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LEAD ARTICLE

Climate Change, Invasive Alien Flora and Concerns for their Management in Sri Lanka

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ABSTRACT

Climate is the key driver of diversity of life in ecosystems. Changes in the climate, would not only alter the spatial distribution of species but also facilitate some of the non-native species to become invasive. This would further imbalance the status quo of native species and may bring about irreversible changes in some ecosystems imposing large economic costs for their management. Few researchers have addressed the issue of the interaction of climate change and invasive species in developing countries. We review the ecological impacts of invasive alien flora on the environment and the necessity to assess the economics of these impacts, particularly in developing countries. The potential implications of climate change on invasive alien flora relevant to Sri Lanka are discussed, highlighting how disturbances to ecosystems during climate change would facilitate the dispersal, establishment and spread of these invasive species and result in a change in the species distribution of native flora within ecosystems. The management of invasive alien species is already formulated for Sri Lanka. We draw attention to how climate change aspects should be incorporated into these management strategies. Important aspects to be considered are assessment of risk, targeting ecosystems vulnerable to climate change and mapping to monitor the location and progress of invasive flora.

Keywords: biological invasions, climate change, developing countries, invasive alien flora, management of invasives

INTRODUCTION

Human migrations across geographical areas of the globe facilitated many plant species to spread beyond their native boundaries. The colonial network of botanic gardens in the tropical countries was largely responsible for providing a pathway for alien plant introductions in many countries (Cronk and Fuller, 1995) as well as trade and transportation contributing towards globalization (Stohlgren *et al*., 2011). This was in an era when the definitions of alien and invasive species were non-existent. Colonial powers also set up botanic gardens in the tropics, which served to house species from other colonial countries, some of which eventually escaped into the surroundings. During the British colonial period (1796-1948), plant species, including seeds and herbarium specimens, were sent out of Sri Lanka, particularly to Kew gardens (Pethiyagoda, 2007). Sri Lanka's major export crops, many of the ornamentals, spices and upland vegetables were deliberate introductions during the colonial period. Thus many alien (non-native) species also became components in ecological communities inadvertently, without the notice of humans. Over time, these species have integrated themselves into the local landscape and ecosystems.

The movement of species beyond their centers of origin has drastically increased in recent decades due to humans via expansion of trade, travel and tourism. Although many of these alien species integrated themselves into local ecosystems over time through naturalization, some have become problematic by invading agricultural and natural ecosystems, displacing native species (Gonzalez *et al*., 2008; Marambe and Gunawardena, 2010; Pimentel *et al*., 2001; Richardson *et al*., 2000; Vila and Weiner, 2004). The alien species, now recognized as invasive alien species (IAS), literally invade ecosystems by successfully competing with the native biodiversity. They are a recent phenomenon, which threatens biodiversity by changing the structure and function of ecosystems (Butchart *et al*., 2010; Chapin III *et al*.,

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2000) and are considered a significant component of human mediated global environmental change (Vitousek *et al*., 1997).

In addition to the threats posed on biodiversity due to direct anthropogenic activities such as land fragmentation, habitat destruction, and pollution, the global phenomenon of climate change acts directly on the native species through increased atmospheric carbon-dioxide concentrations, changes in climate parameters that change the range thresholds, and changes in the competitiveness of species among others (Ziska 2003, Nagel *et al*. 2004). It also acts indirectly through changes in the environmental conditions for growth of the native and non-native species. Species can react to climate change by shifting their geographical range into the new boundaries set by the climate parameters. An example from the temperate climes is the invasion by winter weed (*Poa annua*, Family Poaceae, native to Eurasia) in the deglaciated sites in Heard Island in the sub-Antarctic where it is advancing at more than 100 m a year since 1980 (Scott and Kirkpatrick, 2005). In the northern hemisphere, the range of terrestrial plants has shifted on average 6.1 km/decade poleward or 6.1 m/decade upwards in altitude, and the onset of spring has advanced by 2.3 – 5.1 days/decade over the past 50 years (Parmesan and Yohe, 2003; Scott and Bergstrom, 2006).

The possible consequences of climate change on invasive flora and on the invasiveness of certain species are to a large extent speculative. However, it is prudent to invoke the precautionary principle and to implement appropriate management measures. Extended drought periods are a commonly expected outcome of climate change. An extended period of drought can reduce the fitness of vulnerable native species. This can provide an opportunity for IAS to occupy a new niche, such as an opening in the rainforest canopy that favour drought tolerant open habitat species (Corlett, 2011).

While the increased vulnerability of fauna and flora to IAS in the temperate regions due to climate change is receiving the attention of ecologists and conservationists, it has not received similar attention in the tropics, which is home to the majority of biodiversity hotspots. There is a strong geographical bias in the research conducted on invasion biology with Africa and Asia being neglected (Pyšek *et al*., 2008). This bias is a reflection of the low priority for studies on invasion biology in developing countries and the limited availability of financial and competent human resources to undertake such studies. Research priorities in developing countries are first assigned to applied research with an immediate outcome on the lives of the people and hardly for esoteric studies to understand the theoretical frameworks in ecology, conservation or invasion biology. Nunez and Pauchard (2010) found that of the published literature on ecology and biodiversity conservation, from 2003 to 2007 in the ISI Web of Science, only 6.5% had authors solely from developing countries. The low investment in research in developing countries also results in poor data quality.

The sources of invasions are most often tropical countries in Africa and Asia, where biodiversity is high (Myers *et al*., 2000) and the recipient countries are the developed countries whose high purchasing power enables an increased volume of trade into their countries. Thus, the lack of knowledge on one part of the invasion process – the source of introduction - prevents a complete understanding of the invasion process and the development of prevention and management strategies. Since invasion by alien species is a global problem, developing countries need to be strengthened in their research capacity through financial resources and collaborations with laboratories in developed countries, to better understand the invasion process and eventually develop effective management strategies. Development aid programs that include transfer of species to developing countries (*e.g.* for reforestation, food security, biofuels), should provide a 'climate proof' for such programs by asking if species can become invasive under a different climate scenario.

Sri Lanka has drafted 'The National Invasive Alien Species Policy' to prevent the introduction and spread of IAS and their control with the assistance of the Global Environmental Facility and the United Nations Development Programme. A recent review of the current status of IAS in Sri Lanka identified several existing gaps and needs assessments, one of which was the interaction of IAS and climate change (Marambe, 2010). Absence or non-implementation of an IAS management plan in the country, lack of financial commitment towards IAS control, limited availability and access to information due to the absence of an information management system, and lack of an institutional coordinating mechanism were the other key challenges identified. Moreover, no research publications have addressed the interaction between climate change and plant invaders of national importance (Jayarathne and Ranwala, 2010).

This paper seeks to address the potential implications of climate change on the threat from invasive flora to Sri Lanka. We review the relevant literature on climate change and invasive species, with the focus on flora, and suggest what measures should be included to the existing IAS management and policy frameworks, in order to mitigate the threat to our local biodiversity.

CLIMATE CHANGE

The Fifth Assessment Report (5AR) of the Intergovernmental Panel on Climate Change (IPCC) (Stocker, 2013) released in September 2013, states that warming of the climate system is unequivocal and since the 1950's many of the observed changes are unprecedented over decades to millennia. The atmosphere and oceans have warmed, the amounts of snow and ice have diminished, sea level has risen and the concentrations of greenhouse gases have increased. Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850 (Stocker, 2013). The Fifth Assessment Report of the IPCC further states that in South Asia, the seasonal mean rainfall shows inter-decadal variability, noticeably a declining trend with more frequent deficit monsoons. The literature has documented that greenhouse gas emissions and many aspects of climate are already at the upper boundary of the IPCC projections and many climate indicators, such as global mean temperature, sea-level rise, global ocean temperature, and extreme climatic events, are moving beyond the patterns of natural variability (Stocker, 2013).

In Sri Lanka, analysis of meteorological data has shown significant changes in climate parameters providing evidence for climate change. An analysis of temperature records in Sri Lanka over a 140-year period (1869-2007) by De Costa (2008), showed a highly significant linear increasing trend. An analysis of temperature trends for the 40 year period 1961-2000 carried out by the Department of Meteorology of Sri Lanka, showed an increasing trend in annual maximum temperatures with rates upto 0.046 °C per year, except at two locations in Nuwara-Eliya and Ratnapura, which showed decreasing trends (SNC, 2011). In the same period, increasing trends of annual minimum temperature of 0.0269 °C were observed at all the stations except Trincomalee. A decreasing trend of 9.46 mm per year was observed in the annual mean rainfall over the entire island from 1961-2000. Most of the decrease in the annual rainfall was from the North East monsoon, which brings rains to two-thirds of the island, with no significant change in the South west monsoon (although its variability has increased). The number of rainy days has also decreased increasing the dry spells and increasing the intensity of rainfall and the number of consecutive dry days is increasing in the dry and intermediate zones. This change in rainfall distribution is shifting the demarcation between the dry zone and wet zone within Sri Lanka, with a reduction in the area of the wet zone (SNC, 2011).

These gradual and abrupt changes in our climate would at some stage may or may not facilitate the spread of IAS and the extinction of species, as has been recorded extensively in Australia and other parts of the world (Low, 2008; Thomas *et al*., 2004; Thuiller, 2007; Watt *et al*., 2010). It is thus imperative that Sri Lanka also recognizes the significance of climate change in changing the impact of IAS on our ecosystems, and implement management strategies.

DESCRIBING INVASIVE FLORA

Definitions and concepts

Since the entry of invasive biology as a subject of its own, a variety of alternative terms and concepts to describe invasive species and the process of invasion across the literature has contributed to confusion and misunderstanding. Invasive species itself is associated with exotic, non-indigenous, alien and introduced species, among others. The variety of terminologies, synonyms, and definitions has also hindered the development of robust generalizations of alien species and description of the invasive process (Blackburn *et al*., 2011).

In their global database of invasive trees and shrubs, Rejmánek and Richardson (2013) have linked the term naturalization with alien and used two simple criteria to identify an alien species: a species that has naturalized by consistently reproducing and which is spreading. Native species are, however, indigenous within a particular geographical boundary and particularly in large regions their exact geographic boundaries have also contributed to confusion. Although all naturalized plant species are aliens, all aliens are not necessarily naturalized. Webber and Scott (2012) question the association of alien species with anthropogenic dispersal events, which can create conflicts for active management and global change adaptation strategies. To overcome this they propose the concept of a 'projected dispersal envelope', which describes the area in which a dispersal unit (*i.e.* propagules or individuals) or population of a species could be found, based on natural dispersal or migratory traits in a given time frame. Thus, native species occur within a defined time frame, while alien species are outside the projected dispersal envelope. This concept is independent of human involvement and integrates biogeography and niche theory with invasion terminology to give a spatial and temporal context on the dispersal of species (see Webber and Scott 2012, for a detailed discussion).

The term ‘impact’ is commonly used to describe the consequences of an invasive species on the native population and on the ecosystem. However, an impact can be either positive or negative of varying magnitude and is a subjective concept. Parker *et al*. (1999) developed a general framework to define impact and quantify it so as to distinguish small and large effects, which is central to prioritize management strategies. They identified three parameters that defined impact: range, abundance and the effect per individual or per biomass unit of the invader. It is necessary to consider all three parameters together to provide a holistic picture, while using only one of these, provides an erroneous picture (see Parker *et al*., 1999 for example).

The invasive pathway

To become invasive, a species has to pass through environmental barriers before successfully establishing in a new geographic region. The success of crossing some of these barriers can be modified by climate change (Rahel and Olden, 2008).

Hellmann *et al*. (2008) described four phases in the invasion pathway of an IAS. During the first phase of invasion, the alien plant species must travel from its native range to its new location. This would depend upon the rate at which propagules are moved from one location to another as well as the viability of propagules on arrival. According to Baker and Stebbins (1965), characteristics which are vital for a species to naturally reach a new location are the production of a large number of viable propagules, efficient timing of their release from the mother plant, adaptations for long distance dispersal as well as for secondary dispersal. However, this may not be an essential phase in human mediated dispersal events. During the second phase, the species should be able to tolerate and survive in the new environment and be fertile for a long period. The third phase highlights the successful establishment of species acquiring critical resources and resisting enemies at the new site. Many possible explanations were hypothesized, such as the ‘evolution of increased competitive ability’, which describes high competitive ability, broader niche width and the extent of resource exploitation (Blossey and Nötzold, 1995), the presence of allelopathy or the ‘novel weapons hypothesis’ (Rice, 1984), as well as the Baker characteristics, which describe the successful establishment of the second and third phases. During the final (fourth) phase, species acquire the status of an invader, being able to spread and establish new populations across the introduced landscape. Here too, propagule pressure is vital and according to Baker and Stebbins (1965) species display their weedy and invasive traits. However, Elton (1958) documented that ecosystem properties of the new environment are equally important, since more diverse and stable communities are less susceptible to invasion by exotic species (‘biodiversity resistant hypothesis’). This view also supported the first observations of Darwin (1968) and Williams (1954) that the exotics are released from their natural enemies in the new environment (‘enemies release hypothesis’), which facilitates their spread without control of their population.

The framework to understand the pathway of plant invasions by many plant ecologists (Catford *et al*., 2009; Heger and Trepl, 2003; Hellmann *et al*., 2008; Richardson and Rejmánek, 2004) is that set out by Richardson *et al*. (2000). This framework regards invasion as an overcoming of a series of barriers from the point of introduction of the species to naturalization. This framework is also followed by the IUCN’s Global Strategy on Invasive Alien Species (McNeely, 2001).

Besides the conceptual framework of species overcoming environmental barriers to become invasive, ecologists have proposed new schemes to understand and manage invasive species. Blackburn *et al*. (2011) proposed a unified framework by combining the key elements of the Richardson scheme and that for animal invasions (Williamson and Fitter, 1996). This new framework also incorporates human-mediated invasions, and is a step towards merging the flora and fauna schemes and unite the field of invasion biology, for further discussion.

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Gurevitch *et al.* (2011) identified three major characteristics of invasions: (i) rapid local population increase, (ii) establishment of local dominance, and/or (iii) rapid range expansion. These phenomena do not occur together or lead to one another; any one may occur alone or in combination with either of the others. The authors proposed a general conceptual framework by incorporating these three elements of invasion biology, which contribute to an altered community or landscape structure and composition. This synthetic framework was based on fundamental ecological and evolutionary processes and the authors argue that demographic processes are central to this framework because they ultimately determine if an invasion would proceed or not.

Conceptually, a unified framework of the invasion process is required to understand ‘why invasions occur' and assist us to formulate management measures. However, unifying the biological aspects of different plant taxa such as reproductive biology (sexual, asexual, dispersal mechanisms), life cycle phenology, habitats, host-environment interaction among others are bound to provide exceptions. The different aspects of climate change (climate extremes, temperature and rainfall changes) would further modify the barriers at different stages of the invasion process *i.e*. transport, introduction, establishment and spread of the invasive species. These common frameworks are formulated in developed countries using empirical evidence peculiar to temperate ecosystems. Ecosystems in the tropics and developing countries have a high degree of biodiversity and a uniform climate suitable for growth throughout the year thus not allowing changing seasonal observations. Unifying these disparate aspects in ecosystems, biology, and climate is a very challenging task. The need in the developing countries, where most disturbed tropical ecosystems are located and are now disturbed, are mechanistic explanations for invasions of specific ecosystems, which would help us to develop management options for control of invasive flora.

CLIMATE CHANGE AND IAS

Ecological responses to climate change

The effect of changes in the climate on biodiversity and ecosystems are explained in the short term (climate extremes: floods, seasonal rainfall failure), medium (droughts, temperature increase/decrease) and long term (extended droughts, consistent high/low temperature) consequences. In the short to medium term, anthropogenic factors such as land fragmentation, habitat degradation and destruction through changing land use patterns, pollution by nitrogenous wastes and IAS are important. Walther *et al*. (2002) and Walther *et al*. (2009) have reviewed these ecological responses of both fauna and flora in response to climate change in the phenology and physiology of organisms, the range and distribution of species, the composition of and interactions within communities, and the structure and dynamics of ecosystems. Together, these interactions may result in compounded effects on ecosystem services such as groundwater retention and filtering, pollination, disease suppression and carbon sequestration.

How does climate change affect plant species and what are their ecological responses? Depending on the life histories and related traits, a plant species may promote (i) migration to keep pace with climate change (but limited by habitat fragmentation, dispersal ability and substrate requirements), (ii) adaption *in situ* through selection of tolerance traits, or (iii) extinction to respond to climate change (Aitken *et al*., 2008). These responses combine to alter growth rate, species interactions, trophic levels and composition, re-structure communities and modify dynamics of ecosystems providing opportunities for alien species to enter and occupy open niches (Thuiller, 2007; Walther *et al*., 2002).

Another obvious response to climate change is the area of distribution of species. The factors that determine the distribution of species are (Soberón, 2007): dispersal capacities of the species, spatial distribution of environmental conditions favourable for establishment, survival and reproduction by the individuals, and the biotic environment comprising the species competitors, predators, pathogens and availability of resources. Climate change can modify these factors by acting on the individual components and thereby change the response of species and area of distribution.

Climate change can favour invasive species directly or indirectly. The increased atmospheric Carbon dioxide concentrations can increase the competitive ability of certain invasive species over the native species ((Low, 2008; Nagel *et al*., 2004; Smith *et al*., 2000; Ziska, 2003; Ziska and Bunce, 2007). Ecosystems that are disturbed through climate change such as drought or fire are easily invaded by invasive species (Dukes and Mooney, 1999). It is widely suggested that invasive species have broad environmental and climatic tolerances, wider geographic ranges, fast growth rates, early maturity for an efficient reproduction, high dispersal ability and increased potential for rapid micro-evolutionary changes which would favour them to establish easily and aggravate the extent and impacts with projected climate changes (Goodwin *et al*., 1999; Pyšek and Richardson, 2007; Rejmánek and Richardson, 1996; Richardson *et al*., 2000).

Increased disturbances to ecosystems

Climate change is a disturbance event that imposes a stress on already established native populations (Low, 2008). The IPCC has predicted that disturbances due to extreme climate events, such as strong winds, increasing temperature, floods, cyclones, landslides, prolonged droughts and fire, would increase in the future at regional scales (Stocker, 2013). These events are expected to facilitate movement of the propagules of alien species to colonise and take over habitats which were previously unavailable for them. The diverse consequences from changes in the climate and their impact on ecosystems, contributing to the increased invasiveness of species are summarized in Fig. 1. For example, in Swaziland in 1984, cyclone 'Demonia' blew seeds of *Parthenium hysterophorus* across the country, enabling its establishment in agricultural land and wildlife reserves (Burgiel and Muir, 2010). In the Northern Territory of Australia, flooding was largely responsible for the rapid spread of *Mimosa pigra* (Lonsdale, 1999).

Extreme climate events such as floods, droughts, wind storms, and cyclones can weaken or devastate large extents of vegetation. This opens new habitats with less species richness, fewer competitors for space, light and nutrients, all of which facilitate the occupation by propagules of alien species. Prolonged drought facilitates fire, which devastates large extents of land (Fig. 1). Similarly, cyclones, although a rare event, can devastate coastal vegetation, providing new opportunities for the establishment of IAS. Alien species with a high competitive ability by virtue of the characteristics of their reproductive biology can easily establish or spread into these areas. For example, after the Tsunami in 2004, a significant expansion of prickly pear (*Opuntia stricta*), Mesquite (*Prosopis juliflora*), Lantana (*Lantana camara*) and Siam weed (*Chromolaena odorata*) was reported in the southern coastal areas of Sri Lanka (Bambaradeniya *et al*., 2006).

Future occurrences of such events are possible in nature reserves and protected areas in which alien invaders are found nearby. For example, the wet lowland forests in Sri Lanka share borders with *Clidemia hirta*, *Dillenia suffruticosa*, *Panicum maximum*, *Pennisetum polystachyon* and the sub-montane forest habitat borders with *Austroeupatorium inulifolium* and the strangler *Clusia rosea*.

Protected areas and sanctuaries in the dry zone of Sri Lanka are surrounded by cultivated areas, including the shifting cultivation system of "slash and burn" to clear space for farming. When these are abandoned after a few seasons of cultivation, they are easily colonized by invasive flora such as *Lantana camara*, *Mikania cordata* and *Chromolaena odorata*, which are now a footstep away from entering protected areas in the event of a natural disaster and climate change induced disequilibrium. The spread of *L. camara* in the Uda-Walawe region is an example of a species assuming invasive status due to extensive clearing of the environment (unpublished results). We should recognize the complications added by climate change that threatens ecosystems by providing new opportunities to facilitate the spread of invasive species. Or else, it may be too late to recover irretrievably lost native biodiversity.

Propagule pressure and spread of IAS

Floods can change propagule pressure through dispersal to a particular location, thereby facilitating the spread and establishment of species in new habitats such as *Mimosa invisa*, *M. pigra*, *Prosopis juliflora* and other aquatic species in waterways (Fig. 1). Since IAS often possess efficient dispersal mechanisms, using either wind or animals to spread seeds over long distances, it is assumed that they will benefit from increasing wind speeds and range-shifting animals (Pyšek and Richardson, 2007).

Invasive flora can keep a low profile in the face of competition, multiply rapidly and colonise areas following an extreme event (Grice, 2003; Groves, 1999). Other than creating the potential for increased competition, some alien invaders may indirectly create conditions that favor further spread of other alien species. Invasive grasses such as *Arundo donax*, gorse (*Ulex europaeus*), kikuyu grass (*Pennisetum clandestinum*), and old world climbing-fern (*Lygodium mycrophyllum*) are known to increase fire loads and heat intensity, leading to greater mortality in some fire intolerant species while providing more opportunities for invasion by IAS (Wijte *et al*., 2005). A change in climate can also provide opportunities for previously innocuous alien species to shift their range by changing their growth rates and reproductive capacity (Fig. 1), by changing their physiology and phenology (Cleland *et al*., 2007).

Natural range shift of species

Reviewing the ability of how fast plants need to move in the face of climate change, Corlett and Westcott (2013) concluded that many plant species are likely to lag behind broad scale patterns of climate change over the remainder of the century, although there are significant gaps in our understanding of the processes involved in tracking climate by plants. In other words, the velocity of climate change would be too much for already adapted species to a particular bio-geographical area to escape the new unfavourable climate.

The ability of flora to spread naturally, is determined by the relative mobility of their seeds, or their dispersal mechanisms. Creepers and vines have a faster growth rate and are usually able to recover faster following a disturbance, smothering and overgrowing native species. The old world climbing fern, *Lygodium microphyllum* in the Everglades ecosystem of the USA is spreading rapidly by virtue of its increased propagule pressure and ability to grow in a low light understorey environment (Volin *et al.,* 2004).

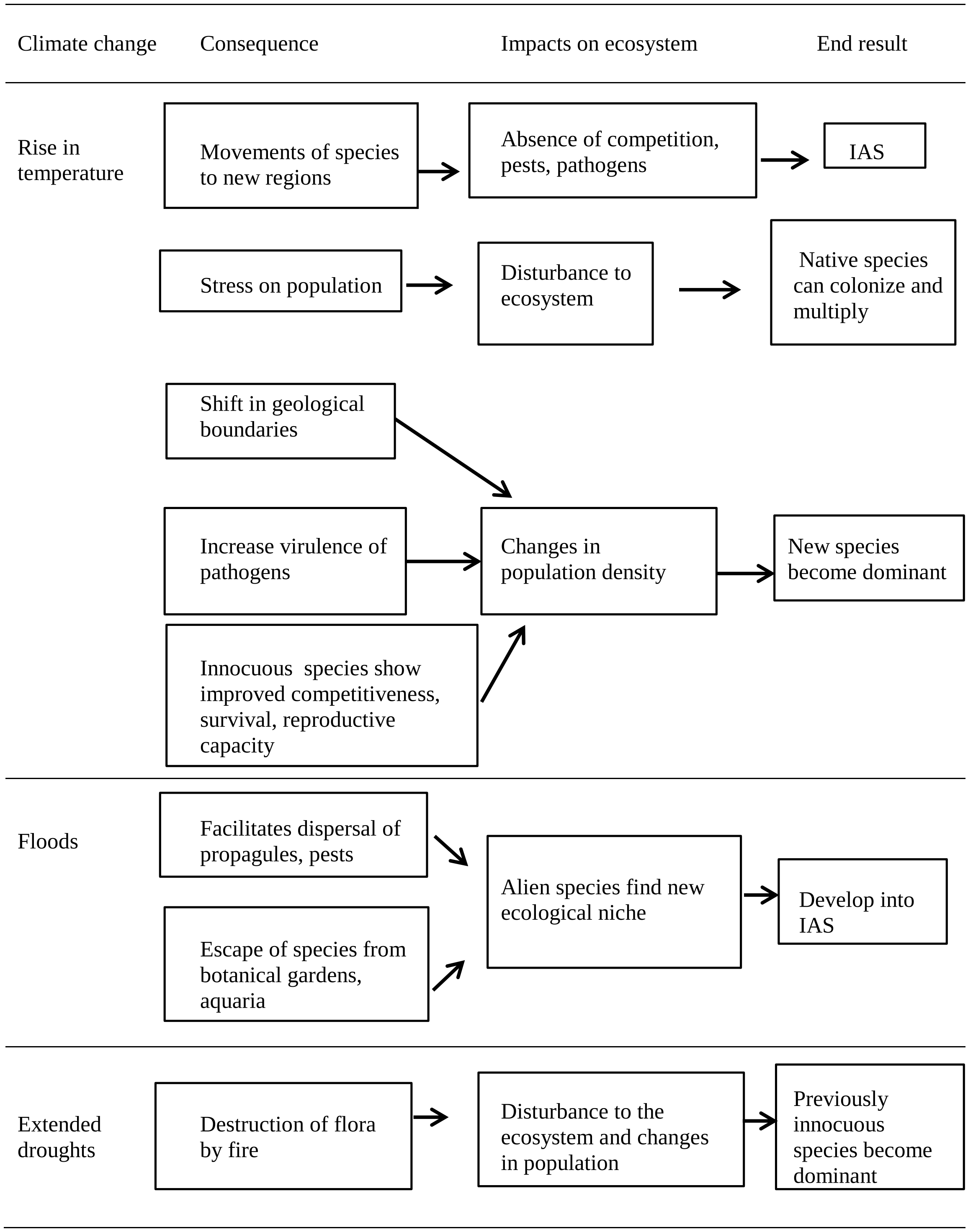

Figure 1. The impact of climate change on species and ecosystems leading to invasiveness of species (IAS - invasive alien species)

In such instances the IAS will be able to dominate native species due to their inherent reproductive and competitive abilities. Shifts of terrestrial flora, are obviously visible and their changes more easily observed, than aquatic species. The movement of species from one region to a new selective matrix of another can also cause them to become invasive. Such a migration can be caused by climate change opening up new niches for their colonization and establishment that were previously unavailable (Fig. 1). Higher latitudes and altitudes will clearly exhibit relocation of species as temperatures increase and 'new' species migrate from adjacent, warming areas (Parmesan, 2006). During this process, range expansion as well as contraction, could be expected (Hellmann *et al*., 2008; Richardson *et al*., 2000).

IMPACTS ON THE ENVIRONMENT

Ecological impacts

Invasive species were recognized as a problem due to their negative impact on the environment. An escalation of these impacts brought awareness among ecologists of the problem of biological invasives, and the scientific community has now realized that an understanding of the ecological impacts is necessary to decide on management principles (Parker *et al.,* 1999; Pyšek and Richardson, 2007).

Ecological responses to climate change have been documented across major taxonomic groups covering most of the biomes of the earth (Parmesan, 2006; Walther *et al*., 2002) and major taxonomic and functional groups of organisms (Lawler *et al*., 2009; Lonsdale, 1999; Panetta and Mitchell, 1991; Solbrig *et al*., 1994; Thuiller *et al*., 2005; Willis and Whittaker, 2002; Woodward, 1987; Ziska *et al*., 2011). There is a close interaction between climate change and IAS (Pyke *et al*., 2008). These include: (i) climate change accelerates or facilitates the establishment of IAS, (ii) IAS have been proposed as biofuels for reducing greenhouse gases to ameliorate the climate, and (iii) the management of IAS could increase the resilience of ecosystems and potentially decrease the adverse impacts associated with climate change.

Wilson *et al*. (2014) have described an assessment scheme for monitoring tree invasive species using six metrics. Trees are perennial, easily detectable, and also to identify. The metrics proposed by Wilson *et al*. (2014) include characteristics which are easily measured. The key characteristics are: current status, potential status, abundance, extent, spread, and impact. The authors describe their parameterization and additional metrics for a more mechanistic understanding of the impacts and describe their application using two examples. The characters, potential status, extent (area covered), and spread (change in extent over time) are important in the context of climate change and would also be a function of climate parameters. However, in the tropics, almost all the problematic invasives are usually shrubs and weeds with short life-cycles, difficult to identify and distinguish from native species and hence remain undetected until they are recognised as an invasion. The metrics for trees can be adopted for the tropics, by assigning weights based on expert opinion, to account for the different groups of taxa such as shrubs, aquatic plants, creepers *etc*.

Economics of ecological impacts

Impacts from invasives are more apparent in economic terms, which more often than not determine whether it is studied or not (Pyšek and Richardson, 2010). This is particularly so in developing countries, where it is the economic impact which attracts attention and the availability of resources for further study, for control or management of the problem. A review of the ecological and economic impacts of invasions in Europe by Vilà *et al.* (2011) showed that only 5.6% and 5.4% of all alien plants had an ecological and economic impact, respectively. Studies on the impacts of IAS are not only low at 20% of the literature reported in the Web of Science upto 2006, but also is geographically biased towards Australia, New Zealand and South Africa, with Asia reporting the least number of studies describing the basic patterns of invasive biology (Pysek and Richardson, 2010). This is a reflection not only of the magnitude of the problem but also on the resources available – financial and expertise – and perhaps the priority for allocation of research funds in developing countries.

Very few countries and regions have determined the financial costs from invasives, due to lack of information and data collection and maintenance of individual species records. Costs are commonly recorded for management such as eradication and control, loss of returns (from crop or timber harvest), and conducting awareness programs. However, economic losses from the impacts of invasions on recreational or cultural heritage values associated with landscapes and water bodies are difficult to cost due to their subjective nature. An example of a species specific cost for management is from South Africa for clearing three invasive tree species, which are also invasives in Sri Lanka: namely *Chromolaena odorata*, *Lantana camara* and *Opuntia* spp. The cost of clearing these species was 57% of the funds (out of a total of USD 48 million for 2002-2003) for their impact on surface water run-off, biodiversity and other ecosystem services (Marais and Wannenburgh, 2008).

MANAGEMENT OF INVASIVE FLORA IN SRI LANKA

A quantitative approach is necessary to describe biological invasions to assess and formulate management policies and strategies. Biological invasions involve taxa of different biological attributes and habitats and invasions do not respect national or geographical boundaries. A common global system of data collection would contribute to understanding and evolving common strategies of assessment and eventually management of invasives.

Such a common standardized global system for monitoring and assessment of invasives across all the taxa is attractive and would fit into a common conceptual framework to describe, monitor, assess and develop management strategies. However, the nature of invasives in a tropical climate, which supports the continuous growth and spread throughout the year, and the financial and human resources available to combat invasions, requires a set of metrics that are amenable to ease of observation, ease of measurement, rapid assessment and low cost to acquire the data. For quantitative assessments, perhaps an index should be calculated using weighted parameters, which can be assigned weights based on the relative importance in the invasion process, including reproductive traits, role of climate facilitating spread, life-cycle traits *etc*. Specialist input from biologists of the taxa concerned, park managers and other experts from relevant fields could formulate a weighted index.

The draft 'National Invasive Alien Species Policy' prepared by the Ministry of Environment of Sri Lanka, comprises various strategies and action plans and is to undergo a broad stakeholder consultative process. We outline below the management options in the context of climate change, which can be integrated into the proposed management plans and a cost conscious approach.

Species identification

The correct recognition and identification of invasive plant species and knowledge of their biology and spread is vital for successful management. In genera with many species, differences are found in their distribution and physiological requirements (light, moisture, temperature, germination, dormancy), which can interact differently with changes in the climate. Webber *et al.* (2011) illustrated the importance of correct identification for the introduced genus *Cercropia* in West Java, whose different species were confused with the invasive species *C. peltata*.

Botanic gardens, with their national collection of herbaria are an important resource for not only correct identification of species, but also to trace when and from where the species in question were introduced. However, because of their non-native status these species are frequently omitted from national floras and herbarium collections, further confusing their identification.

Prevention of entry and pre-entry risk assessments

This is an important management strategy for island nations, who have limited ports of entry compared to mainland nations, where invasive species are not contained by national boundaries. While measures to prevent entry of invasives are generally enforced at ports of entry, they can be enhanced and strengthened by making available a list of potential invasive species from known geographical regions. Species that are imported for commercial purposes should be subjected to risk assessment, based on information already available for the species elsewhere.

Post risk assessment and prioritization of invasive flora

Management measures for IAS can be successfully implemented if the most important invaders are prioritized and their present or potential distributions are identified. A post-entry risk assessment protocol was developed for invasive alien flora in Sri Lanka, through a broad stakeholder consultation in 2009-2010, with technical expertise provided by the United Nations Development Programme, Sri Lanka and the Global Environment Facility. This protocol (Ranwala *et al*., 2011) includes the main themes of (i) Potential ecological and socio-economic impact, (ii) Invasive potential, (iii) Distribution, and (iv) Management options. The themes are further sub-divided in order to include other important areas and are addressed by questions for scoring. A priority list of 12 species was identified from the list of 28 species of invasive alien flora in Sri Lanka, using this post entry risk assessment protocol. Subsequently, the priority areas for their management need to be identified. This assessment scheme needs to be further refined with a view to include the potential changes in invasiveness of species due to climate changes (Pyke *et al*., 2008). In a study of the distribution of alien and native species on a nearly global scale, Stohlgren *et al*. (2011) concluded that the size of invasive ranges of IAS is highly variable. Based on this, they recommended that the potential spatial extent of the invasive species should be identified through risk assessments of the invasiveness of species and their globalization.

Target ecosystems vulnerable to climate change

Ecosystems vulnerable to the changes in climate in Sri Lanka are the intensively cultivated agricultural lands in the lowlands, plantation croplands located at high altitudes, montane forests and grasslands. These would be the first to indicate interactions between IAS and climate change, due to their low biodiversity. Increases in diurnal temperatures, particularly in the higher altitudes, can extend the temperature boundaries for alien invasive plants. *E.g*. wild-sunflower (*Tithonia diversifolia*) and mist flower (*Eupatorium riparium*) which were earlier confined to cooler temperatures are now seen in much warmer areas (pers. comm.). The occurrence of extended drought periods in the dry zone can increase the mortality of native flora followed by replacement with invasive species. The occurrence of floods can create ecosystem disturbances in conserved areas while facilitating the dispersal of seeds of invaders.

Mapping to monitor invasions

Mapping the presence and spread of invasive flora and vulnerable ecosystems is a basic requirement for IAS management. There is very limited baseline information on the distribution and abundance of invasive flora in many of the protected areas of Sri Lanka and maps have not been prepared to identify their spread (Weerakoon, 2008). A study of the above ground status of invasive flora and the below ground potential of the seed bank in the Mihintale Wildlife Sanctuary in Sri Lanka showed that IAS were at a manageable level, with *L. camara* and *C. odorata* having the highest spread (Ranwala and Thushari, 2012); however these findings did not include spatial mapping.

Since the mobility and spread of flora is relatively slow, Geographic Information System (GIS) maps combined with remote sensing techniques can be easily constructed using GPS to locate the invasive species. These maps overlaid on land-use maps, which are available from the National Survey Department, provide information on the association of invasives with land-use patterns which may promote or hinder their spread. Mapping at seasonal intervals is an indicator of the temporal and spatial changes of the species, which can be interpreted by including other information on GIS maps such as natural boundaries, contours, waterways *etc*. A reasonable estimate of the rate of spread can also be estimated from such data. The scale of mapping is important: at a larger scale of mapping, there would be a decrease in data resolution (*e.g*. at kilometre scales), particularly at the country or regional level. This would also tend to overestimate the extent of spread and fail to describe adequately the spatial structure of invasion (Hulme, 2003).

GIS technology enables the integration of different variables. Thus, the inclusion of environmental factors that affect the distribution of invasive species such as climate, soil, waterways and topography can be useful to predict their future distribution (Franklin, 1995). The rate of spread can be accurately monitored by recording the abundance of an invasive species at fixed sites over time (Hulme, 2003). The sites can be determined by mapping and with the availability of human resources and knowledge of the reproductive biology and dispersal mechanisms available to the species.

Containment

Changes in the climate could result in expansion of the territory of already established invasive flora in the country. This is usually manifested as a shift in territory from one climate zone to another. It would be useful to identify potential regions within each climate zone, which have become warmer over the years. The agro-ecological zones in Sri Lanka, which integrates climate and soil types provide a potentially useful resource to identify such regions. The invasive shrub *Austraeupatorium inulifolium*, was initially restricted to an elevation of 4000 ft amsl. However, now it is reported from even higher altitudes indicating the constraints of containment.

Eradication

The popular methods of eradication of invasive species include mechanical removal (cost effective in developing countries), or herbicide spray (expensive and comes with environmental consequences). Eradication is resorted to after the problem is well established and there are many mature core populations of the species supplying propagules to satellite populations responsible for new invasions into vulnerable areas. From a population dynamic perspective (Moody and Mack, 1988), it is best to eradicate the small outlying populations, which contribute to range expansion. A similar conclusion was reached by Masters and Sheley (2001) who recommended the control of satellite populations before the core populations. In riparian ecosystems, the upstream source populations are the target of initial eradication. However, if vegetative growth begins downstream close to the sea, Tiley and Philp (1994) recommended targeting the upstream population first.

Reviewing the different control strategies for management, Hulme (2003) concluded that there are no simple rules to manage a variety of non-indigenous species that invade ecosystems. Generally, clearing strategies that prioritized low-density sites were most cost effective; delaying the initiation of clearing operations affected the eventual costs of the clearing operation and the threat to native plant diversity. In developing countries, where labour is less costly, concerted clearing of outlying populations is cost-effective. This should be combined with mapping the core and satellite populations and implemented before the onset of flowering in the core populations.

Holistic approach

The invasive ability of certain flora is determined by their reproductive biology, which can be limited by other organisms such as pollinators and dispersal agents, rather than the invasive species themselves. Climate change could provide a better environment for these agents thereby promoting the reproduction and dispersal of the invasive species. Dispersal agents are also more responsive to climate change. For example, where birds are the dispersal agents, the sighting of a particular species could provide clues to potential expansion of the range of an invasive species. Climate change could also modify environmental factors (soil chemistry, nutrient availability) to provide a competitive edge for IAS over native species. Thus, where potential invasive species are dormant, a holistic study based on their invasiveness information from other geographical areas should be considered. Such an approach would require eco-physiologists to advise on range expansion or ornithologists to report change in the frequency of bird sightings in new areas. Ecologists, foresters, reserve managers and conservationists need to be made aware of these likelihoods.

Many of the examples of biological invasions reported worldwide, would take time to be rigorously tested by science to prove that the combination of IAS and climate change act in tandem to threaten native species. However, given the proven examples, it is clear that we should invoke the precautionary principle and take pre-emptive steps to halt the spread of invasive species.

Concluding remarks

While biological invasions is a threat to biodiversity conservation, degradation of ecosystems and the resulting ecological and economic consequences are now further compromised by its interaction with climate change. There is a large imbalance in the studies conducted in developed and developing countries on invasive species.

The low priority given for research on invasive biology in the developing countries and the tropics, where most of the biodiversity is located, needs to be addressed internationally through perhaps collaborative research to better understand the invasive process and evolve management strategies to control IAS.

Sri Lanka, as an island, has the advantage of limited points of entry and a good inventory of the indigenous flora. However, the current status of knowledge of the identified alien invasive flora, their distribution and spread needs to be revised and strengthened. Sri Lanka has already initiated a road map to meet the challenges of invasive flora. The implications of climate change need to be addressed and incorporated into the different climate zones. The proposed policies, institutional frameworks, and strategies should be translated into implementation.

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