza, Pseudotomentella, Russula*, and *Tomentella* (Tedersoo et al., 2009). Soil variables, together with site locality, seem to be important drivers that typify EcM fungal communities of Black Alder (Tedersoo et al., 2009). It is unknown which EcM mutualistic partners are associated with Black Alder in South Africa, but given the importance of site locality and soil variables in driving EcM fungal community composition, it seems reasonable to assume that Black Alder in South Africa associates with specific EcM fungal communities different to those recorded elsewhere. This could well be the case since *Alnus* species are generally limited to a set of host-specific EcM fungal mutualists (Bogar and Kennedy, 2013; Molina, 1981; Roy et al., 2013; Tedersoo et al., 2009). However, as in the case of its rhizobial mutualistic associations, this hypothesis needs to be validated.

In its native range Black Alder associates with very specific EM fungi communities (Roy et al., 2013; Tedersoo et al., 2013, 2009), compared to that in its exotic range (Bogar et al., 2015), thus supporting a co-invasions hypothesis (Dickie et al., 2010; Nuñez and Dickie, 2014). The situation regarding its associations with *Frankia* are less clear, and Black Alder seems to associate with *Frankia* assemblages typical to its native range (Clawson et al., 1997). However, irrespective of the specificity of Black Alder's mutualistic associations, such associations are generally considered to be highly advantageous to the establishment and spread of alien plants in new environments (Traveset and Richardson, 2014). It should be noted that, unlike species which require *Frankia* mutualists to establish and become invasive (e.g. *Casuarina*), such requirements are not essential in the case of Black Alder (Traveset and Richardson, 2014).

3.4. Uses

The rapid growth of Black Alder, together with its nitrogen-fixing ability and tolerance for acidic soil conditions has made the species desirable for use in shelterbelts, reclamation, landscaping, and biomass production (Funk, 1990). However, Black Alder is primarily used in forestry (Claessens et al., 2010; Kajba and Gračan, 2003). Black Alder timber is waterproof, and has been used in the making of boats and water pipes, reportedly forms the foundations of numerous buildings in Venice (Housley et al., 2004; Klaassen and Creemers, 2012), is used in the making of furniture, wooden ware, cooperage, charcoal and wood fibre (Genys, 1988), and has even been used in the making of wooden clogs (shoes) in the Netherlands (Houston Durrant et al., 2016; Russel et al., 2007). Black Alder is also an important species used in restoration of forest and alluvial ecosystems (Claessens et al., 2010; Kajba and Gračan, 2003), and has been used as a pioneer species for restoring mining spoil sites such as strip mines (Carter and Ungar, 2002; Funk, 1990; Kuznetsova et al., 2011; McVean, 1956b), since it promotes the growth of adjacent trees due to its nitrogen fixing ability and its fast growth rate (Kuznetsova et al., 2011; Plass, 1977). Also, the fact that Black Alder reduces soil pH is beneficial for remediating high pH (i.e. alkaline) soils resulting from mining activities (Callender et al., 2016). The deep roots of Black Alder has led it to be used as a windbreak (Wenneker et al., 2005), specifically for orchards and croplands (Cao et al., 2020; Funk, 1990), since such deep root systems mean that trees are seldom blown over by wind (McVean, 1956b). Black Alder has also been considered as a potential biofuel crop (Davis et al., 2010), a feed crop for cattle (Funk, 1990), and is considered to be valuable for wildlife since it provides good cover (e.g. for pheasants) as well as a source of food in the form of seeds (e.g. for birds) (Funk, 1990).

We were unable to find any well documented uses of Black Alder in South Africa, and it is conspicuously absent from a prominent book on the history of tree planting in South Africa (Poynton, 2009). However, based on our personal observations, it seems that Black Alder is used on occasion as a windbreak in fruit orchards. It is also recorded from the Stellenbosch Botanical Garden, and is thus at least of some horticultural interest. Moreover, the historical records pertaining to its plantings at various arboreta (see section 4.1) suggest that it was planted deliberately in the past, likely for silvicultural trials, although never extensively. Such uses could potentially lead to a conflict of interest in the future if the species were to gain more acceptance by the public.

3.5. Environmental impacts

IAPs with the ability to alter ecosystem functioning, e.g. by adding nitrogen (via nitrogen-fixing mutualists) or altering soil microbial communities, effectively act as drivers of regime shifts (Gaertner et al., 2014). This has been shown repeatedly for invasive nitrogen fixers (e.g. *Falcataria mollucana* and *Morella faya* in Hawaii, *Acacia* spp. in South Africa and Europe), whereby such invaders significantly change soil abiotic conditions, for example by altering soil nitrogen levels and mineralization rates (Hughes and Denslow, 2005; Marchante et al., 2008; Stock et al., 1995; Vitousek and Walker, 1989; Yelenik et al., 2004), altering soil microbial communities (Kamutando et al., 2017; Le Roux et al., 2018; Lorenzo et al., 2010; Rodríguez-Echeverría et al., 2011; Souza-Alonso et al., 2015), and even altering soil functioning (Kourtev et al., 2003, 2002; Souza-Alonso et al., 2015, 2014). Such changes can often persist decades after the removal of invasive biomass (so-called "legacy effects") (Corbin and D'Antonio, 2012; Elgersma et al., 2012; Marchante et al., 2009; Nsikani et al., 2017). Furthermore, such invasive nitrogen fixers are able to suppress, or even reduce and alter native plant species diversity and composition (Benesperi et al., 2012; Carter et al., 2019; Rook et al., 2011). Plant species recovery following removal of invasive nitrogen fixers might be quick in habitats where native species are able to exploit elevated soil nitrogen levels (Hughes et al., 2012), but in systems where native species are adapted to nutrient poor conditions, such recovery usually occur slowly (Marchante et al., 2009). Moreover, the altered conditions following invasion by nitrogen-fixers can facilitate the invasion of other alien species, whilst simultaneously decreasing native species richness (Hughes and Denslow, 2005; Slabejová et al., 2019; Yelenik et al., 2004). Thus, plant species that can act as drivers of regime shifts, such as invasive nitrogen fixers, should receive high management priority to prevent them from becoming widespread invaders.

Black Alder's mutualistic association with nitrogen-fixing bacteria means that roots and nodules have high concentrations of nitrogenous compounds (Virtanen and Miettinen, 1952), which leach into soil, thus enriching it (Funk, 1990). Apart from nitrogen in roots, Black Alder leaves are also rich in nitrogen (Mikola, 1958), and rapidly release water-soluble organic substances upon decomposition (Funk, 1990). Alder leaves in general increase levels of soil nitrogen, soil available phosphorus, and various soil cations (e.g. total soluble salt concentration) (Claessens et al., 2010; Giardina et al., 1995; Plass, 1977), and Black Alder itself reduces soil pH (Plass, 1977). Moreover, Black Alder stands accumulate large amounts of litter (Funk, 1990). For example, in mine restoration, Black Alder has been found to input twice as much leaf litter compared to similar areas where it is absent (Cao et al., 2020). Apart from leaves, other parts of Black Alder (e.g. branches, bole bark, bole wood) also accumulate considerable amounts of nitrogen, and even young plants can significantly add to the amount of soil nitrogen (Funk, 1990).

Although the nitrogen fixing ability of Black Alder is generally considered beneficial to other species, especially for reclamation purposes (e.g. mine soil sites) (Funk, 1990), such significant alterations in soil nutrient levels, specifically nitrogen content (Gtari and Dawson, 2011; Kajba and Gračan, 2003), can be detrimental to native species. For example, in the USA, Black Alder displaces native plant species (Herron et al., 2007). Such soil nutrient enrichment (especially nitrogen) could be particularly damaging in nutrient-poor systems, such as fynbos, where plants are specifically adapted to low-nutrient conditions

(Rebelo et al., 2006). Moreover, the soil conditioning capacity of Black Alder could potentially promote its own invasion or even facilitate that of other weedy species (Gaertner et al., 2014), i.e. secondary invasion or invasion meltdown, as has been observed for other nitrogen-fixing species (Rodríguez-Echeverría, 2010).

Another aspect of concern is the capacity of Black Alder to elevate stream nitrogen content, a phenomenon termed "nitrogen pollution". Although it has not specifically been investigated for Black Alder, it has been shown for its congener *Alnus rubra* (Red Alder), where the amount of Red Alder cover positively correlates with the amount of nitrate and dissolved organic nitrogen in streams (Compton et al., 2003). Since Black Alder has been repeatedly shown to enrich soil nitrogen levels, there is good reason to assume that it does the same. Coupled with this, Black Alder has the ability to de-oxygenate water where it grows (Cao et al., 2020). Such elevation of stream nutrient levels together with de-oxygenation would almost certainly impact on native stream biota that are adapted to specific stream conditions. Also, apart from altering soil chemistry, Black Alder alters the physical structure of riparian systems by trapping sediments in its dense roots (Funk, 1990).

Very little is known about the impacts of Black Alder on soil microbial communities when it invades novel ecosystems. However, from studies of afforestation there is evidence that, due to its nitrogen-fixing ability and other soil-nutrient impacts, Black Alder impacts on soil microbial communities by significantly increasing total microbial biomass and altering community composition, especially for fungi (Gunina et al., 2017). This is one of the reasons why it is used for restoring mine spoils (Callender et al., 2016). Such changes might be limited to certain horizons and does not seem to affect functional soil diversity (Chodak et al., 2015), although some results suggest otherwise (Callender et al., 2016). Effects are not restricted to rhizosphere modification, since Black Alder also stimulates the entire soil microbial population (Callender et al., 2016). Moreover, overwhelming evidence exists that nitrogen-fixing species in general have the capacity to alter soil microbial communities, both in terms of diversity and composition, in the areas where they invade, in conjunction with altering soil physicochemical properties (Kamutando et al., 2017; Le Roux et al., 2018; Lorenzo et al., 2010; Marchante et al., 2008; Rodríguez-Echeverría et al., 2011; Souza-Alonso et al., 2015; Yelenik et al., 2004). Thus, Black Alder would almost certainly have the same impacts on native soil microbial communities where it invades, although this needs to be verified with field data.

Although no information is available on the water usage of Black Alder, it is a riparian tree species and as such has the potential to uptake large quantities of water from invaded rivers. This could limit water available for native species, and could also potentially impact indirectly on human well-being by reducing the amount of water available for consumption or economic activities (e.g. drinking water, irrigation water for agriculture), as has been demonstrated for other invasive riparian species (e.g. *Eucalyptus*). However, the aforementioned remains speculative, and an in-depth study in South Africa is warranted.

Finally, there is evidence for pest co-introduction with Black Alder. For example, the striped alder sawfly, *Hemichroa crocea*, is a native species of Europe but is now widespread in northern United States and Canada (Funk, 1990). Another example concerns the European alder leaf miner, *Fenusa dohrnii*, which is now widespread in USA and Canada (Funk, 1990). In terms of fungi, Black Alder is susceptible to a natural hybrid pathogen *Phytophthora alni* (consisting of a complex of three subspecies*: P. alni* subsp. *alni, P. alni* subsp. *multiformis*, and *P. alni* subsp. *uniformis*). Although these pathogens decimated populations of Black

Alder in Europe during the 1990s (Brasier et al., 2004, 1999; Gibbs et al., 1999), *Phytophthora* as a genus is not highly host-specific and could have disastrous effects on native vegetation if co-introduced with Black Alder. The genus is well known to cause plant disease epidemics in numerous areas around the globe, and is a well-known destructive pathogen even in South Africa where numerous species have already been found and which affect a wide variety of plant species, e.g. agricultural crops, native forests, plantations, and orchards of alien plant species (Bose et al., 2018; Hulbert, 2017; Hulbert et al., 2019). As such, an investigation into the potential pathogenic *Phytophthora* species associated with Black Alder in South Africa is warranted.

3.6. Native distribution

The native range Black Alder covers the whole of Europe, from Ireland in the west to western Siberia in the east; it also extends south to parts of North Africa and north to latitude 65° (Gtari and Dawson, 2011; Kajba and Gračan, 2003; Russel et al., 2007). Black Alder has a large genetic diversity in its native range, which is a result of the isolated nature of many of the populations across a wide geographic distribution (Kajba and Gračan, 2003). Black Alder's large distribution range indicates that it is adapted to a wide range of temperatures (Claessens et al., 2010). In its natural habitat, Black Alder occupies wet areas such as riparian zones, ponds and wetlands, where it can create its own oxygen supply during prolonged periods of submergence, but does not tolerate areas with stagnant water (Kajba and Gračan, 2003; Russel et al., 2007). Thus, successful establishment of Black Alder is closely linked to the availability and abundance of water, and it requires a high atmospheric humidity to complete its reproductive cycle (Claessens et al., 2010). The species' distribution is restricted by aridity in the east of its native range, since a humidity of 50% and higher must be maintained for a minimum of one month after seed germination for successful seedling development (Claessens et al., 2010).

3.7. Non-native distribution

Although Black Alder has been extensively moved around the world due to its various uses, few studies have investigated its invasive tendencies and its impacts as an invasive species. What follows is a summary of its current tendencies for escaping cultivation and becoming weedy (Figure 2). The species is considered in invasive in Chile, New Zealand, the United States of America, and South Africa (Bogar et al., 2015; Cao et al., 2020; Eckel, 2003; Herron et al., 2007; Randall, 2017), and is at least naturalised in Argentina (Isla Victoria, and northern Patagonia where it potentially hybridizes with *A. incana*), Australia (New South Wales and Victoria), Azores, Canada, Portugal, (Calviño et al., 2018; Hosking et al., 2003; McClay et al., 2010; Mills et al., 1993; Randall, 2017; Rejmánek and Richardson, 2013; Simberloff et al., 2002). It has been recorded as a weed in India, Japan, La Réunion, and Russia (Randall, 2017). The species is also known to have been introduced to the Azores (Kajba and Gračan, 2003).

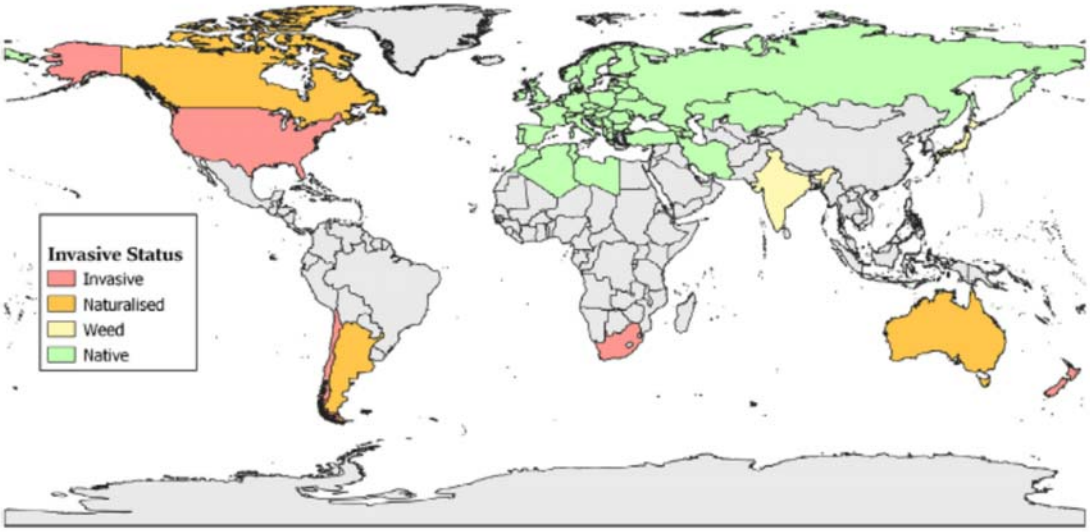

Fig. 2. The global range of Black Alder (*Alnus glutinosa*). Data are from various sources.

In New South Wales, Black Alder is recorded as naturalised around Lake Burley Griffin, along streams in the Southern and Central Tablelands, growing in a wet sclerophyll forest at Katoomba, and growing alongside other exotic species (e.g. *Salix*) in Canberra (Hosking et al., 2003). It was first recorded in Canberra, Australian Capital Territory, in 1999 (Hosking et al., 2003).

Black Alder was introduced to New Zealand as early as 1914 and has invaded the North Island where it forms large invasive stands. It is naturalized and invades to a lesser degree in the rest of North Island (Bogar et al., 2015).

In the USA it is considered a "moderate to serious" invasive species of wet sites, and is currently present in at least 18 states (Cao et al., 2020; Herron et al., 2007). Although the date of introduction to the USA is unclear, it is known to have been introduced during colonial times and was planted in Delaware Park (Buffalo, NY) as early as 1886 (Eckel, 2003; Funk, 1990), and has become widespread around the Great Lakes from as early as 1913 (Cao et al., 2020; Mills et al., 1993). Several thousand specimens were recorded by 1967 in the region of the Niagara river (Beaver Island State Park) (Eckel, 2003). Naturalized stands of Black Alder in the USA are usually found along streams (Funk, 1990).

In north-western Patagonia, Argentina, a total of fourteen naturalized populations of *Alnus* have been documented in the Lanín and Nahuel Huapi National Parks (Calviño et al., 2018), where the trees are mostly found alongside lakes, with some occurring along watercourses (Calviño et al., 2018). However, not all of these populations have been studied in detail, and only six of them have been confirmed to contain Black Alder, together with two other alder species (*A. rubra* and *A. incana*) (Calviño et al., 2018). Black Alder was introduced into Argentina's National Parks at experimental stations in about the 1950s (Calviño et al., 2018).

4. Black alder in South Africa

4.1. Introduction history

No studies have addressed the distribution, impacts, and invasiveness of Black Alder in South Africa. Even the most comprehensive book on the history of tree planting in South Africa (Poynton, 2009) does not mention Black Alder. The oldest known record of Black Alder in South Africa dates from 1908; the species therefore has been in the country for at least 110 years (Figure 3). This earliest record is from a planting at Beginsel Arboretum (Standerton, Mpumalanga); that specimen is known to have died in 1911 (pers. comm. Michael Cheek). Black Alder is also known to have been planted (date unknown) at the DR de Wet Arboretum (Standerton, Mpumalanga) and was still alive there in 2014 (pers. comm. Michael Cheek; herbarium sample 2034, NH), and at Paarl Arboretum (Western Cape; planted 1980) where it was still alive in 2013 (pers. comm. Michael Cheek).

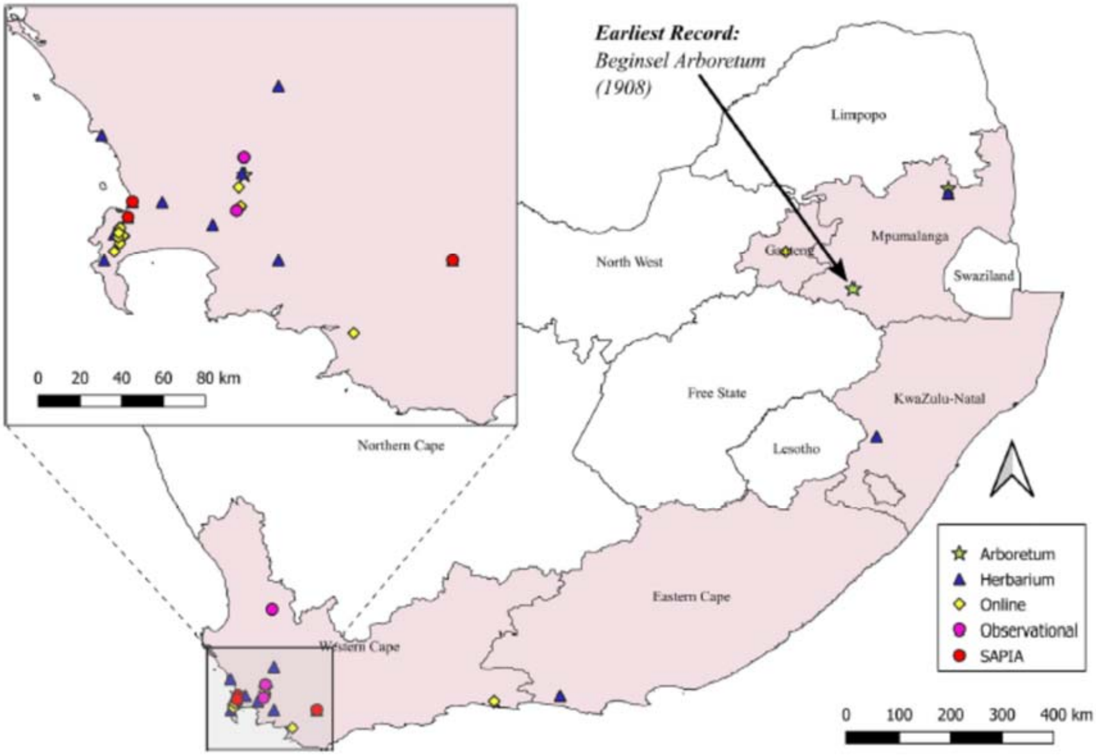

Fig. 3. Localities where Black Alder (*Alnus glutinosa*) has been recorded in South Africa. Shaded provinces are those with at least one Black Alder record. Most records occur in the Western Cape. The earliest known record is from 1908 at Beginsel Arboretum near Standerton, Mpumalanga. "Online" records were obtained from online databases (e.g. iNaturalist, GBIF), and "observational" indicate field observations by the authors.

4.2. Current distribution and status as invasive species

Black Alder is currently recorded from five provinces in South Africa: Western Cape, Eastern Cape, KwaZulu-Natal, Gauteng, and Mpumalanga (Figure 3). Most records are from the Western Cape, with only a few records in each of the other mentioned provinces. The largest known invasive population occurs in the Western Cape, along the banks of the Dwars River (between Kylemore and Pniel, near Stellenbosch) where it is co-invading with *Acacia* *dealbata* and *Populus* spp. (Figure 1C, D). We also recorded scattered individuals along the banks of the Berg River (Western Cape). A large-scale initiative is underway at this site, under direction of Wildlands Conservation Trust (www.wildtrust.co.za), to clear the dense stands of invasive trees, including Black Alder, and to restore the riparian ecosystem.

4.3. Risk Analysis

Our risk analysis, using the RAAT framework (Kumschick et al., 2020b, 2020a), yielded a final *Risk Score* of "High", and *Ease of Management* score of "Medium" (out of three categories: Easy, Medium, and Difficult; see supplementary info). This suggests that Black Alder poses a potentially significant risk and we recommend listing it as Category 1a under NEMBA.

Listing of a species under Category 1a means that a person may not carry out a restricted activity on any specimen of such a species, as listed in terms of Section 71(1) of NEMBA. Such restricted activities include importing, possessing, growing or in any other way propagating, moving or otherwise translocating, selling or otherwise trading in, buying, receiving, giving, donating or accepting as a gift, or in any way acquiring or disposing of any specimen of the listed species. Moreover, Category 1a differs from Category 1b in that it is primarily designated for emergent invasive species that are potential eradication targets, and as such are not yet widespread. Hence our recommended listing of Black Alder under Category 1a, since it is not yet widespread as an invasive species in South Africa and could be a candidate for eradication.

Factors that contributed to the High-Risk Score of Black Alder include its ability to compete with and replace native species, to hybridize with other congeners, to be associated with *Phytophthora* root rot complex, to cause chemical and structural impacts in recipient environments, and to alter soil microbial communities. The high climate and habitat suitability, and high likelihood of entry via both human aided- and unaided primary pathways, also contributed highly to the outcome. Moreover, the detectability of Black Alder is critically time-dependent. Although Black Alder is a large tree, and thus easily detectable (as an adult), it is deciduous. This means that it is not readily identifiable for at least half of the year (late autumn, winter, and potentially the very beginning of spring) when all its leaves are shed. Only when the species is in leaf can it readily be identified as *Alnus*. Although the presence of dried inflorescences aids identification in the absence of leaves, inflorescences are not always present. Black Alder can also be difficult to distinguish from congeners without flowers/fruits, which are only produced during spring/summer.

Finally, although there is scant literature on the socio-economic impacts of Black Alder, its pollen is known to cause allergic reactions in pollen-sensitive individuals (Biedermann et al., 2019; D'Amato et al., 2007; Jantunen et al., 2012; Ozturk et al., 2013; Tomalak et al., 2011). Furthermore, it is suggested that alder pollen can prime pollen-sensitive individuals for reactions towards other types of pollen, such as birch (*Betula*), beech (*Fagus*) and chestnut (*Castanea*) (Biedermann et al., 2019; Jantunen et al., 2012).

4.4. Climatic suitability

Our species-distribution modelling predicted large areas of South Africa to be potentially suitable for the establishment of Black Alder. Regions of high suitability include the southern and eastern parts of South Africa, extending into the high-elevation interior in parts of the

Free State, Mpumalanga, Gauteng, and Limpopo provinces (Fig. 4). Large areas of the Western Cape, Eastern Cape, and KwaZulu-Natal provinces are also potentially highly climatically suitable. The arid interior of the country is largely unsuitable, but surprisingly a region of high suitability is predicted in the Northern Cape.

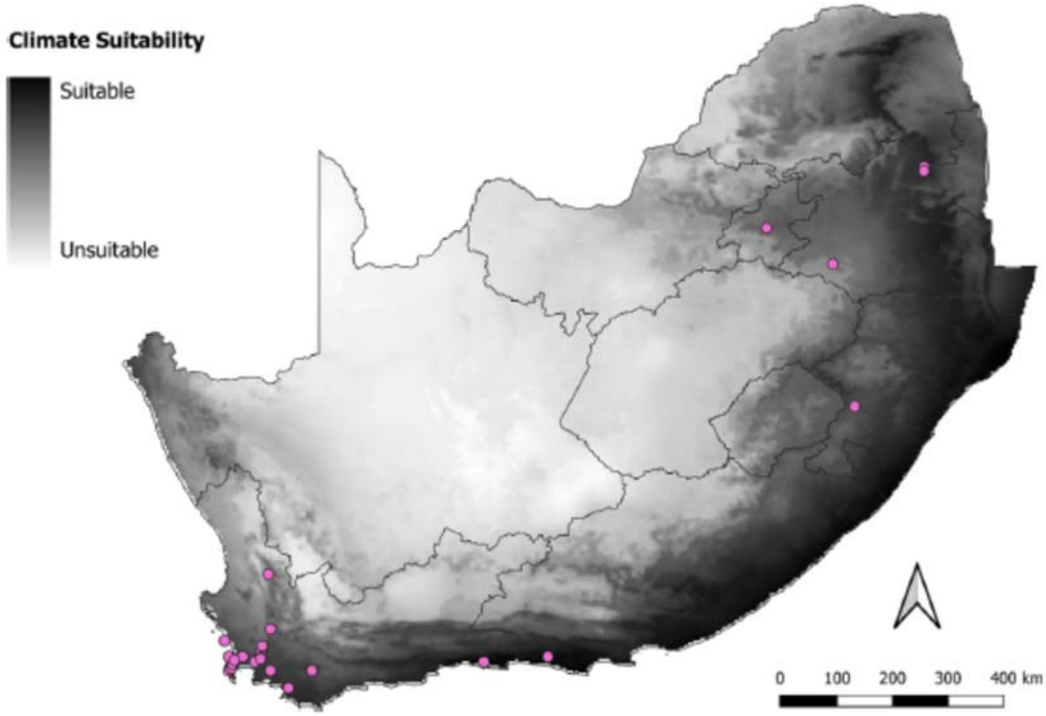

Fig. 4. Predicted climate suitability for Black Alder (*Alnus glutinosa*) in South Africa. Darker shades indicate areas predicted to be highly suitable, while lighter shades represent less suitable areas. Known occurrence points are indicated by the pink dots.

Although Black Alder can tolerate a wide range of temperatures and soil types (Claessens et al., 2010), it has a great affinity for water (Kajba and Gračan, 2003; Russel et al., 2007). Its local-scale distribution is closely linked to the availability and abundance thereof; it requires high atmospheric humidity and the presence of abundant moisture for at least 20 days to complete its reproductive cycle (Claessens et al., 2010; McVean, 1955b, 1953). As such, aridity seems to be a major limiting factor in the establishment of Black Alder (Claessens et al., 2010). Annual range in temperature was the most important predictor variable for two of the algorithms used to produce the model, while precipitation of the driest month was the most important predictor variable for one of the algorithms and the second most important for another algorithm (Table 1). The species is likely to be limited by water availability and will largely be confined to riparian areas, especially in the drier areas of South Africa. Indeed, most South African occurrence records are from areas where the annual rainfall exceeds 500 mm per annum (Fig. 5b). The predictor variable with the greatest importance in all three of the algorithms was temperature annual range (Bio 07, Table 1). This variable has a strong influence on the suitability values for the species, and areas of high suitability in South Africa (Fig. 5a) largely correspond with regions that experience a small annual temperature range (Fig. 5c). These areas with a small temperature range also largely overlap with areas where the annual rainfall exceeds 500 mm (Fig. 5a) and there is reasonable overlap with areas that receive on average more than 12 mm of precipitation in the driest month (Fig. 5d), another variable that was important in the model (Table 1).

Table 1. Predictor variable contributions for each of the three algorithms (GLM – generalized linear model, GBM – generalized boosted model, RF – random forest) used to produce the model for Black Alder. The variables with largest and second largest weighting for each of the algorithms appear in bold.

Abbreviation	Predictor variable name	GLM	GBM	RF
PETDriestQuarter	Potential evapotranspiration driest quarter	0.32	0.04	1.06
BIO03	Isothermality	1.44	0.61	1.44
BIO05	Max Temperature of Warmest Month	0.15	0.29	1.12
BIO07	Temperature Annual Range	**5.14**	**3.85**	**3.8**
BIO08	Mean Temperature of Wettest Quarter	0.54	0.15	1.04
BIO13	Precipitation of Wettest Month	1.38	0.1	1.78
BIO14	Precipitation of Driest Month	0.08	**6.16**	**2.7**
BIO15	Precipitation Seasonality	**2.16**	0.01	1.16

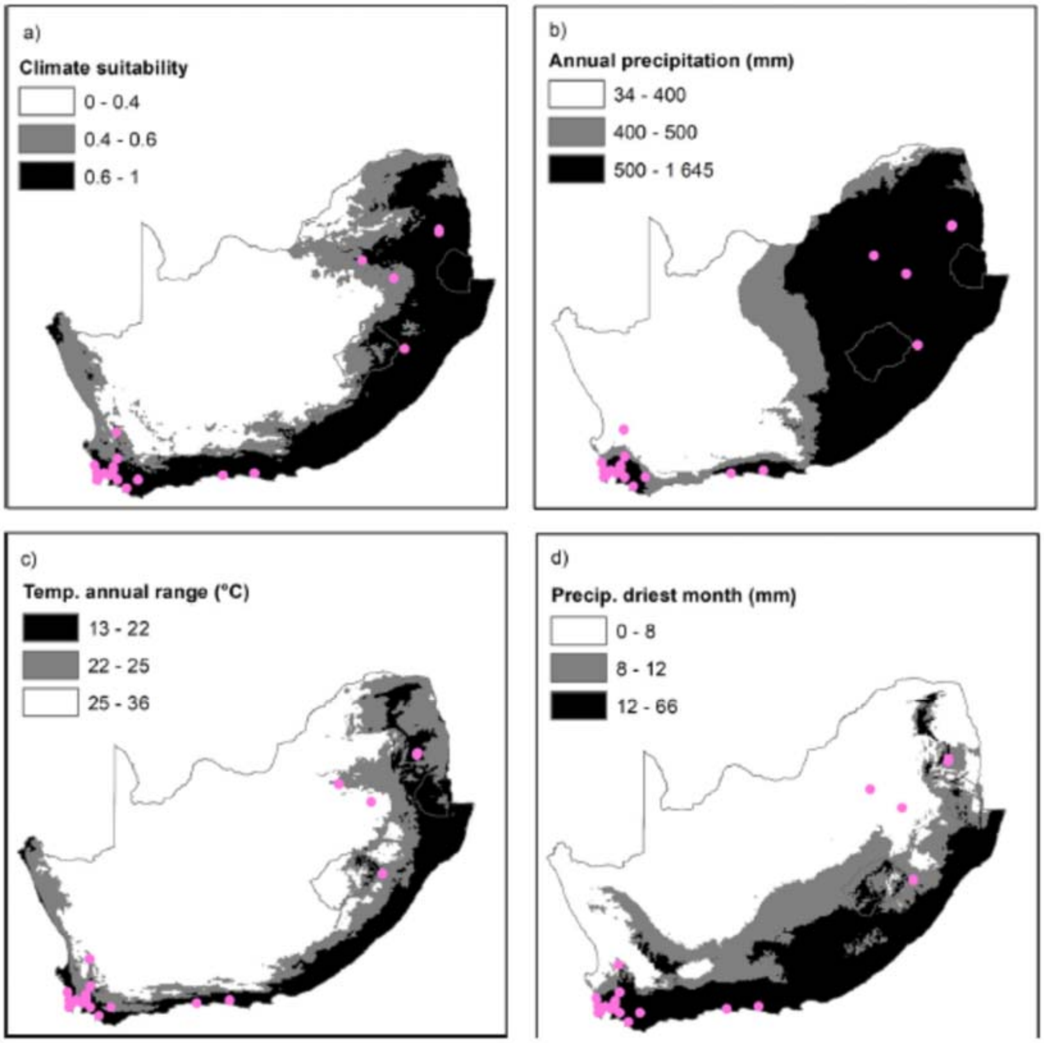

Fig. 5. Climate suitability and climatic variable maps for Black Alder (*Alnus glutinosa*) in South Africa: a) climatic suitability reclassified into three classes; b) annual precipitation; c) temperature annual range; and d) precipitation in driest month. Regions that are most suitable for the species have the darkest shading. Locations where Black Alder has been recorded in South Africa are indicated by pink dots.

Correlative models, such as the one we developed here, use correlations between predictor variables and occurrence records. Examining the predictor variable contributions can provide some insight into the importance of variables in limiting the distribution of the species. However, a variable with a high weighting in the model may merely be correlated with the variable that actually limits the distribution of the species, so care is needed here. The region of high suitability in South Africa appears to be defined largely by areas with a small annual temperature range (Fig. 5a, c). This pattern may explain the region of high suitability in the Northern Cape, which is unlikely to be suitable for the species given the low annual rainfall in that area.

The model developed here was calibrated with records from the entire range of the species, rather than from occurrence records in South Africa. A model for South Africa could provide insights into variables that may be important at finer scales, as has been done for other invasive species such as *Ailanthus altissima* (Walker et al., 2017), but there are currently insufficient occurrence records in South Africa to produce a reliable model. Greater insights into the variables that are important in limiting the distribution of the species in South Africa are likely to emerge as further occurrence records for the species become available.

4.5. Management of Black Alder

4.5.1. Controlling Black Alder

Several key factors must be considered when managing Black Alder as an invader. Firstly, the species is primarily a pioneer and can rapidly colonise bare soil and thus establish itself in early successional stages (Funk, 1990). This allows Black Alder to thrive on a wide variety of soils (Claessens et al., 2010) and to invade a wide range of habitats. Secondly, Black Alder is a vigorous resprouter (Fig. 1e) (Kajba and Gračan, 2003). This means that, as for other coppicing species (e.g. *Acacia saligna, Robinia pseudoacacia*), mechanical control alone is not a viable option for Black Alder; mechanical measures must be used in conjunction with a systemic herbicide that kills the entire root system (Martin, 2019). Such methods are not always successful, even when implemented correctly. Thirdly, Black Alder is a fast-growing species. The first stage of growth is characterized by a rapid increase in height (within five to ten years) (Kajba and Gračan, 2003) and early reproductive maturity and seed set (as early as second growing season), and large quantities of seed are produced by the year six (Funk, 1990). Clearing efforts of invasive stands must therefore be followed up timeously to kill any new seedling recruitment. This is especially important considering that seed germination can be as high as 80% (Kajba and Gračan, 2003). Such a high germination percentage, together with fast growth rates, results in rapid re-establishment of Black Alder in areas where it has been cleared. Black Alder seeds are fortunately short lived, and few seeds survive beyond the first germination season (McVean, 1955b). Lastly, since water is the main mode of Black Alder seed dispersal, and since fruits can float for up to 12 months (McVean, 1955b), the species has the potential to spread significant distances downstream of established populations. We suspect that the scattered individuals we observed occurring considerable distances downstream from the putative source population at Kylemore might have spread in this way. Management should thus start upstream of any populations and work downstream. The fact that Black Alder colonizes riparian systems complicates management using herbicide, since herbicides easily leach into streams. Selecting the appropriate herbicide and ensuring effective application are thus crucial to minimize non-target impacts and prevent herbicides from contaminating streams.

Guidelines for effective management of Black Alder can be compiled from the literature on efforts to manage the species in other parts of the world (Anderson, 2013; Cao et al., 2020; Champion et al., 2008; Kelly and Southwood, 2006; Willoughby et al., 2007). Key issues are summarized here. Small seedlings can be hand pulled if the ground is soft enough to remove entire plants (a weed wrench can be used if necessary). Hand pulling will disturb the soil and stimulate seed germination, and such treatment should thus be followed up timeously. For larger plants, a combination of physical and chemical methods should be used. Herbicide, such as glyphosate, should be applied to cut stumps of felled trees to prevent resprouting. Triclopyr triethylamine is recommended for foliar application, and napropamide is recommended as a pre-emergence herbicide. Although more time consuming, girdling (bark and phloem removal) can also be applied, but must be used in conjunction with herbicide treatment to prevent coppicing. The best time for herbicide application is during autumn. Control methods should be implemented for at least five years, since densities can increase (via regrowth) if any of these methods are implemented only once. No biological control agents are currently available for Black Alder.

4.5.2. Current control cost estimates

We calculated the control costs of Black Alder as the total cost of clearing for the time period over which we collected data divided by the total number of hectares that was cleared over the same period. We standardized all costs to a per month basis (some costs are annual, for example once-off training costs and vehicle maintenance). For the costs calculated here, a clearing team consisted of 12 members: 1 x supervisor, 2 x chain saw operators, 4 x herbicide applicators, 2 x first-aid workers, 2 x health & safety representatives, and 1 x team leader. The team cleared a total of 29.4 hectares in 9 months (average of 3.3 hectares per month) at a cost of R 82 011.15 per month excluding once-off annual training fees (Table 2). The total cost includes monthly salaries, herbicides, equipment costs such as fuel and maintenance for chainsaws, fuel and maintenance for vehicles, and miscellaneous items such as protective clothing and administration costs (e.g. office supplies). Although the costs provided here might be variable and influenced by site-specific conditions (e.g. teams might take longer to clear populations growing in less accessible terrain), these values represent a baseline that might prove useful for projecting costs for new populations.

Table 2. Costs of clearing Black Alder (*Alnus glutinosa*) in South Africa. Data are from a single clearing operation on the banks of the Dwars River from Kylemore to Lanquedoc, Western Cape Province. For standardization purposes costs are calculated per month. Costs were also calculated per hectare: the team cleared a total of 29.4 hectares in 9 months (August 2018 to April 2019). Total cost is given excluding and including annual once-off training. More details appear in Supplementary info.

Description	Cost	Cost/Hectare
Team Salaries	R 38 805.90	R 11 890.07
Herbicide	R 18 957.75	R 5 808.63
Equipment (chainsaw maintenance, fuel etc.)	R 12 614.17	R 3 864.96
Vehicles (maintenance, fuel etc.)	R 8 933.33	R 2 737.16
Miscellaneous (protective clothing, office supplies)	R 2 700.00	R 827.28
Total Monthly Cost (Annual Training Excluded)	R 82 011.15	R 25 128.10
Once off annual training	R 9 133.33	R2 798.44
Total Monthly Cost (Annual Training Included)	R 91 144.48	R27 926.54

4.5.3. Management challenges in South Africa

The efforts of Wildlands Co. in the Dwars River provide valuable information as a case study. The aim of these efforts is the complete extirpation of Black Alder, and the project is currently in the initial clearing phase, with future follow-ups planned. The Wildlands Co team is only involved in Dwars River. The team engaged with every landowner along the Dwars and Banhoek rivers, facilitated by the Banhoek Conservancy and the Dwars River Initiative (managed by the Ranyaka Trust). Consultation occurred in the form of workshops and platform discussion groups.

We gained some specific insights regarding the Black Alder clearing efforts of the WildTrust™ team at the Dwars River population, which we discuss briefly here. Firstly, the team received conflicting advice and recommendations regarding the correct control methods to implement (pers. comm. Lydia van Rooyen), since no herbicide is currently registered for Black Alder. The team proceeded to test two different registered herbicides, with active ingredients glyphosate and triclopyr/clopyralid, respectively. The latter combination was reported to be most effective if cut and sprayed as well as frilled on stumps. However, due to the nature of the species, vigorous resprouting occurs (Fig. 1e).

Secondly, the team reported some challenges, which stemmed mainly from issues related to funding. Department of Environment, Forestry and Fisheries Natural Resource Management (DEFF NRM) programmes are currently often constrained due to funding cycles, which affect continuity of treatment and follow-up. In many cases, riparian sites cleared of invasive trees have major problems with secondary invasion due to teams missing crucial follow-up windows, leading to regression of sites to pre-control conditions (Nsikani et al., 2020). This in turn leads to more funding being required since simpler and cheaper follow-up methods that could have been implemented (e.g. hand-pulling/foliar spray/debarking) are no longer viable; instead, more labour-intense and costly methods are required, such as re-cutting and re-application of herbicide treatment.

Thirdly, the team experienced challenges concerning engagement with landowners. Landowners seemed to show little understanding of the importance of the clearing and restoration work that was done, and were not enthusiastic about making contributions or supporting follow-up treatments (e.g. providing labour to assist with control of post-clearing invasive seedling emergence such as Australian *Acacia* spp. or *Solanum mauritianum*, or debarking Black Alder stumps that coppice). Thus, all such follow-up procedures were the sole responsibility of the implementing agent, increasing the burden on already overloaded teams. The team also reported that the public in the area is not well educated about IAPs and their threats, which represents a big environmental education challenge. Also, although landowners are responsible for biomass removal or stack-burning following felling, they try to avoid this due to the high costs involved (e.g. renting a chipper or transporting biomass to a stacking area, or obtaining a burn permit), the result being that the contractor/implementing agent is obliged to find a solution or add an additional cost or work load to their project.

Finally, the implementing agent was of the opinion that registering of herbicides to treat Black Alder should be taken up by the authority in charge, which unfortunately seems to be a long process. The implementing agents (e.g. WildTrust™) are not regularly informed and updated on the process, and receive little or no feedback on whether such a process is underway or not. There seems to be a lack in communication from officials in the relevant governmental departments. Better communication will greatly assist with operational issues.

5. Conclusions

Although Black Alder has been introduced to many parts of the world outside its native distribution, literature regarding its invasiveness and impacts is scarce (Bogar et al., 2015). This paper has reviewed some important aspects regarding the biology and environmental impacts of Black Alder, and insights on its invasiveness. It also provides the first comprehensive report of Black Alder's introduction history, current distribution and status as an invader in South Africa, and a summary of aspects of its management as an invasive species at the one site where control operations have taken place. Black Alder is currently only known to invade riparian ecosystems in the Western Cape Province of South Africa, but its ability to tolerate a wide range of conditions suggests that it has the potential to invade many other areas. Although Black Alder has numerous uses and benefits, it has great potential to cause substantial environmental impacts.

This paper has addressed some fundamental aspects of the ecology and management of Black Alder, but key knowledge gaps remain. We suggest that the following issues require further attention: 1) Field studies should be conducted over larger areas, especially in zones identified as suitable for the species, to confirm the distribution of planted, naturalized and invasive populations. Such information is crucial for determining the dimensions of invasion debt (sensu Rouget et al., 2016) for the species in South Africa and to guide management. 2) Research is needed to determine which infraspecific varieties of Black Alder are present in South Africa. There is also potential to gain valuable insights on the invasion dynamics of the species from population genetic studies. 3) The environmental impacts of Black Alder in South Africa need to be studied and quantified; these include impacts on soil biotic (e.g. microbial communities) and abiotic (e.g. soil chemistry) conditions, impacts on the health of watercourses (e.g. stream nitrogen pollution, streamflow alterations), and impacts on native species and communities (e.g. changes in plant diversity and community composition). 4) Nothing is known about the mutualistic associations that Black Alder forms with *Frankia* species in South Africa to facilitate nitrogen fixation nor about fungi with which it associates to form mycorrhizae; such knowledge will be valuable for understanding the invasion dynamics of the species in South Africa and its potential to cause impacts in invaded ecosystems. 5) An assessment of the pests and pathogens (native and non-native) associated with Black Alder in South Africa would be useful. 6) Further work is needed to determine the most efficient way of controlling Black Alder. Current knowledge in this regard for South Africa, as summarized in this paper, is based on insights over a short period and at a single site. Effective management is crucial to prevent Black Alder from becoming a widespread invader in South Africa. Management approaches for dealing with plant invasions in riparian ecosystems in South Africa have developed with consideration of challenges pertaining to a suite of long-established and widespread invasive species (Holmes et al., 2008, 2005). New protocols are needed to ensure efficient response to emerging invasive species such as Black Alder.

Declaration of Competing Interest

The authors have no conflict of interest to declare.

Acknowledgments

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