Impacts of Climate change, Land-use change and Natural disasters on biological invasions and the management of invasive alien species

This report has been compiled by expert members of the IUCN SSC Invasive Species Specialist Group (ISSG) and the Climate Change Specialist Group (CCSG).

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INTRODUCTION

Loss of habitat (caused by **land use change**, modification of natural areas), **impacts of a changing climate, biological invasions by invasive alien species,** overexploitation and pollution are recognised as the direct drivers of biodiversity loss and reduction in ecosystems services (Millennium Ecosystem Assessment, 2005; Secretariat of the Convention on Biological Diversity, 2010; Secretariat of the Convention on Biological Diversity, 2014).

In accordance with Article 8(h) of the Convention on Biological Diversity (CBD), each contracting Party is expected, as far as possible and as appropriate, to prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species. This provision has enabled the setting of global priorities and guidelines to address this threat, as well as to collect information and help coordinate international action on Invasive alien species (IAS).

An ***'Alien Species'*** is described by the CBD as *'A species, subspecies or lower taxon, introduced outside its natural past or present distribution; includes any part, gametes, seeds, eggs, or propagules of such species that might survive and subsequently reproduce'*. An ***Invasive alien species*** is described by the CBD as *'An alien species whose introduction and/or spread threaten biological diversity'* (Convention on Biological Diversity CBD, 2019).

The problems caused by IAS were captured in the *Guiding Principles for the Prevention, Introduction and Mitigation of Impacts of Alien Species that Threaten Ecosystems, Habitats or Species*, adopted by the 6th Conference of the Parties to the Convention with decision VI/23.

The Guiding Principles provide a detailed guidance on prevention of introduction and mitigation of impacts of alien species that threaten ecosystems, habitats or species, and define the key principles in addressing this threat. It stresses the importance of adopting a hierarchical approach to the management of IAS, meaning a priority emphasis on prevention; early warning and rapid response as the best option when prevention fails; eradication as the best management alternative; and, long-term control measures as a fall-back option.

Decision XIII/13 *'Invasive alien species: addressing risks associated with trade, experiences in the use of biological control agents, and decision support tools'* was adopted at the CBD COP in December 2016 in Cancun, Mexico. The Conference of the Parties (COP) requested the Executive Secretary of the CBD and its partner organisations **to develop guidance on invasive alien species management that takes into consideration the impacts of climate change, natural disasters and land-use change.** This brief aims to provide a basis for such a guidance document.

The increase and geographic redistribution of IAS will have diverse societal and environmental impacts. Invasive alien species through mechanisms such as competition, predation, disease transmission, parasitism, hybridization, biofouling, physical disturbance (browsing, rooting, trampling and herbivory) have caused severe negative impacts on habitats, directly on species, and socio-economic values (Simberloff, et al., 2013; Pimentel, Zuniga, & Morrison, 2005; Bradshaw, et al., 2016) and consequently on ecosystem services (Vila & Hulme, Impact of Biological Invasions on Ecosystem Services, 2017)

Biological invasions are a major threat to global food security and livelihoods, with developing countries being the most susceptible. These countries, which have high levels of subsistence and smallholder farming, often hold limited capacity to prevent and manage biological invasions. IAS reduce the resilience of natural habitats, making them more vulnerable to the impacts of climate change. For example, some grasses and trees that have become IAS can significantly alter fire regimes, especially in areas that are becoming warmer and drier. This increases the frequency and severity of wildfires and puts habitats, urban areas and human life at risk. IAS can also impact agricultural systems, by reducing crop and animal health. The economic costs of IAS and their management are in the billions of US$ annually and biological invasions are among the top drivers of biodiversity loss and species extinctions across the world.

Essential services that are required for human well-being and food security are provided by biodiversity and ecosystems: provisioning services (water, food, timber etc.); regulating services (regulation of climate, water, floods, disease and waste); supporting services (soil formation, nutrient cycling and primary production) and cultural services (spiritual, educational, recreational and aesthetic) (Millennium Ecosystem Assessment, 2005). IAS may cause loss of livelihood and socio-economic values by damaging agriculture, forestry, fisheries, aquaculture, mariculture, and limiting access to land and water. For instance, water hyacinth (*Eichhornia crassipes*), a native of South America has been introduced widely across the world as an aquatic ornamental species (Invasive Species Specialist Group , 2018). A fast growing plant it can cover water bodies very rapidly causing reduction in water quality, altering nutrient concentrations in the water, abundance and diversity of aquatic species, and physical disturbance including access to freshwater, blocking boat traffic, fishing and recreational uses of water (Villamagna & Murphy, 2009; Waithaka, 2013; Oliviera, et al., 2018; Masifwa, Twongo, & Denny, 2001) .

Impacts on native species leads to declines in native species populations leading to extinctions, species range change, alteration of genetic resources, plant and animal health. The Ruddy duck (*Oxyura jamaicensis*), is a native of North America and an IAS in the United Kingdom where it was intentionally introduced in the 1940's. It has subsequently 'escaped' and feral populations have been recorded as far out as Spain (Invasive Species Specialist Group, 2018). In Spain and other areas of Europe, the Ruddy duck is a threat to the Endangered White-headed duck *Oxyura leucocephala* (BirdLife International , 2017) through introgressive hybridisation and competition

The biological invasions threat shows no sign of slowing down (Seebens, et al., 2017). Other drivers of biodiversity loss may promote biological invasions. Climate change (including extreme events) and land use changes are expected to alter invasions stages from transport to spread of alien species by facilitating alien populations or species to overcome barriers to invasions (Hellmann, Bierwagen, Dukes, & Byers, 2008; Walther, et al., 2009) (see Figure 1 & Figure 2). For instance, climate change is opening new pathway of introductions (e.g., tourism, new roads).

Further, destruction of landscapes due to the impacts of climate change linked weather events exacerbate the spread of IAS, that further compromise the integrity of these ecosystems. A changing climate may influence the behaviour of alien species Results of a study (Muhlfeld, et al., 2014) , conducted using data over a 30-year period found that climate warming has influenced cross-breeding (hybridization) between and native Westslope cutthroat trout (*Oncorhynchus clarkii lewisi*) and an alien invasive rainbow trout (*Oncorhynchus mykiss*) in the Flathead River System, North America.

The conversion of land from natural to human dominated systems causes harm to ecological communities and species habitats, leading to reduction in species richness and the fragmenting of natural systems (Jetz, Wilcove, & Dobson, 2007; Martinez, et al., 2009). Fragmented ecosystems and 'disturbed areas' are more vulnerable to biological invasions than robust ecosystems (Jessen, Wang, & Wilmers, 2017; With K. A., 2004). IAS through their impacts compromise the integrity of ecosystems further exacerbating the impacts of climate change.

It is important to note however that changes to the biotic and abiotic environment due to a changing climate, land use change and natural disasters, may be equally likely to impede the establishment of IAS.

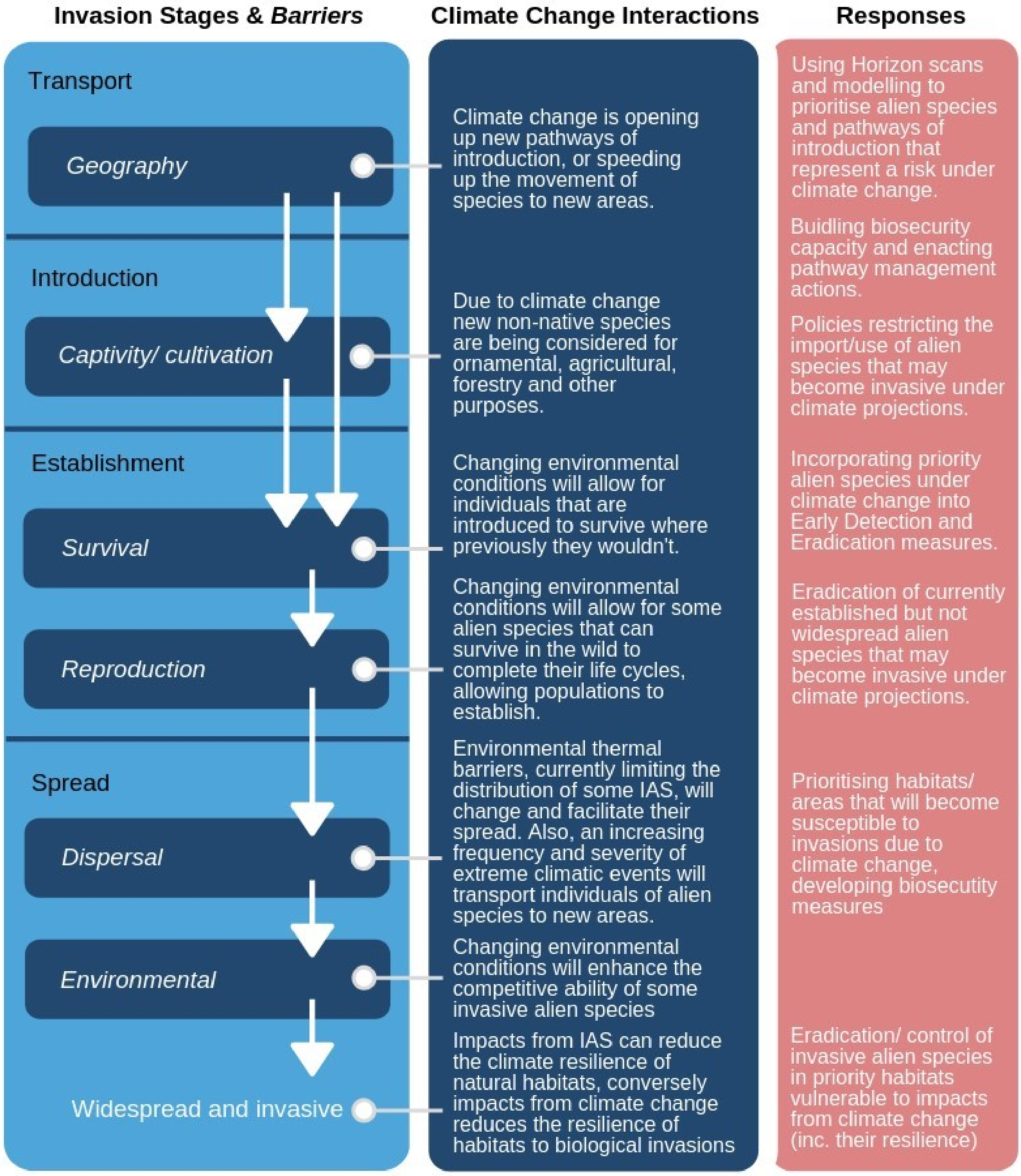

Figure 1 / Climate change interactions at various stages of biological invasions, from introduction to impacts, and potential responses inspired from Walther et al. 2009 and Blackburn et al. 2011

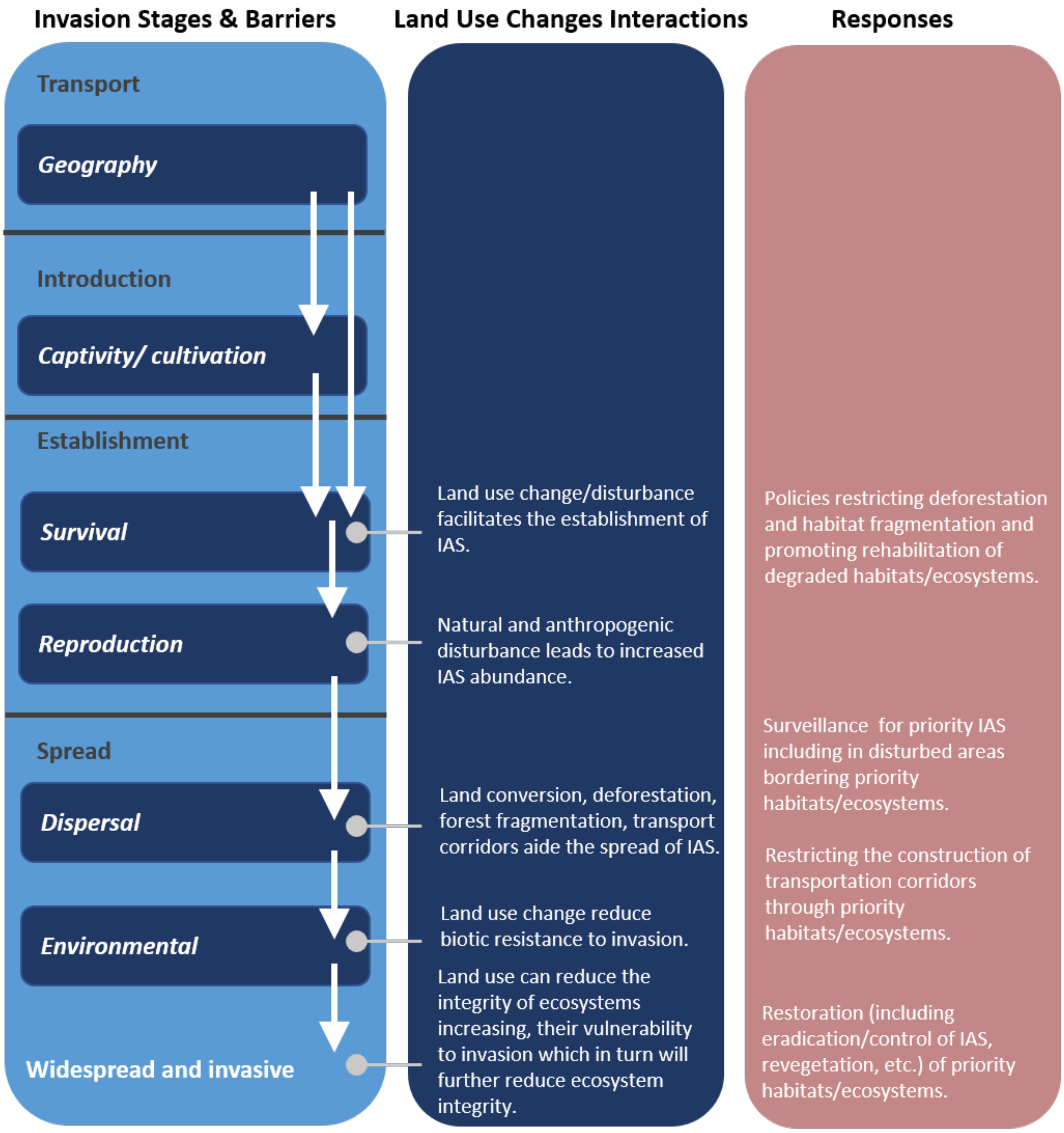

Figure 2 / Land use change interactions at various stages of biological invasions, from introduction to impacts, and potential responses inspired from Walther et al. 2009, Blackburn et al. 2011 and With 2002.

How can climate change, land-use change, and natural disasters affect the transport and introduction of alien species across geographical barriers?

It is important at the outset to remind ourselves that it is often not possible to know in advance whether a colonising alien will become invasive (or even established), and so this section considers movement of alien species in the broadest sense. The section does not, however, consider the spread of already-established alien species populations (invasive or otherwise) beyond their current range in the absence of human actions, irrespective of whether environmental change is involved in this expansion or not.

Following the definitions indicated above, alien species are introduced to new locations via human activity. Therefore, introductions can be either intentional or unintentional - see the *Guidance for the interpretation of categories of introduction pathways* (Convention on Biological Diversity CBD, 2018). Intentional introductions can occur for a variety of purposes, including agriculture, horticulture, aquaculture, forestry, biocontrol, recreation (e.g. hunting or pets) (Hulme P. E., Trade, transport and trouble: managing invasive species pathways in an era of globalization, 2009; Hellmann, Byers, Bierwagen, & Dukes, 2008). Unintentional introductions occur through human-mediated transport, travel and trade. They are transported as stowaways or contaminants (or hitchhikers) on goods, commodities and transport vessels. Many unintentional introductions are a by-product of intentional introductions.

With the above in mind, we may next consider how such processes might be affected by changes in the environment, such as climate change, land-use change and natural disasters. Of these three types of environmental change, climate change has received the most research attention in the context of alien species introductions, and so accordingly forms the bulk of this chapter, though reference is made to the other two types as appropriate.

An increasing number of extreme climatic events, such as hurricanes, floods and droughts have the potential to transport of IAS to new areas and decrease the resistance of habitats to invasion. A study by (Carlton, et al., 2017) found that following the 2011 East Japan earthquake and tsunami, most of the 289 recorded living Japanese coastal species were transported to the shores of the Pacific coasts in the Northwest America on the remains of human-made structure (Carlton J. T., et al., 2018; Tanaka, Yasuhara, & Carlton, 2018; Murray, Bychkov, Therriault, Maki, & Wallace, 2015)

Over the past few decades globalisation has increased the movement of people and goods around the world, which has led to a rise in the number of species introduced to areas outside their natural ranges, and this rate of introductions is showing no sign of slowing down. Climate change is also opening up new pathways of introduction, through changes to tourism or commerce, including through changes to associated transport routes (Hellmann et al., 2008). For example, reductions in Arctic ice cover will allow shipping access through formerly inaccessible areas, which may act as a transport mechanism for alien, cold water-adapted species (Walther, et al., 2009). Climate change will facilitate and sometimes necessitate geographical changes in the production patterns of agricultural (including aquaculture) and forest products (Ramankutty et al., 2002). Such changes in the origins of products and the routes they take to reach their destinations could provide opportunities for new species to be transported to areas to which they previously did not have access.

Rahel and Olden (2008) note that (in aquatic systems) climate change may affect accidental introductions of alien species as opportunities arise for aquaculture, or the keeping of non-native species for recreational purposes, in previously unsuitable areas (e.g. due to increased water temperatures or reduced ice cover). They also note that escapes from aquaculture and tropical fish farm facilities could increase in frequency due to alterations in hydrological regimes such as flood events that cause rearing ponds to overflow (Padilla and Williams, 2004 in Rahel and Olden, 2008).

Related to this, the culture or keeping of species in newly climatically-suitable areas, particularly if using individuals from wild sources, brings with it the risk of introducing alien parasites or diseases (Marcogliese, 2008) which may themselves have the ability to colonise and affect local wild species, even where the host vectors do not.

Alien species introductions may occur because of adaptive measures that humans take in preparation or response to change. For example, in some areas it may be necessary to build canals or aqueducts to transport water from areas of abundance to areas of scarcity, and this may well open new pathways for aquatic organisms to travel between watersheds (Rahel and Olden, 2008).

Relief efforts to respond to natural disasters such as flooding and tropical cyclones have the potential to facilitate the introduction of IAS via the movement of foodstuffs, equipment, construction materials and personnel (Murphy & Cheesman, 2006). Another example is the introduction of alien and invasive species for coastal planting to prevent erosion after destruction of coastal areas due to natural disasters (Sudmeier-Rieux & Ash, 2009). The invasive Australian Pine (*Casuarina equisetifolia*), has been planted as a coastal buffer along the eastern coast on India after such extreme weather events

(Das & Sandhu, 2014); studies have shown that Australian Pine planting has potential negative impacts on Olive Ridley turtle nesting sites along these coasts (Chaudhari, Devi, & Shanker, 2009).

On the one hand, IAS are known to cause changes in land-use such as the invasive pine in the South African fynbos changing shrublands to woodlands (Richardson & Brown, 1986). On the other hand, disturbances caused by land-use change could potentially provide dispersal pathways for the spread of IAS dependant on factors such as the historical legacy of land-use in that area, and spatial distribution and configuration of land-use types (Vila & Ibanez, Plant invasions in the landscape., 2011; With K. , 2002).   Activities in the forest sector such as conversion of natural forests to planted forests and construction of roads and access points for people and vehicles to enter these areas are a potential dispersal corridor for alien and invasive species (Brown & Gurevitch, 2004).

How can climate change, land-use change, and natural disasters facilitate survival and reproduction of alien species across geographical barriers?

In addition to propagule pressure, establishment of alien species is influenced by the suitability of environmental conditions in recipient biomes and the ability of the invading species to adapt to these conditions or otherwise to self-create suitable conditions. The conditions needed for alien species to survive and reproduce are driven by both abiotic and biotic factors (D'Antonio, Levine, & Thomsen, 2001; Lonsdale, 1999). Favourable abiotic factors such as temperature, soil moisture, salinity and light intensity are essential to the survival of alien species. Indeed, temperature is a known limiting factor to the survival and reproduction of plants and numerous animals (Walther G., et al., 2009). Biotic factors such as competition or predation can either facilitate or impede establishment of alien species (Lockwood, Hoopes, & Marchetti, 2013). The effects of climate change, land use change and natural disasters on abiotic factors of recipient ecosystems may facilitate IAS establishment by (1) rendering previously unsuitable abiotic conditions suitable, (2) reducing biotic resistance or (3) promoting biotic interactions favourable to the survival and reproduction of alien species by altering food availability, competitive interactions or predator-prey relationships (Blaustein, et al., 2010).

Evidence shows that shifts in temperature and rainfall patterns attributed to climate change can increase the probability of establishment of alien species, which were previously constrained by climate (Hulme P. , 2017; Walther, et al., 2009). For instance, in the Mediterranean Sea, long-term data show that increases in temperatures facilitates establishment of tropical species (Raitsos, et al., 2010). Whilst in Southern Islands, milder winter temperature may favour mouse survivorship (Angel, Wanless, & Cooper, 2009). Climate models predict that a decrease in precipitation could lead to a 45% increase in land suitable for cheatgrass establishment (Bradley, Oppenheimer, & Wilcove, 2009). Alterations to abiotic factors caused by climate change may reduce biotic resistance by giving a competitive advantage to alien species over native or previously established species. Evidence shows that warmer temperatures in freshwater ecosystems would favour alien species as these generally have a greater heat tolerance than related native species (Bates, et al., 2013). For example, laboratory experiments found that introduced water flea *Daphnia lumholtzi* may out-perform native *Daphnia* spp. at temperatures >25°C, as it has a higher reproductive rate at elevated temperatures (Lennon, Smith, & Williams, 2001). Likewise, warmer winter give introduced ascidian species a competitive advantage over native species by giving them an earlier reproduction start (Stachowicz, Terwin, Whitlatch, & Osman, 2002) and may facilitate establishment of introduced limpets and oysters (Nehls, Diederich, Thieltges, & Strasser, 2006). In temperate terrestrial ecosystems, warmer climate conditions promote survival of desiccation in the invasive springtail species and reduce it in the indigenous ones (Chown, Slabber, McGeoch, Janion, & Leinaas, 2007).

Whilst disturbances are integral to ecosystem dynamics, altered or new disturbances from human land transformations provide increased opportunities for species invasions (Hobbs & Huenneke, 1992) Indeed, land use changes such as urbanisation, deforestation, ecosystem fragmentation or agricultural intensification can facilitate establishment of species (Hobbs, Land-use changes and invasions., 2000; Strubbe & Matthysen, 2009; Burnham & Lee, 2010). Although both specialist or generalist native species and introduced species, can take advantage of land-use changes and disturbances, introduced species perform as well or better in the new conditions than species native to the area (Hobbs, Land-use changes and invasions., 2000)

Replacement of ecosystems for agricultural or horticultural purposes, for instance, has brought about the establishment and spread of alien species from planting sites. The introduction of *Pinus* spp. to the southern hemisphere in high numbers (increased propagule pressure) and over large areas, for example, has facilitated its establishment and spread (Richardson, Forestry trees as invasive aliens, 1998). In addition, agricultural settings may provide conditions favourable to the reproduction of alien species. For instance, a study by (Sanz-Aguilar, Carrete, Edelaar, Potti, & Tella, 2015) suggest that alien passerine species in the Mediterranean region reproduced along more months and later than native coexisting species by taking advantage of resources provided by croplands. Similarly, agricultural areas were the best predictors for American bullfrog invasions in Italy, which confirms that bullfrogs take advantage of irrigation systems (Maret, Snyder, & Collins, 2006; Ficetola, et al., 2010). Furthermore, historical land-use along with position with respect to roads and soil chemistry were associated with alien plant invasions in Bent Creek, North Carolina, USA (Kuhman, Pearson, & Turner, 2011).

Like climate warming, urban heat islands may provide alien species with suitable abiotic conditions for survival and reproduction. For instance, (Groeneveld, Belzile, & Lavoie, 2014) found that compared to smaller towns, germination rate of Japanese knotweed seeds was greater in, or in proximity of major urban centres in Canada, suggesting that urban heat islands delay first fall frosts and enable Japanese Knotweed seeds to mature.

Natural disasters produce resource pulses or stressors, which affect biotic resistance and thereby facilitate the establishment of alien species (Diez, et al., 2012). Strong storms (e.g. hurricane/typhoon) for example, damage forest canopy and subsequently increase forest floor light levels. Likewise, wildfires generate space in ecosystems by burning existing vegetation and produce additional compounds and nutrients. Several alien species exploit and thrive in the altered environmental conditions. Bishop wood (*Bischofia javanica*), for example, rapidly develops sun leaves with high photosynthetic capacity after typhoon disturbance compared to native trees (Yamashita, Ishida, Kushima, & Tanaka, 2000) whilst the spores of invasive fern *Lygodium microphyllum* accumulate in greater numbers in canopy gaps than in closed canopies (Lynch, et al., 2011). Fire derived smoke-water compounds enhance germination of the common milkweed, *Asclepias syriaca L*., by breaking seed dormancy, which may facilitate its establishment and spread in non-fire dependent ecosystems of central and eastern Europe (Mojzes & Kalapos, 2015). Stresses induced by events such as extreme temperatures, drought or flood can negatively impact native species, giving generally tolerant alien species a competitive advantage. For example, a number of plant species invasive to the Iberian Peninsula including Radiata pine (*Pinus radiata*), Australian blackwood (*Acacia melanoxylon*), Pepper tree (*Schinus molle*), Russian olive (*Elaeagnus angustifolia*), and Blue gum (*Eucalyptus globulus*) have a higher thermal tolerance of Photosystem II than native counterparts, which allows them to photosynthesise during periods of water stress and high temperatures (Godoy, de Lemos-Filho, & Valladares, 2011). Similarly, under drought conditions, invasive herb *Centaurea diffusa* can maintain energy production and react less strongly than native populations (Turner, Fréville, & Rieseberg, 2015). Moreover, prolonged drought conditions were found to facilitate establishment of alien green sunfish, *Lepomis cyanellus*, and invasive zooplankton in California (Bêche, Connors, & Resh, 2009; Winder, Jassby, & Mac Nally, 2011). In Australia, winter flooding was also found to favour the reproduction of alien fish species, as water temperatures were below the spawning threshold of native fish (Rayner *et al.* 2015). Understanding alien species ecophysiological responses to disturbances is very important especially in the context of climate change, as extreme events frequency is expected increase in parts of the world. Furthermore, natural hazards can act synergistically with climate or land-use change to facilitate alien species establishment (Winder *et al*., 2011). For instance, in areas that experience drought, invasive Asian Tiger mosquito *Aedes albopictus* may outcompete native Eastern tree-hole mosquito (*Aedes triseriatus*) due to changing rainfall patters (Smith, Freed, & and Leisnham, 2015).

How can climate change, land-use change, and natural disasters facilitate dispersal of alien species across geographical barriers?

In the last stage of invasion (Figure 1 & 2), alien species spread, establishing populations in new sites. We expect that climate change will also alter this stage of invasion (Hellmann, Byers, Bierwagen, & Dukes, 2008; Walther, et al., 2009). Indeed, species distributions worldwide are mostly determined by climate factors, tectonic movements, and orographic barriers (Ficetola, Mazel, & Thuiller, 2017). Expected climate change will therefore have a major impact on species range and distributions irrespective of whether species are native or alien to a particular region. In theory, the current limits of alien established species is set up by the environmental constraints (Beerling, Huntley, & Bailey, 1995; Walther, et al., 2009). We can expect that climate change, altered habitats and natural disasters may further alter range of established alien species and help to successful spread into new areas (Figure 1 & 2). For example, the rate at which species spreads may increase if disturbed corridors are in place (D'Antonio, Levine, & Thomsen, 2001; Hellmann, Bierwagen, Dukes, & Byers, 2008). We already observed shifts in spatial distribution of marine and terrestrial species and species introductions (Sorte, Williams, & Carlton, 2010) . For instance, a recent meta-analyses on marine range shifts and species introductions showed that climate change is considered to be the cause of over 70% of the range shifts recorded (out of the 129 marine species experiencing range shifts) (Sorte, Williams, & Carlton, 2010). We also expect that alien species shifts (northward and upward) more quickly than native species to newly suitable environmental conditions due to their general high ability to disperse and compete for resources (Sorte, Williams, & Carlton, 2010). For example, climate change already induced a shift in spatial distribution northward of two exotic species on the United States Pacific coast the invasive Sea squirt (*Styela clava*) and the solitary ascidian *(Molgula manhattensis*) in the last 20–50 years (Carlton, Global change and biological invasions in the oceans, 2000). Evidences of upward expansion of alien plant in European Alps were found, with alien plants spreading upwards twice as fast as natives (Dainese, et al., 2017). Pulse in rainfall associated with climate change are also accelerated the spread of invasive shrub Lantana (*Lantana camara*) compared to native shrub (Masocha, Dube, Skidmore, Holmgren, & Prins, 2017).

Fast life history traits of alien and invasive species enable them to expand their range to new areas. For instance, (Capellini, Baker, Allen, Street, & Venditti, 2015) showed that successful spread among established mammals is related with larger and more frequent litters. Amphibians that spread have earlier maturity and successful invasive reptiles showed shorter reproductive lifespans (Allen, Street, & Capellini, 2017). Because of these characteristics, we expect that current invaders might be quite successful to spread following climate change (including extreme events) and land use changes.

Therefore, there is an urgent need to understand the relationship between climate change and the spread of invasive species, especially those that may have a major impact on biodiversity. Some studies concluded that climate change may increase the areas occupied by invasive species (Barbet-Massin, et al., 2013; Gilioli, Pasquali, Parisi, & Winter, 2014; Kriticos, Sutherst, Brown, Adkins, & Maywald, 2003), while others show that climate change limits their distributions (Bellard, et al., 2013; Bradley, Oppenheimer, & Wilcove, 2009; Xu, Peng, Feng, & Abdulsalih, 2014). For instance, the suitable area of the invasive fire ant (*Solenopsis invicta*) is predicted to be 21% greater than it currently is with a northward expansion of 133 km by the end of the century (Morrison, Porter, Daniels, & Korzukhin, 2014). Conversely, worldwide land suitable for the Velvet tree (*Miconia calvescens*), is predicted to be reduced within both native and invaded areas due to climate change by the 2080s (González-Muñoz, Bellard, Leclerc, Meyer, & Courchamp, 2015).

In South America, predictions show an overall decrease in suitable climatic conditions for the invasive American Bullfrog, *Lithobates catesbeianus*, but also a shift into protected areas (Nori, Urbina-Cardona, Loyola, Lescano, & Leynaud, 2011)

A recent meta-analyses of 71 publications and 423 case studies, show that the spread of known invaders is predicted to increase for invertebrates and diseases at the world scale, while it is mostly predicted to decrease for plants and vertebrates (Bellard, Jeschke, Leroy, & Mace, 2018). This is largely due to oceans preventing terrestrial invaders from spreading poleward. The potential species range change following climate change were projected to do so by +35%, while the projected decrease was lower (-24%) (Bellard, Jeschke, Leroy, & Mace, 2018). It is also important to highlight that those studies are generally biased towards plant terrestrial ecosystems (Bellard, Jeschke, Leroy, & Mace, 2018). In addition, many invasive species in temperate conditions are geographically restricted by extreme cold temperature and are predicted to shift at higher latitudes following climate and land use changes (Bellard, et al., 2013; Chytrý, et al., 2012; Gallardo, et al., 2017). The displacement of invasive species will be highly problematic.

Besides overall change in temperature and precipitation, extreme climatic events can also facilitate the spread of established alien species by either overcoming dispersal barriers or reducing biotic resistance (Diez, et al., 2012). Evidence suggests that natural disasters such as storms and floods may contribute to both the release and movement of propagules over long distances (Pysek & Prach, 1993; Nathan, 2006; Engeman, Jacobson, Avery, & Meshaka Jr, 2011). Hurricanes for instance promoted the dispersal of Cactus moth (*Cactoblastis cactorum*), a moth introduced to the Caribbean region as a biocontrol for Prickly pear- *Opuntia* species (Andraca-Gómez, et al., 2015). Hurricane frequency was also positively correlated to the expansion of invasive perennial wetland grass *Phragmites australis* stands on the Gulf Coasts of the USA, explaining 81% of growth variation (Bhattarai & Cronin, 2014). Further anecdotal evidence attributed the release of captive animals to strong storms such as the Burmese python, *Python bivittatus*, or the lionfish, *Pterois volitans*, which are believed to have escaped following 1992 Hurricane Andrew in Florida (Hare & Whitfield, 2003; Engeman, Jacobson, Avery, & Meshaka Jr, 2011; Willson, Dorcas, & Snow, 2011). Likewise, flood events may increase pool connectivity and provide alien species access to newly inundated areas, which was the case for the common carp, *Cyprinus carpio* in south-eastern Australia (Vilizzi, Thwaites, Smith, Nicol, & Madden, 2015). The strength of storm triggered floods can transport propagule over long distances thereby facilitating spread. Large propagules of the invasive green alga *Codium fragile* for example, which tend to have a low dispersal potential get transported further during floods (Watanabe, Metaxas, & Scheibling, 2009).

By generating disturbances, resource pulses and stresses to native biota, extreme climatic events can reduce the biotic resistance of an ecosystem and facilitate the spread of alien species (Diez *et al*., 2012). Already established invasive species may take advantage of additional resources such as light, space or nutrients (Snitzer, Boucher, & Kyde, 2005). For instance, a number of alien plant species, including Mile-a-minute (*Polygonum perfoliatum*), Japanese honeysuckle (*Lonicera japonica),* Climbing fern *(Lygodium microphyllum)* and Australian cheesewood (*Pittosporum undulatum*), responded positively to higher light levels after hurricane damage in the USA and Jamaica by increasing growth rates or spore production (Bellingham, Tanner, & Healey, 2005; Schnitzer, Kuzee, & Bongers, 2005). Similarly, in Panama, wildfires promote the spread of the invasive Sugarcane (*Saccharum spontaneum*) by removing litter and stimulating shoot growth (Saltonstall & Bonnett, 2012). In central Mexico, increased phosphate availability following wildfires promotes Southern cattail (*Typha domingensis*) seedling growth (López-Arcos, Gómez-Romero, Cisneros, & Zedler, 2012). Alterations to abiotic conditions of invaded ecosystems may also give a competitive advantage to alien species over natives. For example, the invasive Gemsbok diet gives it a competitive advantage over native pronghorn during droughts as it feeds on forage with lower nutritional value (Cain-III, Avery, Caldwell, Abbott, & Holechek, 2017). Likewise, droughts in the United States favour invasive Asian Tiger mosquito over native Eastern tree-hole mosquito (Smith, Freed, & and Leisnham, 2015). In France drought tolerance of non-native Black bullhead (*Ameiurus melas*) and Eastern mosquito fish (*Gambusia holbrooki*) favours them over native fish species (Cucherousset, Paillisson, Carpentier, & Chapman, 2007). In the upper Gila River, New Mexico, USA, the effects of wildfires are more pronounced in native species of insects and fish thus giving a competitive advantage to alien species (Whitney, Gido, Pilger, Propst, & Turner, 2015).

Natural disasters may also impede the spread of alien species.

Invasive alien species management that takes into consideration the impacts of climate change, land-use change and natural disasters

No matter how successful efforts may be to mitigate the consequences of climate change through lesser reliance on fossil fuels and the adoption of renewable energy sources, the considerable inertia in the earth's system will require the development of adaptation strategies directed at global warming impacts over the next 100 years. Nevertheless, the natural variability of the climate makes it difficult to attach high-levels of confidence to some of the predicted changes, particularly those associated with extreme events (including climate driven natural disasters) and/or where large natural variability is inherent (Bellard, et al., 2013). There is similar high uncertainty in future projection of land-use change, particularly with regard to forest and pasture ecosystems but less so for croplands (Prestele, et al., 2016). Unfortunately, levels of confidence do not map onto potential impact and some of the potentially most severe changes to the global environment that might drive alien invasions, such as changes in the frequency of cyclones or extent of forest fragmentation are the hardest to predict. Uncertainty also occurs in the response of both native and alien species as well as ecosystems to a given climate or land-use change scenario. While environmental pressures will have a direct impact on the performance and demography of many species, for others the strongest impact will be indirect and will result from changes in the spatiotemporal availability of natural resources, competitors, predators and/or pathogens.

Given the inherent uncertainty in future forecasts of environmental change and the potential responses of both native and alien species, what then are the management options available to tackle biological invasions? Although policies to address the management of biological invasions need to factor in the interplay between climate and land-use change drivers on the introduction, establishment and spread of alien species (Figure 1 & 2) such coordinated policy frameworks are absent from most national regulations. Thus, it is likely that the backbone of future responses will be built upon current strategies. The CBD proposes three successive steps in alien species management: prevention, eradication and, if neither of the other steps is possible, control. The ultimate goal of such actions should be the conservation or restoration of ecosystems to preserve or re-establish native biodiversity and functions. These successive steps form the cornerstones of recommended best prevention and management practices aimed at targeting IAS (Wittenberg & Cock, 2001). Management responses mirror the sequential stages in the invasion process: transport, introduction, establishment, spread and impact (Hulme P. E., Beyond control: wider implications for the management of biological invasions, 2006). Prioritization of management actions undertaken earlier in the sequence is recommended as this should prove the most cost-effective strategy. There is therefore a clear connection between increased understanding of the invasion process and the transfer of this knowledge to support effective management strategies.

Approaches to the **prevention** of the entry of new alien species is often the most effective strategy for managing biological invasions yet even high-profile pests have slipped through pre-border prevention measures resulting in outbreaks (Walther, et al., 2009). The relative risk of natural spread of aliens from one country to another is poorly understood (Hulme, 2015) and the extent to which climate change will magnify the scale of this pathway is uncertain. It remains unclear to what extent the pressure at the borders will increase because of climate change and recent horizon scanning in both the United Kingdom (Roy, et al., 2014). and in Europe (Roy, et al., 2019) identified a wide range of potential future alien species that are likely to arrive independently of climate change, natural disasters or land-use change. The ability to prevent biological invasions is being progressively compromised by the rapid increase in the movement of goods and people (Hulme, 2009). Even where bioclimatic models[1] are used to predict those alien species posing the highest risk of establishment, current prevention regimes cannot expect to be completely effective in preventing entry. Hence, the importance of surveillance programmes to enable early detection while eradication is still a possible option i.e. **prevention** of establishment.

Given the inherent uncertainties with regard to which species may or may not enter into a particular country and therefore science based risk assessment of biological invasion is not available for determining risk reduction management measures, efforts may be better targeted at **eradication** of alien species already present but whose establishment is constrained by climate or land-use and whose expansion would result in negative impacts on the economy or biodiversity to address the potential of multiple environmental threats. This is particularly important since in most regions a significant proportion of alien species have failed to establish persistent populations and should climate or land-use or limited propagule pressure be a limiting factor for these species then any change, could result in a significant increase in establishment rates of such sleeper aliens. Given the large pool of potential sleeper aliens[2], tools will need to be applied to prioritise the most high-risk species under the multi-environmental changes. Initial screening may use expert opinion based on a priori expectations regarding the likely response of aliens to temperature, urbanisation,

[1] "*Bioclimatic models (also known as envelope models or, more broadly, ecological niche models or species distribution models) are used to predict geographic ranges of organisms as a function of climate. They are widely used to forecast range shifts of organisms due to climate change, predict the eventual ranges of invasive species, infer paleoclimate from data on species occurrences, and so forth*" (Jeschke & Strayer, 2008)

[2] "*Casual alien species (sleepers) whose population persistence is limited by climate are expected to exhibit greater rates of establishment under climate change assuming that propagule pressure remains at least at current levels*" (Hulme P. , 2017)

eutrophication or cultivation but any subsequent management that might include control costs or pathway interventions (including banning from sale) would need a sound quantitative approach. Recent effort to provide a framework for implementing Environmental Impact Classification for Alien Taxa (EICAT) (Hawkins et al; 2015) will contribute to establish priorities of biological invasion risk management among species to address the multi-environmental changes, if a framework combined with statistical analyses on climate, land use and extreme events are undertaken. .

Control or **containment** provides considerable economic, environmental and social benefits to containing outbreaks and actively slowing the spread of the established alien species before their impacts can be fully realised and widespread management is required. However, there has been little systematic work in most regions of the world to model future distributions of alien species outside of a handful of countries (Bradley, Oppenheimer, & Wilcove, 2009; Duursma, et al., 2013; Hulme P. , 2017). This in part reflects the fact that many established alien species will expand their ranges irrespective of climate change and their future dynamics may be shaped as much, if not more, by human-mediated long-distance transport and anthropogenic habitat modification. Discerning the climate signal in future alien range expansions requires realistic models of range expansion under current climates validated against historical distribution data that can be used to assess the reliability of future projections attributable to climate change. Approaches to predict species' responses to climate change or land-use change have tended to address either changes in abundance with time or in spatial distribution. Both approaches are limited by the availability of either sufficiently long temporal records or suitably extensive spatial data. The scarcity of repeat distribution censuses over time for many species has severely limited the integration of these two approaches (but for one such approach, see (Catterall, Cook, Marion, Butler, & Hulme, 2012)

In many cases the primary tools for the control of alien species will be culling, trapping or the application of pesticides or herbicides or biocontrol. Climate change and land-use change may result in an increase in the frequency and/or intensity of existing management regimes, e.g. pesticide application. This may increase costs of management and challenge environmental stewardship previously delivered through less intensive management approaches. However, new invasive alien species, pests and pathogenic agents may shift the status quo and require different pesticide regimes or the development of less socially acceptable control methods. Predicting and mitigating potential impacts of alien species in the natural environment exacerbated by climate change or land-use change is thwarted by ecosystem complexity. Since neither the direct impacts of climate change on semi-natural ecosystems nor on alien species impacts is well understood, any attempt to understand future interactions between the two is a challenge. Under these circumstances, an ecosystem rather than an alien species focus to management may be warranted. Such strategies require that scientists, managers and policymakers work together to:

1. identify climate-sensitive ecosystem components;
2. assess the likelihood and consequences of impacts of alien species;
3. identify and select options for adaptation.

Adaptation strategies should aim to increase the range of options available for the management of vulnerable ecosystems, enhance the inherent adaptability of the species and ecosystem processes within vulnerable natural systems, and reduce trends in environmental and social pressures that increase vulnerability to climate variability. Thus, an ecosystem perspective would help identify which ecosystems will become more vulnerable to alien species and allow options for the protection of such ecosystems to be implemented e.g. through the management of introduction pathways and prohibition of degradation of such ecosystems. Underpinning this approach is the assumption that adapting to current climate and land-use risks is consistent with adapting to future changed conditions and thus current knowledge can be applied to address future risks. But current ecosystem management practices may not be sustainable under future climates and ecologists must attempt to go beyond describing the potential impacts of climate change and begin addressing possible solutions. Two complementary strategies may work under these conditions of high uncertainty. First, prioritise ecosystems in terms of their perceived vulnerability to climate or land-use change and prevent ingress or expansion of alien species therein that may exacerbate problems. Second, target those ecosystems already threatened by alien species and implement management to prevent the situation deteriorating under multiple environmental pressures.

Challenges to managing Invasive alien species under a changing climate, land-use change and natural disasters

As both climate and land-use change facilitate the expansion of native species into regions previously unoccupied in historical times, the challenges of addressing biological invasions will increase as the distinction between native and alien species status becomes blurred. While there are clear definitions as to what constitutes an alien species that emphasise the role of deliberate or inadvertent human transport in range expansion, there will undoubtedly be increasing uncertainty as to the exact pathway through which species arrive in a new region. Under these circumstances, definitions of what is native and alien need to be robust to this uncertainty (Essl, et al., 2018). This will certainly be the case where differences between native and alien taxa occur at the infraspecific level such as in the case of the spread of frost-tolerant horticultural cultivars of native Common Holly (*Ilex aquifolium*) in Scandinavia (Skou, Toneatto, & Kollmann, 2012). While the issue of species definitions is more than an academic interest, the management of biological invasions is likely to be far more pragmatic. Given the limited resources most states have available to address biological invasions, whether at the border in terms of screening and risk assessment, post border surveillance and rapid response or longer-term eradication or control efforts, there will need to be prioritisation. Under such circumstances, we can expect those species posing the greatest risks to ecosystems, human health or the economy to be prioritised, and most likely in that order. This risks that management of alien species that impact negatively on biodiversity or ecosystem functions being less well-resourced than those species that impact humans more directly either through the spread of pathogenic agents (e.g. mosquitoes as vectors) or by reducing economic productivity (e.g. agriculture pests). Under these circumstances research must deliver more than predictions of potential future range but also an estimate of the impact of such range expansions since simply being a widespread species does not necessarily equate to having a greater impact on biodiversity (Bernard-Verdier & Hulme, 2019). While models of future species distribution now include climate and land-use change (Gallardo & Aldridge, The 'dirty dozen': socio-economic factors amplify the invasion potential of 12 high-risk aquatic invasive species in Great Britain and Ireland, 2013), no attempt has been made to integrate such projection with potential impacts on biodiversity or ecosystem services.

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