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Conceptual design of a software tool for management of biological invasion

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Abstract. Invasion of alien species is recognized as one of the most pressing global challenges altering the composition, structure and functioning of invaded ecosystems as well as the services they generated before the invasion. We consider the case of Norway maple (*Acer platanoides*) which was intentionally introduced to North America as an ornamental street shade tree, but now has been viewed as a serious threat to native forest ecosystems in the United States and Canada. Decisions about the management of invasive cases are inherently difficult because of the multifactorial and multiattribute scope of the problem. To facilitate management efforts, decision-makers and environmental practitioners require a software tool integrating relevant knowledge and acting as a supporting expert. The underlying methodology, conceptual design of the tool and its main modules are discussed in the paper. In particular, we argue for an approach taking into account the entire ecosystem purview of the problem, phases of invasion process, tree development stages and driving mechanisms underlying the cases of biological invasion. Functional architecture of a software tool for environmental modelling and decision making in managing of invasive cases (EMDMIC) is presented. Largely, the EMDMIC consists of the three main modules: “Factors”, “Ecosystem Modelling” and “Management”. Functionality of each module is articulated in the paper. At the current stage of architectural design, the principles of multi-layered designs and platform independence have been applied. The latter enable to keep the options for future implementations of the tool open and also makes it potentially suitable for various targeting environments.

Keywords: Invasive species · Ecosystem · Norway maple · Software tool · Functional architecture · Decision-making.

1 Introduction

Biological invasion of nonnative species is considered as one of the major threats to sustainable development and as a major danger to marine and terrestrial biodiversity (Molnar et al. [24]; Hughes and Worland [12]). Alien species are seen as one of the primary means for human-accelerated global change: they pose a threat to biodiversity, re-work ecosystem arrangements, tasks and services, and induce huge economic costs and serious health complications to humans (Mazza et al. [23]). The effects of having

no control in place for invasion species could be costly in terms of both direct monetary values and the negative consequences for human life (Andersen et al. [1]).

In the present study, we focus on the case of Norway maple (*Acer platanoides*). 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 20th century (Webb et al. [39]; Wangen and Webster [38]). Nowadays, it has invaded northeastern forests of the United States and the riparian and mesic montane forests of the northern Rocky Mountains (Reinhart et al. [31]). *A. platanoides* has been recognized as a serious threat to native forest ecosystems in the United States and Canada.

The scales of invasive spread call for managerial actions aimed at the protection and restoration of native ecosystems (e.g., removal of *A. platanoides* from invaded areas, Webb et al. [39]) 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. To facilitate the management efforts, decision-makers and environmental practitioners should be equipped with a software tool integrating relevant knowledge and acting as a supporting expert.

2 Methodology

Biological invasion is a complex phenomenon making decisions about management of invasive cases 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). In the sub-sections below, we discuss some important aspects of the problem.

2.1 Phases of invasion process

The process of plant invasion comprises certain stages (Fig. 1). Thus, Radosевич et al. [30] defined three phases: introduction, colonization and naturalization. Wangen and Webster [38] paralleled them with the phases of stratified diffusion by Shigesada et al. [34]. Andersen et al. [1] argued for four phases of entry, establishment, spread and impact. In the latter classification, the entry phase marks the arrival of a non-indigenous species into a new environment; the establishment phase occurs where this arriving population begins to reproduce in situ and escapes immediate danger of local extinction; in the spread phase, the species disperses from its initial site of establishment and occupies available habitat within its new environment; and in the impact phase, an established species persists and competes in its new geographical range (Andersen et al. [1]).

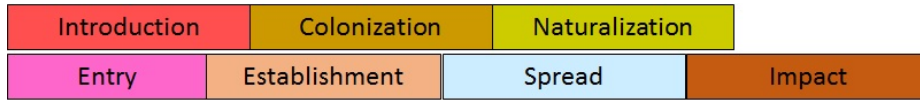


Fig. 1. Phases of invasion process (after Radosevich et al. [30]; Andersen et al.[1])

2.2 Tree development stages

The starting point in the tree life history is seed planting (Fig. 2). Surviving seeds will germinate and establish the seedlings. Seedlings are defined as trees whose height does not exceed the maximum seedling height for a given species (e.g., 1.00 m, Wyckoff & Webb [41]; 1.35 m, Murphy [26]). Accordingly, seedlings have no diameter at breast height (DBH); their primary size measurement is the diameter at a height of 10 cm (diam10). When a seedling reaches the maximum seedling height, it becomes a sapling, for which a DBH is greater than 0 and less than the minimum adult DBH (Murphy [26]). The sampling phase continues until the tree reaches a specific threshold height (e.g., 3 m; Senbeta and Teketay [33]) or the minimum adult DBH (e.g., 2.5 cm, Wyckoff & Webb [41]), after which it becomes adult. Snags are standing dead trees which are produced when either saplings or adults die due to normal tree mortality or a disturbance event, such as disease. Fallen snags form woody debris.

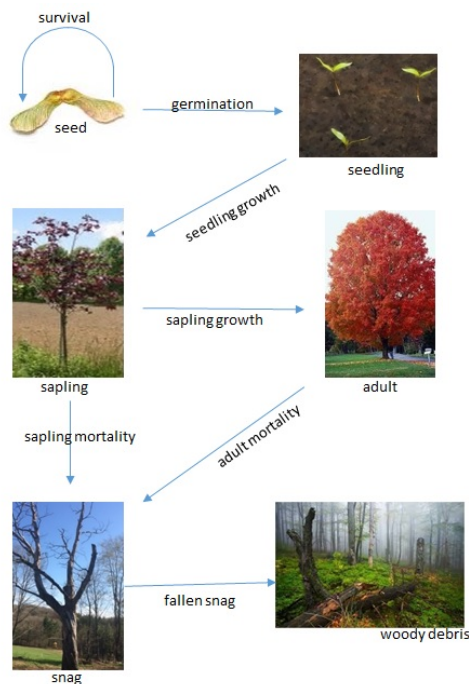


Fig. 2. Tree development stages

2.3 Ecosystem scope

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. [10]; Wangen and Webster [38]). Therefore, the ecosystem scope needs to be taken into consideration in the analysis for decision-making associated with 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* Khaite and Erechtkhoukova [15]; Gutiérrez et al. [8]) enables differentiation between specific categories of stress, on the one hand, and the 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 (Khaite and Erechtkhoukova [14]) 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. [31]).

2.4 Driving mechanisms

From the ecosystem perspectives, persistence to invasion occurs in the form of competition from the native communities (Martin and Marks [22]), and a dominating concept since seminal paper by Elton [6] 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. [39]) 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. [35]). However, invasive plant species may bring novel symbiotic mutualisms into the ecosystem (Vitousek et al. [36]). The resistance to invasion in forest ecosystems can be modified by environmental factors, such as soil moisture and nutrient levels (e.g., nitrogen, Walters and Reich [37]) or soil pH. Strongly acidic soils offer the highest resistance to invasion, while base-rich soils can significantly reduce invasion resistance (Martin and Marks [22]). 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. [35]), i.e., ecosystem services.

3 EMDMIC design

In this section, the development of a software tool for environmental modelling and decision making in managing of invasive cases (EMDMIC) is presented. Following its introduction (Khaiter et al. [16]), architectural design and detailed aspects are considered in the paper. Though the motivation for the study has been the case of *Acer platanoides*, there are good reasons to believe that the suggested software tool is suitable for a broader range of biological invasions in forest ecosystems. The tool consists of the three main modules (Fig. 3): “Factors”, “Ecosystem Modelling” and “Management” which are discussed in the corresponding sub-sections below.

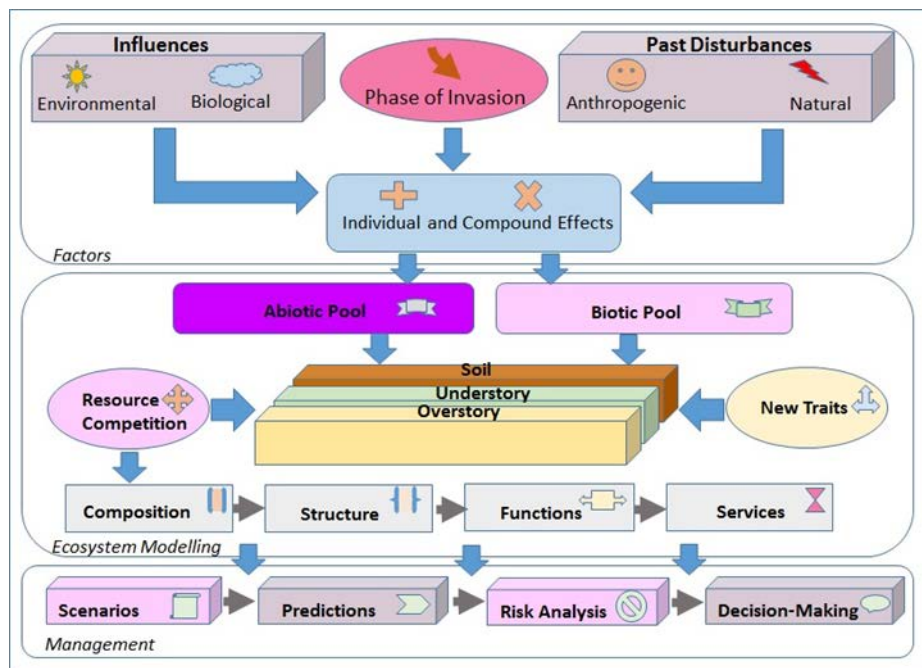


Fig. 3. The EMDMIC functional architecture

3.1 Module “Factors”

The “Factors” module specifies a particular stage of the invasion process (see sub-section 2.1) as well as environmental factors (e.g., topology, geology, soil composition, hydrology and meteorology, including the annual insolation above the forest canopy, Botkin et al. [3]) and biological factors (e.g., shade tolerance, soil nutrient cycling, phenotypical plasticity, animal and plant parasites and pollinating insects, etc.) creating

traits for invasion. In particular, studies on *A. platanoides* unveiled such invasive advantages of this tree species as:

- high shade tolerance and adaptation;
- light interception that reduces light availability (both quantitatively and qualitatively) for native communities (e.g., Reinhart et al. [31]);
- physiological mechanisms including early leaf expansion and late leaf drop for a longer growth season compared to native species (Webb et al. [39]);
- allocation plasticity (Urgenson et al. [35]) changing patterns of dominance due to higher inherent growth rate, by increasing nutrient availability (i.e., Ca, Mg, K, N) and their recycling rates (Gómez-Aparicio et al. [7]).

Ultimately, these specific properties of *A. platanoides* form important drivers of native suppression, leading to decreased survival and growth of native species (e.g., Reinhart et al. [31]). The module “Factors” will take into account the history of past disturbances experienced by the ecosystem under consideration, both natural (e.g., fire, flooding, extreme weather events, diseases, herbivory, etc.) and anthropogenic (e.g., pollution, habitat destruction, introduced pets and pathogens, logging, climate change, dam and road construction, etc.). As the outcome, the module implements an assessment of individual and compound effects of the contributing factors from the perspective of potential drivers creating favourable conditions for successful invasion of nonnative species (e.g., Reinhart et al. [31]).

The entry phase of invasion is characterized by the native tree canopies and exotic invaders attempting to establish themselves in the understory. The dynamics of the process may vary with a particular tree development stage. For example, the establishment of seedlings is viewed as a key phase in forest succession (Martin and Canham [20]; Morrison and Mauck [25]) during which closely related species are more likely to compete against each other on the basis of their shared characteristics (Lapointe and Brisson [17]). Comparing very similar native and exotic congeners (e.g., *A. sacharum* and *A. platanoides*) *in situ*, it is recommended to identify which traits promote invasiveness (Mack [18]). In particular, while observing that Norway maple is highly shade-tolerant, it was reported that this species is more shade-tolerant as a seedling than as a maturing tree (Nowak and Rowntree [27]; Wyckoff & Webb [41]), thus, conferring it invasive advantages by enabling to dominate in the understory and displace or diminish the native *A. sacharum* during the seedling stage.

3.2 Module “Ecosystem Modelling”

The “Ecosystem Modelling” module provides 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 any such transformations. Some of the computational formulae are shown in (1)-(6). Seed germination is estimated as:

$$NSG = \%G * NSP, \quad (1)$$

where NSP , NSG are number of seeds planted and germinated, respectively; $\%G$ is germination rate, as defined by Ologundudu et al. [28]. The cumulative growth of biological organisms at the juvenile phase occurs with the accelerating rate, at the mature phase – with the constant rate and at the senescent phase – with the decelerating rate. The lifespan cumulative growth curve (CGC) is, thus, sigmoidal, and a growth variable (e.g., DBH, height, volume, etc.) can be found from the following formula (Brack and Wood [4]):

$$DBH = \exp\left(a + \frac{b}{TA}\right), \quad (2)$$

where TA is the tree age; a and b are species-specific regression parameters. Non-linear (sigmoidal) growth functions are widely used in developing tree height-diameter relationships (Huang et al. [11]). Zhang[43] investigated the performance of six functions and concluded that each growth function was equally well-fitted to data of ten species collected in the inland Northwest of the United States with a minor superiority of three functions, one of which is the Weibull-type formula (Yang et al. [42]):

$$TH = 1.37 + c * [1 - \exp(-d * DBH^f)], \quad (3)$$

where TH is the total tree height; c , d and f are species-specific parameters. Crown width (CW) can also be estimated as a function of DBH (Peper et al. [29]):

$$CW = \exp\left\{\frac{MSE}{2} * [g + h * \log(\log(DBH + 1))]\right\}, \quad (4)$$

where MSE is the mean standard error; g and h are species-specific parameters. Light regime in forest is largely determined by the overstory canopy gaps (CG), which can be predicted from:

$$CG = D_{i,j} - (CW_i + CW_j)/2, \quad (5)$$

where $D_{i,j}$ is the distance between two neighbouring trees; CW_i and CW_j are their respective crown widths. Then, the light level ($\%L$) will be found as:

$$\%L = \frac{CG}{D_{i,j}} * 100\%. \quad (6)$$

In the open, $\%L = 100\%$ (i.e., full sun regime) while for the closed canopies, $\%L = 0\%$. Formulas (5) and (6) are a simplified version of the gap light index by Canham [5].

Table 1. Characteristics of the variables and parameters in (1)-(6).

Variable symbol	Description	Unit
NSP, NSG	Number of seeds planted and germinated	
$\%G$	Germination rate	%
TA	Tree age	years
DBH	Diameter at breast height	m
TH	Total tree height	m
CW	Crown width	m
D	Distance between two neighbouring trees	m
CG	Canopy gap	m
$\%L$	Light level	%
a, b, c, d, f, g, h	Species-specific parameters	

Dependant variables (Table 1) in formulas (1)-(6) are computed under the assumption of optimal (i.e., most favourable) conditions for the dynamics of contributing processes. In reality, they will be affected by environmental, biological and anthropogenic influences which can be factored through the corresponding transformation functions for each affected state variable and for each type of the influence (Khaiter [13]), i.e.:

$$x_i^A = TF_{i,k} * x_i^U, \quad 0 \leq TF_{i,k} \leq 1, \forall i = 1, \dots, n, \forall k = 1, \dots, K, \quad (7)$$

where x_i^U and x_i^A are the i th state variable before and after the influence of the k th type

factor, respectively; $TF_{i,k}$ is the transformation function of the k th type factor on i th state variable. A compound effect of multiple factors can be expressed through the resulting transformation function (TFR) built either from the ecological Liebig's law of the minimum of limiting factors (8) or in the multiplicative form (9):

$$TFR = \min_{k=1,\dots,r} \{TF_k\}, \quad (8)$$

$$TFR = \prod_{k=1}^r \{TF_k\}. \quad (9)$$

3.3 Module "Management"

The "Management" module generates possible scenarios of management interventions to cope with the invasiveness. It should be noted that measures can be taken at different decision-making levels, which can be divided into three categories: (1) decisions about preventing the entry of potentially invasive species (through existing laws, agreements on ballast water and shipping, etc.); (2) decisions about targeted control of invasive species after they have been introduced, whether purposely or accidentally; and (3) restoration of invaded habitats and ecosystems. For example, to restore an old-growth oak forest at the Washington Grove in Rochester, NY to its original and native state, Rogers [32] recommended a two-step approach. The first step foresees the removal of mature *A. platanoides* trees from the forest area, along with other invasive species, which would also create open canopy conditions. By also removing *A. platanoides* trees from the streets near the Grove and replacing them with stress-resistant native trees, the propagule pressure of invaders will be reduced. The second step of the management plan would encourage native species diversity and oak recruitment by installing physical barriers inhibiting disruption of the leaf layer.

Once the set of scenarios is formed, 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 and also when controls are being applied (Maguire [19]). Thus, woody plant invasion of shade-tolerant species can endure periods of suppressed growth before reaching the canopy layer, which, in combination with the long generation time of trees, makes it difficult to perceive as it unfolds, and, hence, difficult to manage in its early stages (Herron et al. [9]; Lapointe and Brisson [17]; Martin et al [21]; Wangen and Webster [38]; Webster et al. [40]).

The resilience limits of invaded ecosystems also remain unclear. Theoretical ecologists question the ability of a 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 the introduction of invasive species (Webb et al. [39]).

Given various sources of 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. Specific features of risk analysis in application to the cases of biological invasion have been examined by Andersen et al. [1] and Bartell and Nair [2]. The outcome of this module and the entire tool will be 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

In this paper, we presented functional architecture of the software tool and its internal structural logic, focusing on the modelling module as a backbone of the framework. The principles of multi-layered designs and platform independence have been applied at this stage. The latter enable future implementations of the framework suitable for various targeting environments. At the same time, the transition from the current stage of architectural design to detailed design and further to implementation phase of the software tool described above will require the following groups of models:

- models of pre-invaded dynamics of native species and the ecosystem as a whole;
- models of invasive dynamics of the alien species, including mechanisms underlying their invasive success;
- models of invasive-resident species interactions (e.g., competition for light, space, nutrient resources; possible symbiotic mutualisms, etc.) and their modification by biotic and environmental drivers;
- models of persistence capabilities to sustain the invasion and probable transformations in invaded ecosystems;
- models of effect of invasion on critical functions of the ecosystem; that is ecosystem services;
- models predicting ecosystem components, their short- and long-term dynamics, ecosystem persistence capacity and restoration capabilities in response to each potential managerial effort or scenario;
- models aimed at selection of the best possible scenario for managing the invasion

Prior to the realization of the tool, a number of non-trivial issues should also be addressed. This includes, e.g., predictions of the invasive stress dynamics of the ecosystems. It appears that 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.

There is a view that an integrated ecosystem perspective of invasive species is amenable to mathematical formalization and system dynamic modelling (Gutiérrez et al. [8]), 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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