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# A Framework for Decision-Making in Cases of Invasive Species

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**Abstract:** Invasion of nonindigenous species is one of the most pressing global challenges, causing substantial environmental, economic and social harm. Invasion of alien species alters the composition, structure and functioning of invaded ecosystems as well as the services they generated before the invasion. Decisions about the management of invasive cases are inherently difficult because of the multifactorial and multiattribute scope of the problem. In particular, the resilience limits of invaded ecosystems to fully recover original, pre-invaded states remain unclear. To facilitate management efforts, decision-makers and environmental practitioners require a framework integrating relevant knowledge and acting as a supporting expert system. The underlying methodology and a conceptual architecture of the framework in support of decision-making in invasive cases (FDMISC) are presented in this paper. The framework consists of three main modules: “Environment”, “Forest Ecosystem” and “Management”. The functions of each architectural model as well as challenges in the implementation of the framework are also discussed.

**Keywords:** Invasive species; ecosystem; intentional and unintentional introduction; framework; decision-making.

## 1 INTRODUCTION

Invasive species are organisms (plant, animal, fungus, or bacterium) occurring in nonnative locations outside of their natural habitat, being able to successfully compete with indigenous populations to establish themselves in foreign environments and spread to the extent of causing damage to the environment, human economy and human health. The introduction of nonindigenous species may happen due to intentional or unintentional (i.e., accidental) human actions (Walther et al., 2009). Table 1 shows the cases of invasive species along with the ecosystem type, way of introduction, areas of origin and invasion, native species, factors of successful settlement, subject of resource competition and adverse effects caused to the invaded ecosystems.

Intentional introductions can be motivated by economic, environmental and/or social considerations (Chenje and Mohamed-Katerere, 2006). For example, a number of species were introduced during colonial times to develop European style parks in tropical countries (Abendroth et al., 2012). Yan et al. (2001) demonstrate a long history of introduction of nonnative species in China associated with immigration and trade routes since as early as the 4th century B.C. They have identified 380 species of vascular plants belonging to 62 families and 210 genera that have become invasive in China, including species in natural ecosystems, agricultural lands and other intensively managed areas. The pathways of unintentional introduction are diverse. For example, in the cases of aquatic invasion, alien species have been often brought to new habitats by cargo ships through the release of their ballast water. Accidental introduction cases now account for the majority of successful invasions (Lowe et al., 2000). Drake (2004) directly links most biological invasions to the anthropogenic introduction of nonindigenous species. Some examples of the world's worst invasive alien species include the rinderpest virus, crazy ant (or *Anoplolepis gracilipes*) in Hawaii, the brown tree snake (or *Boiga irregularis*) in Guam and the caulerpa seaweed (or *Caulerpa taxiflora*) in the Mediterranean Sea (Lowe et al., 2000).

**Table 1.** The cases of invasive species.

| Ecosystem type                          | Invasive species  | Origin area                | Invaded area                                | Native species   | Way of introduction | Factors of successful settlement                        | Subject of resource competition | Adverse effect                          | Source                    |
|---|---|----------------------------|---|--|---------------------|---|---------------------------------|---|---------------------------|
| Terrestrial (forest)                    | Norway maple ( <i>Acer platanoides</i> )                  | Eastern and Central Europe | Eastern North America                       | <i>Acer glabrum</i> ,<br><i>Betula occidentalis</i> ,<br><i>Elymus glaucus</i>         | Intentional         | Sandy/clay soils, cold temperatures                     | Light                           | Reduced growth due to light deprivation | Reinhart et al. (2006)    |
| Aquatic (sea water)                     | Mediterranean mussel ( <i>Mytilus galloprovincialis</i> ) | Mediterranean sea          | Western and Southern waters of South Africa | <i>Choromytilus meridionalis</i> ,<br><i>Perna perna</i> ,<br><i>Aulacomya ater</i>    | Accidental          | Adequate seabed and food                                | Food, habitat                   | Decrease in population                  | Branch and Stefani (2004) |
| Terrestrial (forest)                    | Brown tree snake ( <i>Boiga irregularis</i> )             | Australia, Pacific Islands | Guam forests                                | <i>Emoia caeruleocauda</i> ,<br><i>Nactus pelagicus</i>                                | Accidental          | Forest cover, abundant prey                             | Food, habitat                   | Extirpation of species                  | Rodda and Fritts (1992)   |
| Aquatic (freshwater)                    | Nile perch ( <i>Lates niloticus</i> )                     | Lake Chad                  | Lake Victoria                               | Detritivores and phytoplanktivores species   | Intentional         | Abundance of prey                                       | Food, space                     | Decimation of species                   | Goldschmidt et al. (1993) |
| Terrestrial (trees)                     | Big-headed ant ( <i>Pheidole megacephala</i> )            | United States              | Hawaii                                      | <i>Laupala</i> cricket   | Accidental          | Abundance of prey                                       | Food, space                     | Decrease in population                  | LaPolla et al. (2000)     |
| Terrestrial (scrublands and dry forest) | Small Asian mongoose ( <i>Herpestes javanicus</i> )       | India, Malay Peninsula     | Amami-Oshima Island, Southern Japan         | <i>Pentalagus furnessi</i> ,<br><i>Scolapax mira</i> ,<br><i>Dinodon semicarinatum</i> | Intentional         | Absence of natural predators                            | Food, habitat                   | Decrease in population                  | Watari et al. (2008)      |
| Terrestrial (agriculture)               | Yellow crazy ant ( <i>Anoplolepis gracilipes</i> )        | Asia, East Africa          | Arnhem Island, Australia                    | Native ant species   | Unknown             | Humidity, high daytime temperature                      | Food, habitat                   | Decrease in population                  | Hoffman and Saul (2010)   |
| Terrestrial (forest)                    | Eastern grey squirrel ( <i>Sciurus carolinensis</i> )     | North America              | Northern England, Northern Italy            | Red squirrel ( <i>Sciurus vulgaris</i> )   | Intentional         | Presence of food, shelter, absence of natural predators | Food, habitat                   | Reduced fitness of native species       | Gurnell et al. (2004)     |
| Terrestrial (grass)                     | <i>Eucalyptus camaldulensis</i>                           | Australia                  | Iberian Peninsula                           | Cistus   | Intentional         | Ability to regenerate from root fragments               | Soil nutrients                  | Outcompeting native species             | Diez (2005)               |

Invasive alien species are emerging as one of the major threats to sustainable development, on a par with global warming, and are recognized as a major danger to both marine and terrestrial biodiversity (Molnar et al., 2008; Hughes and Worland 2010). Nowadays, biological invasions are the leading threat to the diversity of freshwater lakes world-wide (Sala, 2000). Alien species are one of the primary means for human-accelerated global change: they pose a threat to biodiversity, rework ecosystem arrangements, tasks and services, and induce huge economic costs and serious health complications to humans (Mazza et al., 2014). The effects of having no control in place for such species could be both costly in terms of monetary value and in the effect they have on human life (Andersen et al., 2004). As estimated by Pimentel et al. (2005), there are approximately 50,000 invading species in the United States, and the number is increasing, causing major environmental damages and losses adding up to almost \$120 billion per year.

About 400 of the 958 species in America's lakes and rivers that are listed as threatened or endangered under the Endangered Species Act are considered to be at risk primarily because of competition with or predation by non-indigenous species (Wilcove et al., 1998). In other regions of the world, as many as 80% of the endangered species are threatened and at risk due to the pressures of nonnative species (Armstrong, 1995).

The scope and importance of threats created by invasive species increasingly call for adequate management actions at different decision-making levels, which can be divided in two categories: (1) decisions about entry of potentially invasive species; and (2) decisions about control of invasive species after they have been introduced, whether purposely or accidentally (Maguire, 2004). The magnitude and nature of the impact being produced by alien species on natural systems demand the development of a framework for managing the invasions (Higgins et al., 1996) on the basis of models that predict which species will invade certain environment (e.g., Tucker and Richardson, 1995) including the rates, spatial patterns and determinants of invasion (Macdonald, 1993) as well as short- and long-term consequences of the invasion for the affected ecosystem and human society. On the basis of this information, the framework can be used by practitioners and governmental authorities for the analysis and selection of the adequate managerial actions to address the challenges of the invasiveness. The underlying methodology and a conceptual architecture of the framework are presented in this paper.

## **2 METHODOLOGY**

It is commonly accepted that alien species produce substantial negative effects on the composition, structure and functioning of the invaded ecosystems (e.g., Higgins et al., 1996; Wangen and Webster, 2006). Therefore, ecosystems as a whole need to be taken into consideration in the analysis for decision-making in the invasive cases. The introduction of nonnative species is a stress onto invaded ecosystems, and this stress, in most of the cases, will be compounded with, and possibly amplified by, other natural and anthropogenic influences. The impacted ecosystem, its components and functions will react to stress in different ways. A typology of ecosystem stresses (*sensu* Khaiteer and Erechtkhoukova, 2009; Gutiérrez et al., 2014) enables to differentiate between specific categories of stress, on the one hand, and distinct functions and ecosystem components (biotic and abiotic) being influenced, on the other.

Furthermore, it is important for practical environmental management to predict the persistence capacity and probable transformations in invaded ecosystems. It has been demonstrated (Khaiteer and Erechtkhoukova, 2007) that there are common patterns in the behaviour of ecosystems as they respond to exogenous disturbances, and the following five scenarios in ecosystem stress dynamics have been determined: (1) resistance; (2) deformation; (3) resilience; (4) degradation; and (5) shift. To predict a particular scenario, a good understanding of the impact mechanisms driving the changes is necessary, but by far, it remains rather limited (Reinhart et al., 2006).

From the ecosystem perspectives, persistence to invasion occurs in the form of competition from the native communities (Martin and Marks, 2006), and a dominating concept since seminal paper by Elton (1958) has been that resistance to invasion is greater in intact or undisturbed communities. However, recent studies are not so definitely supportive of this paradigm (e.g., Webb et al., 2000) and rather unveil a more complicated interplay of biotic and environmental drivers in the resulting ecosystem resistance to biological invasion.

In addition, competition with resident species can take on multiple forms – e.g., in the cases of woody invasion in forest ecosystems, for light, soil nutrient resources, as allelopathic interference and disruption of mycorrhizal associations (Urgenson et al., 2012). However, invasive plant species may bring novel symbiotic mutualisms in the ecosystem (Vitousek et al., 1987). The resistance to invasion in forest ecosystems can be modified by the environmental factors, such as soil moisture and nutrient levels (e.g., nitrogen, Walters and Reich, 1996) or soil pH whereby strongly acidic soils offer the highest resistance to invasion while base-rich soils can significantly reduce invasion resistance (Martin and Marks, 2006).

The outcome of this competition can affect critical functional roles in both terrestrial and adjacent aquatic habitats: regulating microclimate, stabilizing stream banks and water flow and providing energy and nutrients to soil and aquatic food webs (Urgenson et al., 2012), i.e., ecosystem services.

As a particular example, the case of Norway maple (*Acer platanoides*) is considered in the study. This plant species was introduced intentionally from continental Europe during the mid-1700s to eastern North America (initially to Philadelphia around 1760) as an ornamental shade tree and then widely planted during the latter half of 20<sup>th</sup> century (Webb et al., 2000; Wangen and Webster, 2006). Nowadays, it has invaded northeastern forests of the United States and riparian and mesic montane forests of the northern Rocky Mountains (Reinhart et al., 2006). *A. platanoides* has been recognized as a serious threat to native forest ecosystems. Studies on *A. platanoides* impact demonstrate the following mechanisms underlying its invasive success: high shade tolerance and adaptation, light interception reducing light availability (both quantitatively and qualitatively) for native communities as an important driver of native suppression leading to decreased survival and growth of native species (e.g., Reinhart, 2006), physiological mechanisms including early leaf expansion and late leaf drop for a longer growth season compared to native species (Webb et al., 2000), allocational plasticity (Urgenson et al., 2012) ultimately changing patterns of dominance due to higher inherent growth rate, by increasing nutrient availability (i.e., Ca, Mg, K, N) and recycling rates (Gómez-Aparicio et al., 2008).

The scales of invasive spread call for managerial actions aimed at protection and restoration of native ecosystems (e.g., removal of *A. platanoides* from invaded areas, Webb et al., 2000) which are associated with considerable difficulty and expense and whose effect is not easily foreseeable due to the complexity and substantial non-linearity of the contributing factors and processes. Decisions about management of invasive cases are inherently difficult because of the multifactorial and multiattribute scope of the problem, a great level of uncertainty regarding the outcomes of possible management actions, multiple, sometimes conflicting, objectives and numerous parties involved in the process (Maguire, 2004). To facilitate the management efforts, decision-makers and environmental practitioners should be equipped with a framework integrating relevant knowledge and acting as a supporting expert system.

### 3 A FRAMEWORK: CONCEPTUAL ARCHITECTURE

In this section, a framework in support of decision-making in invasive cases (FDMISC) is presented. Though the starting point for the study has been the case of *Acer platanoides* invasion to North America, there are good reasons to believe that the suggested conceptual architecture is suitable for a broader range of biological invasions in the forest ecosystems. The framework consists of three main modules: “Environment”, “Forest Ecosystem” and “Management” (Fig. 1).

The “Environment” module specifies natural environmental factors (e.g., topology, geology, substrate, hydrology and meteorology, including the annual insolation above the forest canopy, Botkin et al., 1972), history of past disturbances experienced by the ecosystem under consideration, both anthropogenic (e.g., pollution, habitat destruction, introduced pets and pathogens, logging, climate change, dam and road construction, etc.) and natural (e.g., fire, flooding, herbivory, etc.) and the assessment of their individual and compound effects forming favourable conditions for successful invasion of nonnative species (e.g., Reinhart et al., 2006). It also takes into account a particular stage of the invasion process which can span over the phases of introduction, colonization and naturalization as defined by Radosevich et al. (2003) or entry, establishment, spread and impact as suggested by Andersen et al. (2004).

The “Forest Ecosystem” module is a formalized description of the invaded ecosystem. The abiotic (or non-living) pool includes physical factors (e.g., temperature, light, pressure, energy, acidity measure, soil depth, soil moisture-retention capacity, etc.) and chemical factors (e.g., oxygen, carbon, phosphorus, nitrogen, sulphur, calcium, etc. levels and availability). The biotic (or living) pool is organized in hierarchical structures of organisms depending on their roles in the energetic and metabolic processes at the overstory, understory and soil levels. Invaders will compete with native species for resources (e.g., light, space, mineral nutrients, etc.), and new traits in the ecosystem can be formed as a result (e.g., novel symbiotic mutualisms, means of acquiring resources, adaptation plasticity, allelopathic compounds, amplifying of native traits, etc.). The invasion of alien species will alter the composition, structure and functioning of the invaded ecosystem as well as the services it generated before the invasion occurred. The ultimate task of this module is to predict all of these transformations.

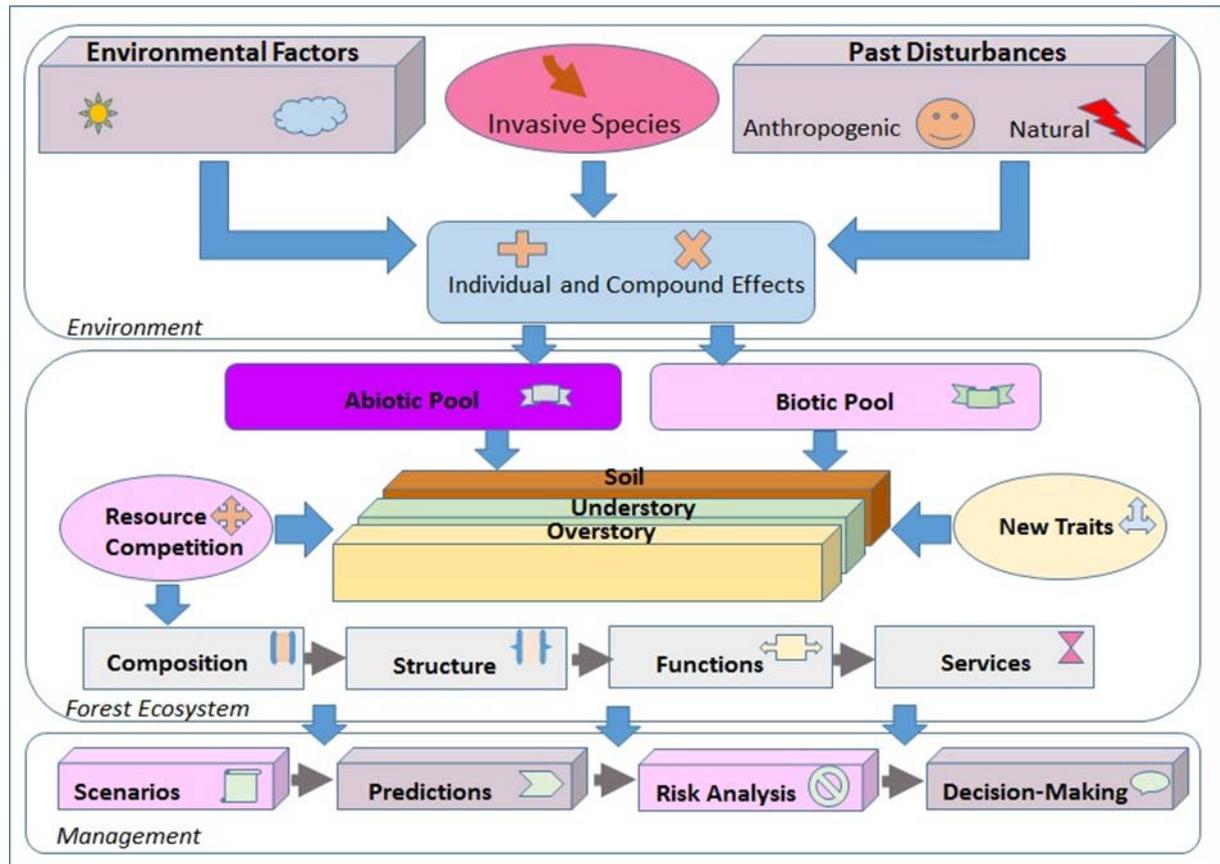


Figure 1. The structure of the framework FDMISC.

The “Management” module collects possible scenarios of the management interventions to cope with the invasiveness, both in the cases of potential entry of nonnative species and to control them after they have arrived and successfully established in a new habitat. On the next step, the module executes predictions of ecosystem components, their short- and long-term dynamics, ecosystem persistence capacity and restoration capabilities in response to each potential managerial effort. It takes into account the mechanisms of invasion, typology of stresses and the common patterns in the ecosystem stress behaviour. As it was mentioned above, a high level of uncertainty concerns each phase of the invasion – at the point of introduction, establishment and spread, and also when controls are being applied (Maguire, 2004). Given the uncertainty and likely significant cost associated with the implementation of controls in view of scarce budgeting resources, a risk analysis becomes a necessary step of the decision-making process. Taking no actions to control the invasive species is one of the alternatives to be considered. Specific features of risk analysis in application to the cases of biological invasion have been examined by Andersen et al. (2004) and Bartell and Nair (2004). The outcome of this module and

the entire framework is a set of recommended measures aimed at addressing the intervention of alien species in the most efficient way and suggesting resilient solutions for the impacted ecosystems.

#### 4 DISCUSSION AND CONCLUSIONS

Implementation of the framework requires the addressing of a number of non-trivial issues, including predictions of the invasive stress dynamics of the ecosystems. Prediction of the invasive potential of a certain alien species to invade a given environment can be viewed as a problem of machine learning and solved by classification algorithms, provided that sufficient volumes of relevant empirical data are accumulated and available. Prediction of endogenous ecosystem dynamics caused by biological invasion and resulting in compositional, structural and functional transformations most likely calls for process-based models.

The resilience limits of invaded ecosystems remain unclear. Theoretical ecologists question the ability of forest ecosystem to fully recover to the original, pre-invaded state in the face of complex interactions among anthropogenic impacts: forest fragmentation, climate change and introduction of invasive species (Webb et al., 2000).

There is a common view that an integrated ecosystem perspective of invasive species is amenable to mathematical formalization and system dynamic modelling (Gutiérrez et al., 2014), and it is shared by the authors. It also is a subject of our ongoing endeavours on the topic of decision-making and management of biological invasion.

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