Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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Developing guidelines for quantifying ecosystem impacts of terrestrial species invasion within the framework of Life Cycle Assessment

Master's thesis in Industrial Ecology
Supervisor: Francesca Verones
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Abstract

Biological invasions present a significant threat to the functioning of ecosystems and communities around the planet and are one of the main drivers of global biodiversity loss. Terrestrial Invasive Alien Species (IAS) cause damages to ecosystem quality, human health, and socio-economic assets, but we are lacking a methodology to quantify these impacts. The quantification of impacts of terrestrial IAS is necessary so that proper allocation of the impacts between products and services can be done. Life Cycle Impact Assessment (LCIA) framework is chosen to develop a characterization factor to quantify the impact on ecosystem quality. To realize this, fate and effect factor models are developed. The value of the fate factor is decided by three parameters. A propagule size factor predicting the probability of fraction of IAS introduced, a species survival factor to determine whether the species can establish a self-sustaining population in the invading region, and a human intervention factor to predict whether human efforts existing in the region can prevent the invasion. An effect model is also developed, to quantify the impacts from IAS in terms of the potentially disappeared fraction of species. Many assumptions had to be made while modelling the characterization factor due to the lack of data availability, damages to ecosystem quality only indicate a fraction of the actual damage caused by IAS. Further models must be developed to include damages to human health, ecosystem services, socio-economic assets, cultural and natural heritage.

Sammendrag

Biologiske invasjoner utgjør en betydelig trussel mot funksjonen til økosystemer og samfunn rundt om i verden, og er en av de viktigste driverne for globalt tap av biologisk mangfold. Terrestriske invasive fremmede arter (IAS) forårsaker skader på flere beskyttelsesområder som økosystemkvalitet, menneskers helse og sosioøkonomiske eiendeler, men vi mangler en metodikk for å tallfeste disse virkningene. Kvantifisering av virkningene av terrestrisk IAS er nødvendig for at riktig fordeling av virkningene mellom produkter og tjenester kan gjøres. Life Cycle Impact Assessment (LCIA) rammeverk er valgt for å utvikle en karakteriseringsfaktor for å kvantifisere innvirkningen på økosystemets kvalitet. For å realisere dette utvikles skjebne- og effektfaktormodeller. Verdien av skjebnefaktoren bestemmes av tre parametere. En forplantningsstørrelsesfaktor som forutsier sannsynligheten for at en fraksjon av IAS ble introdusert, en artsoverlevelsesfaktor for å bestemme om arten kan etablere en selvbærende befolkning i den invaderende regionen, og en menneskelig intervensjonsfaktor for å forutsi om menneskelig innsats som finnes i regionen invasjonen. En effektmodell er også utviklet for å

kvantifisere virkningene fra IAS når det gjelder potensielt forsvunnet fraksjon av arter. Mange antagelser måtte gjøres mens man modellerte karakteriseringsfaktoren på grunn av manglende datatilgjengelighet, og skader på økosystemets kvalitet indikerer bare en brøkdel av den faktiske skaden forårsaket av IAS. Ytterligere modeller må utvikles for å omfatte skader på menneskers helse, økosystemtjenester, sosioøkonomiske eiendeler, kultur- og naturarv.

Acknowledgment

This Master Thesis is a presentation of my work from spring 2021 as a part of my M.Sc. degree in Industrial Ecology at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU), Trondheim.

I would like to express my sincere gratitude to my supervisors Francesca Verones and Jan Borgelt for their continuous support, motivation and for being patient with me, providing valuable materials and insightful feedback. It would have been tough without help from the two of them.

Problem Description

1. Based on the conducted literature review identify the largest potential for further development regarding endpoint (ecosystem quality or ecosystem services). 2. Develop a complete cause-effect pathway 3. Decide upon whether to continue with a fate and/or effect model and explain why; based on the complete cause-effect pathway and after conducting a (brief) data screening 4. Develop the model to quantify the fate/effect of (selected) invasive species. 5. If time permits: sketch the other part of the characterization model (fate or effect)

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Abbreviations

AoP	Areas of Protection
CF	Characterization Factor
EF	Effect Factor
EICAT	Environmental Impact Classification of Alien Taxa
FF	Fate Factor
GISD	Global Invasive Species Database
IAS	Invasive Alien Species
ISO	International Organization for Standardization
ISSG	Invasive Species Specialist Group
IUCN	International Union for Conservation of Nature
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PDF	Potentially Disappeared Fraction of species
SSC	Species Survival Commission
UN	United Nations
UNEP	United Nations Environment Program

1. Introduction

1.1 Problem setting

Human-induced biological invasions and climate change are regarded as the most difficult to reverse pressures on biodiversity (Millennium Ecosystem Assessment, 2005). Since the age of exploration and expansion, humans have accelerated the pace and ease of species dispersal to new ecosystems. Globalization facilitates this dispersal, making new regions vulnerable to invasion as international commerce develops new trade routes, markets, and products (Meyerson & Mooney, 2007). However, we depend on biodiversity for provisioning, regulating, supporting, and cultural services (Millennium Ecosystem Assessment, 2001). Biodiversity loss disrupts the functioning of ecosystems and reduces the supply of these needed services to humans. In addition, every species has the right to exist in its native habitat, adding an intrinsic value to the ecosystem (Taylor, 1984). Invasive species, along with land-use change, climate change, pollution, and natural resource use, are a major cause of biodiversity loss (IPBES, 2019). Invasive Alien Species (IAS) are those species that are introduced, either accidentally or purposefully, to a new geographic region and spread from the point of introduction to become naturalized and subsequently alter the new ecosystem and its functioning negatively (Russell & Blackburn, 2017). Invasive species can cause harm to both the natural resources in an ecosystem and the use of these resources by human beings. While biological invasions continue to expand in both frequency and geographical extent (Mooney & Cleland, 2001), they impact native biota through competition, predation, interbreeding, and altering natural habitats. Some invasive species also cause huge agricultural and industrial losses, acting as pests to agriculture and forestry and by spreading disease or preying on the livestock (Paini et al., 2016). Among the list of one hundred of the world's worst invasive alien species released by the International Union for Conservation of Nature (IUCN) thirty two (32) are terrestrial plant species and thirty nine (39) are terrestrial animal species (Lowe et al., 2000). Halting and reversing biodiversity loss is part of the United Nations (UN) 15th Sustainable Development Goal (SDG). Early detection and rapid response to species invasion are recommended to effectively minimize the impacts (Reaser et al., 2020). Leung et al. (2002) state that an optimal allocation of resources to prevent invasion is more effective and cheaper than efforts to control and eradicate an established IAS. Even though several frameworks for the prevention of IAS exist, only a few regions have the resources to effectively follow these frameworks and keep the invasion in check (Early et al., 2016) .

The number of invasions is directly proportional to the degree of international trade happening in the region (Westphal et al., 2008). Allocation of impacts from species invasion must therefore be done for various trade activities so that these impacts can be attributed to the products and services linked to the trade activities. This allocation helps to bring the impacts from IAS under the social responsibility of the stakeholders and to distribute the resources in helping prevent human-induced biological invasion efficiently. So far, there is no established methodology to quantify the impacts of terrestrial invasive alien species on biodiversity within a common framework. This project aims to develop guidelines for quantifying impacts from terrestrial biological invasions, within the framework of Life Cycle Assessment (LCA). LCA is a tool used to assess environmental impacts associated with all stages of a product, process, or service (ISO, 2006). To account for biological invasions within LCA, a model to quantify the impacts need to be developed, which can be inducted into the Life Cycle Impact Assessment (LCIA) framework.

2. Background

2.1.1 LCA and LCIA

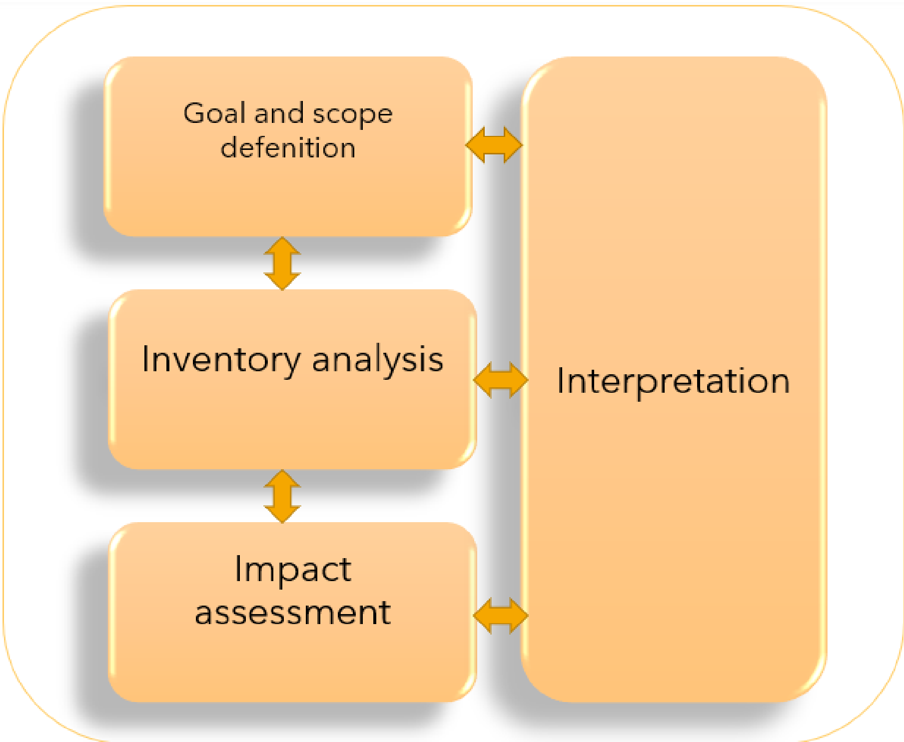

Figure 1: Life cycle assessment framework (ISO, 2006)

According to the International Organization for Standardization (ISO), the LCA framework has four iterative phases (Figure 1). They are (a) the goal and scope definition phase which includes the system boundary and level of detail, (b) the inventory analysis phase where the inventory of input out data about the defined system being studied and it involves a collection of data for the defined goal, (c) the impact assessment phase where the environmental significance of a product system is assessed and (d) interpretation is the last phase but has flows with all the phases, this is where the results of Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) is summarized and discussed to conclude. LCIA is defined as the process in which effects of the resource use and emission generated in a product life cycle are grouped and quantified into a limited number of impact categories which may then be weighed for importance (Jolliet et al., 2004).

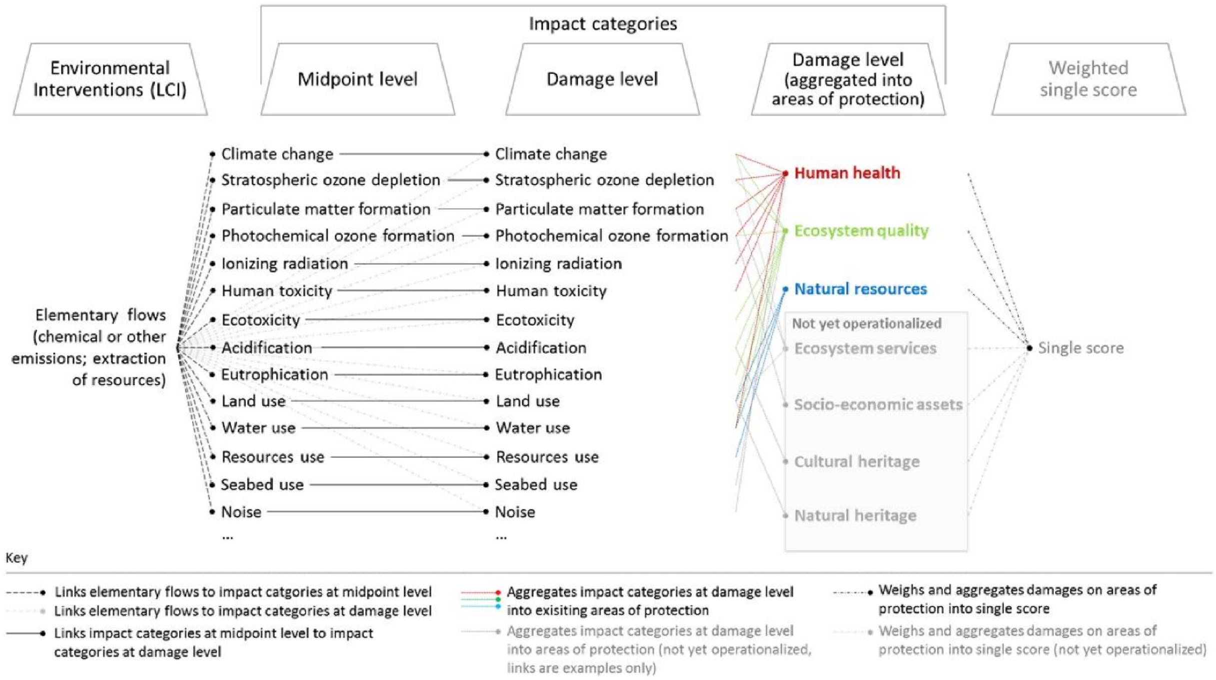

Figure 2: Updated LCIA framework with proposed additional impact indicators, (Verones et al., 2017)

During the LCIA phase inventory items are linked to the midpoint and/or endpoint indicators (see Figure 2) through a cause-effect chain, where potential human health impacts, impacts on natural resources, environmental impacts, and environmental releases are evaluated, (Curran, 2012). In LCIA impacts can be aggregated into three areas of protection to indicate damages, they are damages to human health, damages to ecosystem quality, and depletion of natural resources. Verones et al., (2017) propose to include damage on ecosystem services, socioeconomic assets, cultural heritage, and natural heritage along with the existing areas of protection into the framework of LCIA. To realize the inclusion of impacts from biological invasions under LCIA, a characterization model must be developed, that can aggregate the impacts into damages on the area/s of protection covered under LCIA.

2.1.2 Characterization models

Within LCIA, the impact on human wellbeing and the environment is commonly quantified using certain models that aggregate life cycle emissions into scores for human health and ecosystem quality damages, these models are so-called characterization models (De Schryver et al., 2009). These models produce weighing factors that aggregate the emissions and extractions from life cycle inventories (LCI) that cause damage based on the impact pathways, these factors are called characterization factors (CF) (De Schryver et al., 2009; Zhou et al., 2013). The characterization factors also allow the comparison of different elementary flows quantitatively in terms of their ability to contribute to the specific impact category indicator (Hauschild et al., 2013). Characterization factors are multiplied with LCI results (resource use) to obtain category impacts (indicator results) as in Equation 1, usually expressed in a unit common to all contributions within the impact category (ISO, 2006).

$$Impacts_c = \sum_s Characterization\ Factor_{c,s} \times Resource\ Use_s \tag{1}$$

In equation 1 ‘c’ represents the impact category and ‘s’ represents the substance or pressure the CF is modeled for. To develop a characterization factor for quantifying the impacts from terrestrial exotic species introductions, the various actors, variables, and parameters along the whole process, from introduction to damage, must be clearly understood and are detailed below.

2.2 Global Invasive Species Database (GISD)

The Invasive Species Specialist Group (ISSG) under the Species Survival Commission (SSC) of the IUCN has compiled the most geographically comprehensive database on invasive species worldwide, the Global Invasive Species Database (GISD) (Westphal et al., 2008). GISD covers all taxonomic groups that threaten native biodiversity and natural areas, from micro-organisms to animals and plants. The database has some useful information components such as species description, habitat description, introduction pathways, and general impact information, that can be used in quantifying the impacts.

3. Materials and Methods

3.1 The Invasion Process

The invasion process and establishment of the species in a new ecosystem is very complex making it difficult to accurately assess monetary and biological impacts from biological invasions. For instance not all introduced species become invasive, as some species are unable to maintain a self-sustaining population, and these species are referred to as casual species (Keller et al., 2011). Only if a species can survive and reproduce without direct human intervention it is considered established. When established species can spread and cause environmental, economic, or human health impacts, they are referred to as invasive species, (Keller et al., 2011).

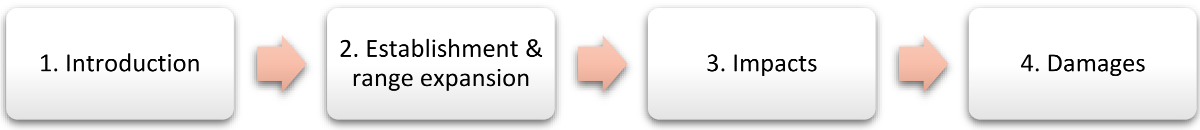

Figure 3: Stages involved in the Invasion process, the cause-effect pathway of IAS.

The process of invasion of terrestrial alien species can be divided into different phases (Figure 3). During the introduction phase, the alien taxa are transported from their native/invaded range to a new environment through different transport vectors known as introduction pathways. The second phase is when the introduced species establishes and expands its range in the introduced region. The third phase which can often overlap with the second phase is when the established species starts influencing the ecosystem to which they are introduced, through different impact pathways. The impacts on the ecosystem can cause damages to the functioning of the introduced region.

3.1.1 Introduction pathways

Globalization has shortened the distance between communities and improved trade and resource sharing, but it comes with the cost of biological invasions through the trade corridors (Perrings et al., 2010). The process that results in the introduction of alien species from one location (their native region or an invaded region) to another location can be defined as an introduction pathway. Hulme et al., (2018) identified three general mechanisms for alien species to enter a new region, they are imported as a commodity, arrival with a transport vector, and dispersal by the species themselves (Figure 4).

Import as a commodity arises from the direct human movement of goods, which can be intentional (released or escaped), and unintentional (containment) introduction of species as mentioned in Figure 4. Introduction of the Burmese python *(Python bivittatus)* to southern Florida is an example of intentional species introductions (Willson et al., 2011) and the introduction of the Asian tiger mosquito (*Aedes albopictus*) to central Europe from the trade of used tires (Schaffner et al., 2009) is an example of introduction along with a commodity. The second mechanism is when species hitchhike on vessels or other human transport medium to regions beyond their natural range. One example of this is the brown tree snake (*Boiga irregularis*) hitchhiking on planes from Australia to Guam and causing damage to the native bird species (Wiles et al., 2003). The third mechanism is the dispersal of species by themselves, through human-made infrastructures or geographical modifications (e.g., bridges or canals) but without any human aid.

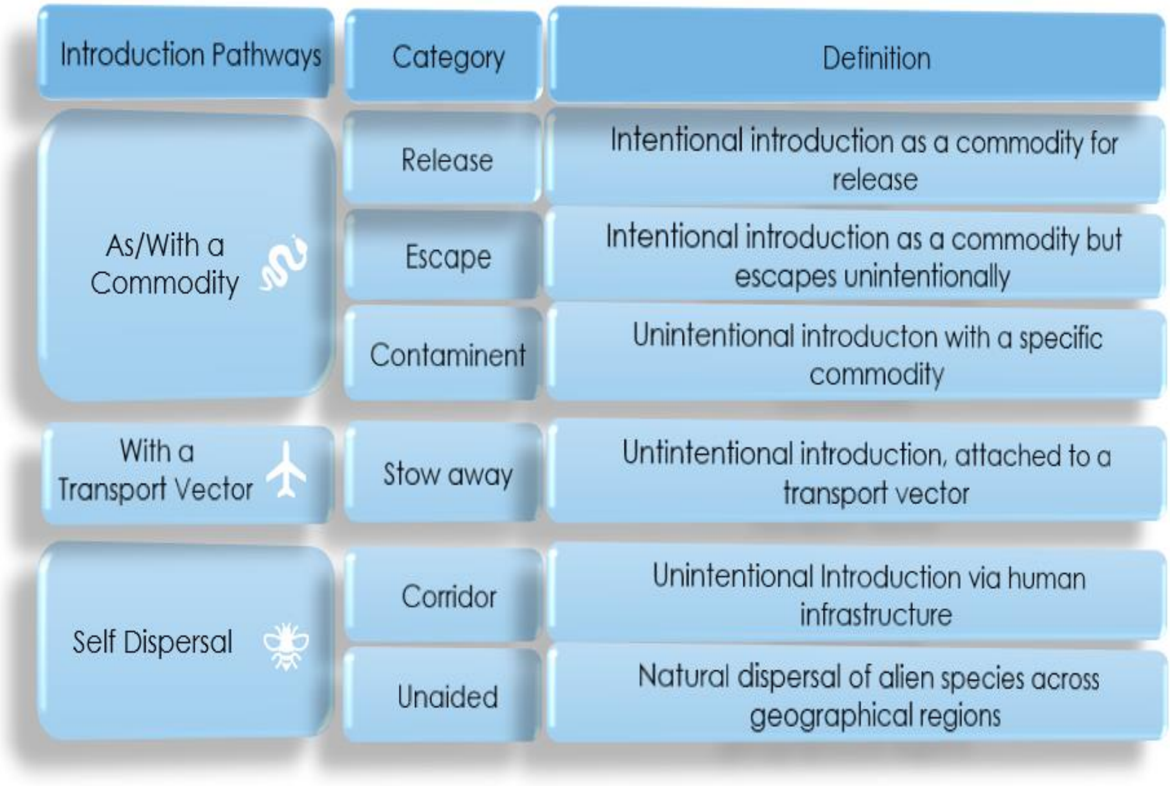

Figure 4: Classification and definition of different type of Invasion pathways, adjusted from (Hulme et al., 2008)

The dispersal through mediums constructed by humans can be categorized as dispersal through corridors. Understanding introduction pathways are very important in formulating regulations, United Nations Environment Program (UNEP) has given out guiding principles for the prevention of introduction and mitigation of impacts of alien species that threaten ecosystems based on introduction pathways. In the context of LCA, introduction pathways are the link between trading activities and species getting introduced through them, thus important in modelling impact outcomes from the introductions. As the project focus on developing a characterization model for impacts of terrestrial invasive species from trade, intentional species introductions and dispersal by the species themselves are excluded from the model.

3.1.2 Establishment and range expansion

Once an exotic species is introduced to a new geographical region, it has the potential to become invasive. The period from the introduction of these species to establishing a population capable of harming the functioning of an ecosystem consists of three phases (Figure 5).

Figure 5: Different phases during the establishment of an IAS, adjusted from (Ficetola et al., 2009)

Initial dispersal can be defined as the period when an introduced species disperses within the alien range. Then the species start adapting to the conditions and begin reproducing to establish a self-sustaining population, this is the second phase. Once a self-sustaining population is established the species population starts expanding causing damage to the native species through different impact mechanisms (Puth & Post, 2005). There is a lag time between the introduction phase and impact phase along the cause-effect chain of an IAS, this lag time can be as short as days or be in years which is dependent on the rate of establishment and the rate of spread of the introduced species, (Crooks et al., 1999). Once established, species may start causing changes to the structure and functioning of the ecosystem and its components in many ways, known as impact mechanisms.

3.1.3 Impact mechanisms

The impacts from the introduction and establishment of invasive species on ecosystem traits present one of the major challenges of applied ecological risk. Environmental Impact Classification of Alien Taxa (EICAT) provides 12 impact mechanisms that can be used to categorize the impacts exerted by IAS on the ecosystem, see Figure 6. The same IAS can cause damage to native species through different impact mechanisms. e.g. the brown tree snake (*Boiga irregularis*) can cause damage to the native reptile population through competition for food and space, the same species can reduce the native bird population through excessive predation on eggs and chicks(Wiles et al., 2003). These impact mechanisms can affect the performance of an ecosystem by altering the structure and composition of the native ecosystem. Competition to native species for food and shelter can cause extinction or reduce the population of similar native species significantly, (Gurevitch & Padilla, 2004). Extensive predation happens when the native species are not adapted to the new predator and are very vulnerable. The poor breeding success of Tristan Albatrosses is accounted for by the vulnerability of its nesting area to the invasive house mouse (*Mus musculus*) (Wanless et al., 2007). Even though these two impact mechanisms are the most pronounced mechanism by invasive species others can also lead to significant damage to the native population.

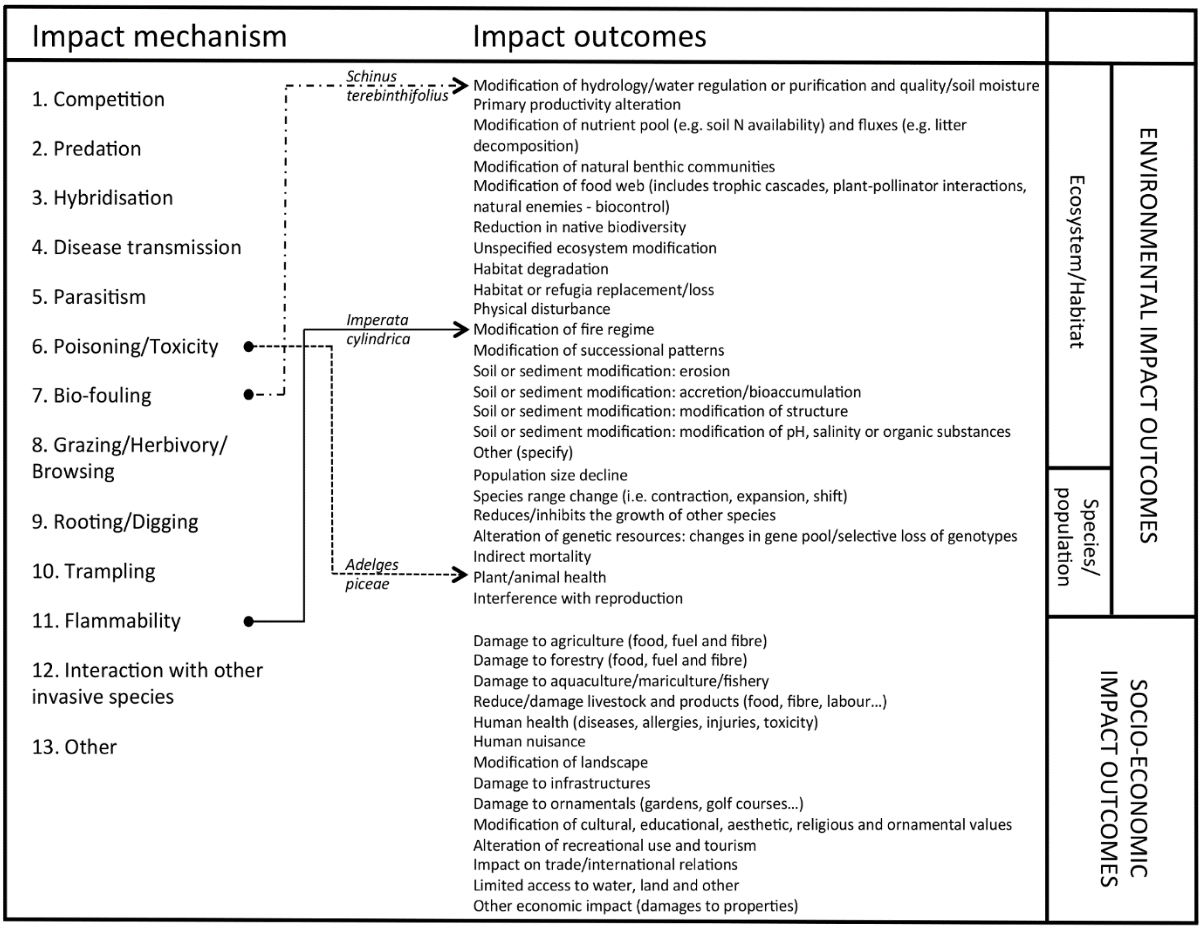

Figure 6: Impact scheme of global invasive species database, implemented by the International Union for the Conservation of Nature (IUCN) Species Survival Commission (SSC) Invasive Species Specialist Group (Blackburn et al., 2014). Ex of impact mechanism and impact outcomes of three species, Imperata cylindrica, Schinus terebinthifolius, and Adelges piceae as how it is stored in the database.

3.1.4 Damages (Ecosystem quality)

The introduction of invasive alien species results in both environmental and socio-economic impact outcomes through various mechanisms like predation, competition, overgrazing, disease transmission, etc (Blackburn et al., 2014). These impacts can be covered by assessing the damage from the introduction of IAS to different areas of protection (AoPs) such as damages to human health, ecosystem quality, ecosystem services, and socioeconomic assets. The current LCIA framework has only three operational AoPs, which are damages to human health, ecosystem quality, and natural resources (Verones et al., 2017), therefore it is only possible to assess damages to ecosystem quality and human health under the current framework. The area of protection "Ecosystem Quality" deals with damages on the intrinsic value of natural ecosystems (Verones et al., 2017), and most models using this indicator focuses on the compositional attribute of biodiversity such as species richness (Curran et al., 2011). Verones et al. (2017) recommend certain guidelines to the model developers in assessing damage to ecosystem quality. The first one is the use of the potentially disappeared fraction of species (PDF) as a common endpoint metric or providing a conversion factor to convert from other metrics to PDF. Another recommendation is to report PDFs in a disaggregated way (i.e., separately for freshwater, marine, and terrestrial ecosystems), and for specific taxonomic groups (i.e., specifically for plants, or invertebrates, when those were used to define a PDF). PDF is a relative measure of the damage to ecosystem quality, accounting for a fraction of species richness that may be potentially lost due to an environmental mechanism (Verones et al., 2017).

3.2 Developing a mathematical model

Berry and Houston (1995) recommend 6 major steps in developing and improving a mathematical model (Figure 7) for solving a problem. (a) Understanding and defining the problem, in our context is defining the characterization factor that has to be developed. (b) Choosing the variables and making assumptions which translate to choosing the parameters for fate and effect factor required to model the CF. (c) Mathematisising the problem, which is to represent the relation between the parameters mathematically as fate and effect factor equations. (d) interpreting the mathematized model i.e. interpreting the developed fate and effect factor equations. (e) Testing and validating the model, is where the developed fate and effect factors are validated using real-life examples. (f) criticizing and improving the model in this final step where the results from testing and validation are carefully studied, from this data the shortcomings are identified and necessary improvements are made to the equations. The first four steps are for developing the model and the last two are for validating and improving the model.

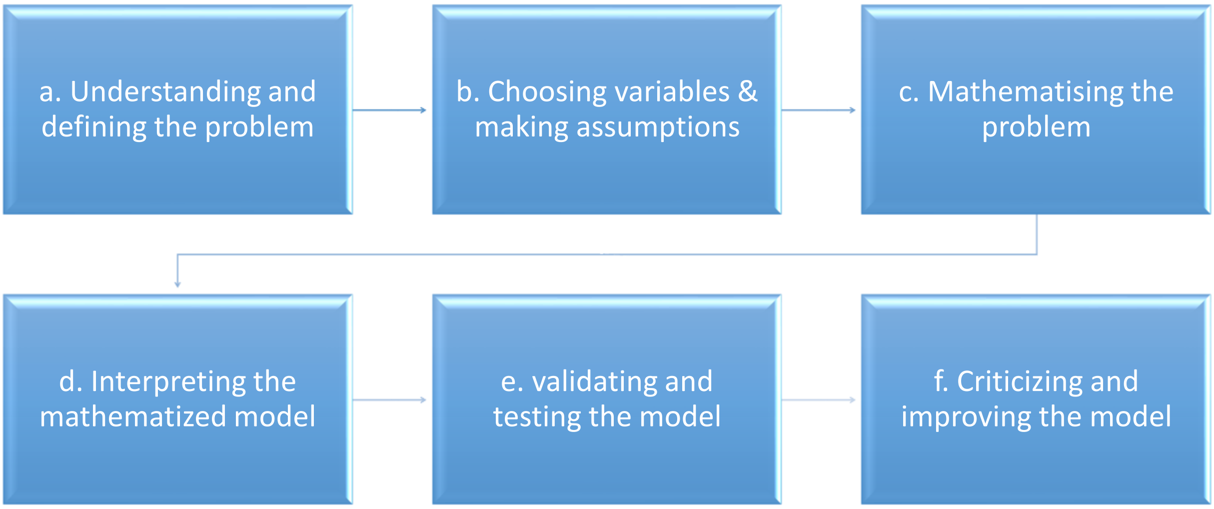

Figure 7: Steps involved in developing a mathematical model adjusted from Berry and Houston (1995)

The method section covers the first two steps i.e., defining the characterization factor and choosing parameters required to represent the CF mathematically, the results and discussion section covers the last two steps in developing the model i.e., representing the CF mathematically and interpreting the developed equations. To simplify the process fate factor (FF) and effect factor (EF) are modeled separately.

3.3 Characterization factors

The ISO 14044 standard recommends that the impact categories, category indicators, and characterization models should be internationally accepted, and LC-IMPACT methodology can be used for the same. LC-IMPACT is a methodology that provides a global life cycle impact assessment methodology for the three main areas of protection (human health, ecosystem quality, resources), including spatially differentiated information wherever necessary and feasible(Verones et al., 2020). The methodology recommends a general equation for characterization factors (CFs) in ecosystem quality (Equation 2) within the framework of LCIA.

$$CF_{ecosystem\ quality} = VF \times EF \times XF \times FF \tag{2}$$

The characterization factor consists of four factors a vulnerability factor (VF), an effect factor (EF), an exposure factor (XF), and a fate factor (FF). The vulnerability factor is used to translate species loss from local or regional level to global level enabling to model both regionalized and global impacts (Verones et al., 2020). Curran et al. (2011) explain the fate factor as a factor that models the spatial distribution and intensity of pressures induced by an intervention, the pressure here being the introduction of IAS. Also, they explain the effect factor as a factor that relates the intensity of a unit of pressure (here: introduction of IAS from transportation) to a quantified loss in biodiversity, usually Potentially Disappeared Fraction of species (PDF). Exposure factor (XF) does not have a conceptual meaning in assessing impacts from IAS as the model is developed to include all the species affected by the presence of IAS in the region and therefore can be given a value equal to one.

A regional characterization factor (CF_{reg}) can be expressed as the product of the fate factor (FF) and effect factor (EF) when XF has a value of one. CF_{reg} for IAS can be expressed as the product of impact on biodiversity (EF) and the intensity of the introduction of IAS (FF). The FF is modeled to quantify a value of introduction intensity of IAS per unit of transportation, and the EF to quantify a value of PDF per introduction intensity of IAS.

3.3.1 Fate Factor

In life cycle impact assessment, the fate factor models the spatial distribution and intensity of environmental pressures induced by an intervention (Curran et al., 2011). In the characterization model for impacts from terrestrial IAS, the fate factor (FF) can be defined as the number of units of alien species (intensity) that are introduced by a unit transportation activity (intervention). A unit transportation activity is defined as the event of transportation from one ecoregion to another ecoregion by a type of transportation through which potential invasive species are introduced. While calculating the fate, the source, the destination, and the type of transportation involved in the trade are important. Throughout the life cycle of a product/service/process, there could be multiple types of transportation determined by three parameters, the mode of transportation, the source, and the destination. The mode of transportation can be generally classified as road, rail, ship, and air. The CF must be calculated separately for each transportation type and each potential invasive species present in the source region, the final CF will be the summation of CF of each type of transportation and each potential IAS.

The number of Alien species getting transported and the probability of establishing an invading colony in the alien region depends on many factors (variables). Lonsdale (1999) stated that the number of invasive species in a region can be represented as the product of the number of exotic species introduced and the survival rate of exotic species in their new range. There is a variable lag time between the introduction and establishment of an exotic species, but this is insignificant in calculating fate as our characterization model is not time-dependent. Instead, we consider all the potential impact from the alien species irrespective of what time it occurs in the future, after the introduction. Another important variable in determining the fate of an alien species is the national-level legislation existing to prevent or control IAS and their application (Early et al., 2016). The presence of measures to check invasion varies across geographical and political borders. Some researchers like Elton (1958), Levine & D'Antonio (1999) proposed that the rate of establishment of an alien species in a region is dependent on the biotic resistance of the region, the proposal states that the higher the species richness of a region the less prone it will be to invasion. However, some researchers (Fridley et al., 2007; Peng et al., 2019; Smith & Cote, 2019) oppose this theory making it inconsistent to be included in determining the fate factor.

The fate factor for IAS can be modeled by improvising Lonsdale's (1999) proposal for calculating the number of exotic species in a region. The human intervention potential measured by the existing regulations in a state to check invasions is inducted into the proposal by Lonsdale (1999). Therefore, the fate factor is dependent on three parameters 1. The population of invasive species transported (propagule size factor 'P(ps)' 2. Survival factor of the introduced exotic species 'S' and 3. Human intervention factor 'H' indicating the potential of the region to prevent and remove IAS.

3.3.1.1 Propagule size factor

In invasion biology, propagule size is defined as the number of individuals introduced in a single introduction event (Wittmann et al., 2014). We assume that every pair (a unit) of alien species transported to the alien range can establish a self-sustaining population, owing the pair overcome certain challenges. The survival rate in overcoming these challenges is modeled in the upcoming sessions. The propagule size factor is defined as the probability of the introduction of a unit exotic species, which can damage the alien ecosystem it is introduced into per transportation event of a type.

When modelling a fate factor, it is important to predict how many events of transportation (introduction events) from the native range to the alien range are required for the introduction of a unit exotic species. The frequency of the previous occurrence is a good measure to predict the introduction event. As there is no data on the number of introductions per transportation type available yet, ideally, ten random transportation events in the same type of transport from the native (i.e., the source) range are studied and the propagule size in each event is recorded.

The total propagule size from these samples can be used to predict the probability of introduction of a unit exotic species in a single introduction event. A database can be created for storing these data, which will make future calculations easier. The propagule size factor is a probability function P(ps) and can take a value between 0 and 1 (Equation 3).

$$0 \leq P(ps) \leq 1 \qquad (3)$$

I predicted P(ps) from the random samples/studies according to the condition satisfied in Table 1. If there are no recorded data/studies available on the propagule size of a species, I recommend making reasonable assumptions based on the introduction events of similar species with comparable size and characteristics and use it for calculating P(ps).

Table 1: Possible values of the propagule size factor

Propagule size factor P(ps)	Interpretation	Definition
1	Extremely likely to happen	Presence of at least 8 unit exotic species in 10 samples
0.7	Very Likely to happen	Presence of at least 6-7 unit exotic species in 10 samples
0.5	Moderately Likely to happen	Presence of at least 3-5 unit exotic species in 10 samples
0.2	Slightly Likely to happen	Presence of at least 1-2 unit exotic species in 10 samples or at least one previously recorded occurrence in the same mode of transportation
0	Not Likely to happen	No occurrence in a sample, no previous reports of occurrence

In probability, an event that is certain not to occur has, by definition, probability equal to zero. In this case, we say the risk of the introduction of exotic species does not exist. Also, a probability event that is certain to occur has a probability equal to one. In this case, we say the presence of a unit exotic species turning invasive in the event of transportation is a surety.

3.3.1.2 Exotic species survival factor

The survival factor 'S' of an introduced exotic species can be defined as the probability of the species overcoming the challenges in the invading region to establish a self-sustaining population that can cause potential damage to the ecosystem quality. In modelling potential damage from species introductions, we assume that there can be only two outcomes from an event of introduction, a) the exotic species survive the challenges in the alien conditions eventually establishing a self-sustaining population capable of damaging the invading ecosystem or b) getting eradicated at some point in time and failing to cause damage to the ecosystem. The events leading to damage before establishing a self-sustaining population are not taken to account. This means S can have two values either 0 which means the introduced species fail to survive the challenges or the value 1 which indicates that the introduced species survive the challenges and become invasive at some point in time.

The survival factor of a particular exotic plant species can be explained in terms of invasibility of the invading region concerning the exotic species, invasibility of the region depends on the ability of introduced species in overcoming certain challenges to survive in the invading region (Lonsdale, 1999). The challenges defined for invading plant species by Lonsdale (1999) are a) the rate of survival after extinction due to competition from native species, b) the rate of survival after extinctions due to predation from native species and mortality due to pathogens c) the rate of survival after events of extinction due to chance events during establishment such as droughts, floods, etc and finally d) the rate of survival after extinction due to maladaptation such as aquatic species released to a terrestrial environment. I adapted these challenges to determine the survival factor of a terrestrial invasive species introduced to an ecoregion j and this factor can be determined by assessing whether the exotic species can survive by overcoming three challenges. They are:

1. The event of survival after extinction due to predation by native species and mortality from disease transmission through pathogens (event A)
2. The event of survival after extinction due to the occurrence of chance events like flood, drought forest fire, etc during establishment (event B)
3. The event of survival after extinctions due to maladaptation (event C).

Each event can take a value of 0 or 1, 0 indicating the probability of a unit exotic species failing to survive the challenge and 1 indicating the probability of a unit exotic species surviving the challenge. The value of S can be 1 if the introduced species is already listed as invasive (already proved to survive in the modeled ecoregion) in Global Invasive Species Database (GISD), if not the data regarding these challenges must be collected from studies. All three are independent events and the species must survive all three events to establish a self-sustaining population (which means all three events must occur together), the species survival factor can be modeled using Equation 4.

$$S = P(A \cap B \cap C) \tag{4}$$

where $P(A \cap B \cap C)$ indicates the probability of three independent events A, B, and C occurring together.

Table 2: Probable outcomes of the survival events

Probability of survival event	Interpretation
P(A) = 0	The introduced species fail to survive extinctions due to predation by native species and mortality from disease transmission through pathogens
P(A) = 1	The introduced species survive extinction due to predation by native species and mortality from disease transmission through pathogens
P(B) = 0	The introduced species fail to survive extinctions due to the occurrence of chance events like flood, drought forest fire, etc during the establishment
P(B) = 1	The introduced species survive the extinction due to the occurrence of chance events like flood, drought forest fire, etc during the establishment
P(C) = 0	The introduced species fail to adapt in the conditions of the new environment of the alien region
P(C) = 1	The introduced species successfully adapt to the conditions of the new environment of the alien region

3.3.1.3 Human intervention factor

Human Intervention factor 'H' can be defined as the potential of existing human efforts in the region in preventing and removing an IAS. Early detection and rapid response along with prevention of exotic species is an effective strategy to minimize the chances of establishment and spread of Invasive species establishing in a new environment(Westbrooks, 2004). Early et al, 2016 found out that the proactive and reactive capacity in preventing biological invasion varies across different political borders. They defined the proactive capacity as the comprehensiveness of measures to prevent the introduction of IAS, and the existence of programs for research, monitoring, and public engagement to tackle IAS threats existing in a country. Reactive capacity is defined as the extent of knowledge regarding the current national IAS problem and the degree to which a national action plan exists to prioritize and coordinate IAS management activities.

Table 3: The measure of proactive and reactive capacities of a nation adapted from (Early et al., 2016)

No	National Policy	Type of capacity
1	IAS considered a major threat to national biodiversity or economy	Reactive
2	A list of current and/or potentially problematic IAS has been developed	Reactive
3	Engages in management of existing IAS problems	Reactive
4	Measures are in place to control the introduction of potential IAS	Proactive
5	Active research into IAS or international coordination of control efforts	Proactive
6	Efforts to monitor IAS emergence or expansion within the country	Proactive

The combined measure of the reactive and proactive capacity of a region can indicate the Human intervention potential of the region. Table 3 shows the reactive and proactive policies that can help prevent and remove IAS in a region and indicate the human intervention potential existing in the region. The maximum potential for human intervention is when the region satisfies all criteria and the minimum when there are no existing policies.

A scoring system is developed to measure Human intervention factor H (Table 4) based on the policies existing (Table 3) in the modeled region. According to the National Invasive Species Council (NISC) in the United States of America, even the best efforts cannot stop all invasive species, which means human intervention cannot always identify and destroy the IAS completely. Taking this into consideration, the value of H cannot be maximum in any region. Therefore a maximum score of 0.7 is given to H in places where all 6 criteria are followed. If a region satisfies at least 5 criteria according to Early et al., (2016) the region has some capability to prevent introduced species from turning invasive, taking this into considerations these regions are given a score of 0.4 for H.

Table 4: scoring criterion of H.

H	Interpretation
0.7	All 6 criteria/policies are existing in the region
0.4	At least 4 policies are existing in the region
0	3 or less than 3 policies existing in the region

Early et al., 2016 also suggest regions, where 4 or less policies are existing, are highly vulnerable to invasions and therefore these regions are assumed to be powerless in stopping invasions. Ideally, if an error-proof system for preventing, identifying, and removing IAS exist in the region the fate factor will take a value zero, in this case, the human intervention potential should acquire a maximum theoretical value which is one. Using the (1 - H) we can represent the percentage of alien species surviving after human intervention in the ecoregion the fate factor is modeled for.

3.3.2 Effect Factor

The effect factor for the introduction of a terrestrial IAS can be defined as the damage to ecosystem quality area of protection in an ecoregion due to the introduction of a unit of IAS. A unit of IAS is defined as the minimum population of alien species introduced to the region which can establish a self-sustaining population and can cause damage to the ecosystem quality of the invading region. Invasive alien species can affect the performance of an ecosystem by affecting the health of the native species population (indicated by PDF) in the area through different impact mechanisms such as competition and predation (ref Figure 5). If an IAS can cause any harm to at least one native species in the ecoregion through any of the previously mentioned impact mechanisms, the IAS has a damage contribution to the ecosystem quality area of protection. IUCN has recommended classifying these IAS based on the magnitude of the impact of the biological invasion in the form of an Environmental Impact Classification of Alien Taxa (EICAT) shown in Figure 8.

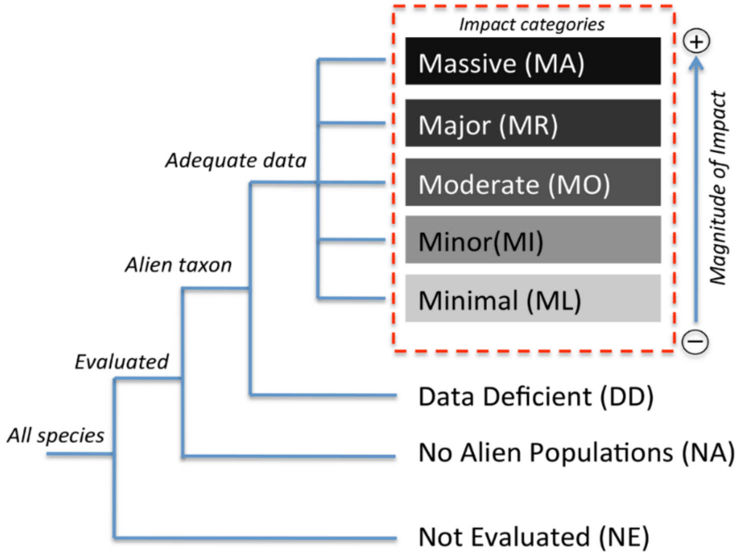

Figure 8: Different categories in the alien impact scheme by Blackburn et al., (2014)

The impact categories, defined by Blackburn et al., (2014) are:

1. Massive Impact - "When an introduced species replaces and causes local extinction of at least one native species and produce irreversible changes in the structure of communities and the composition of ecosystems".
2. Major impact - "When an introduced species causes the local or population extinction of at least one native species but leads to reversible changes in the structure of communities and the composition of ecosystems".
3. Moderate Impact - "When an introduced species causes declines in the population densities of native species, but no changes to the structure of communities or the composition of ecosystems and has no impacts that would cause it to be classified in a higher impact category".
4. Minor Impact- "When an introduced species causes reductions in the fitness of individuals native species, but no declines in native population densities observed or predicted and have no impacts that would cause it to be classified in a higher impact category".

5. Minimal Impact - "When an introduced species is unlikely to have caused deleterious impacts on the native environment".

The effect factor EF can be modeled in such a way that it represents the sum of effect on each taxonomic group in an ecoregion, following the recommendation by Verones et al. (2017) to report PDFs in a disaggregated way separate for different taxonomic groups. The taxonomic groups for calculating the effect factor on damages to the ecosystem quality recommended are Amphibians, Birds, Invertebrates, Fishes, Mammals, and Reptiles. Not all taxonomic groups show the same vulnerability to environmental pressures (Verones et al., 2020), this classification helps to identify the impact on each taxonomic group from the introduced IAS. The scale of impact will be different on each native species in the modeled ecoregion by an IAS. I developed an impact scale adjusting the EICAT classification to represent the different degrees of impact an IAS can have on each native species (Table 5). If the total number of affected species and the degree by which they are affected in an ecoregion is known, it can be used to indicate the overall damage to ecosystems. PDF is a measure that takes species richness into account and the PDF metric reflects the potential extinction of species(Verones et al., 2017). The ratio of species going potentially extinct (from the impact outcomes of IAS) to the species richness in the area can therefore indicate the potentially disappeared fraction of species in the ecoregion.

Table 5: Classification of Impact category on individual species by IAS based on the degree of extinction.

Category	Scale	Definition	β
Massive	MA	Causes local extinction of the species, Irreversible change	1
Major	MR	Causes local extinction of the species, Reversible change	1
Moderate	MO	Causes decline in the population of the species	0.7
Minimal	ML	Causes and impact on the fitness of the species	0.5
Minor/No impact	MI	Insignificant impact on the species	0

To represent the qualitative information mathematically a scoring(β) system is developed, representing the degree of extinction (Table 5) from an impact mechanism represented by the parameter ‘β’. Both massive and major impacts can cause local extinction, the only difference is the reversibility of extinction happening to the affected species. Therefore the native species which have a massive or major impact from the introduction of IAS can be represented completely by PDF with a score of 1. In the case of the moderate and minimal impact category, they represent an effect on the population health of the native species with different degrees but do not cause an extinction. They are given a score of 0.7 and 0.5 species disappeared contributions while calculating PDF. Minor Impact does not account for any species extinction or the population size and thus can be ignored and are assumed to have no contribution in calculating disappeared species, therefore given a score 0.

As the impact on each native taxonomic group is modeled separately, the potentially disappeared fraction of species is the weighted sum of disappeared species in each taxonomic group going potentially extinct (from the impact outcomes of IAS) to the species richness in the area can therefore indicate the potentially disappeared fraction of species in the ecoregion. To represent the qualitative information mathematically a scoring system is developed, representing the degree of extinction (Table 2) from an impact mechanism represented by the parameter ‘β’. This helps in representing the damage as the weighted average of impact on each species. Both massive and major impacts can cause local extinction, the only difference is the reversibility of extinction happening to the affected species. Therefore the native species which have a massive or major impact from the introduction of IAS can be represented completely by PDF with a score of 1.

In the case of the moderate and minimal impact category, they represent an effect on the population health of the native species with different degrees but do not cause an extinction. They are given a score of 0.7 and 0.5 species disappeared contributions while calculating PDF. Minor Impact does not account for any species extinction or the population size and thus can be ignored and are assumed to have no contribution in calculating disappeared species, therefore given a score 0. As the impact on each native taxonomic group is modeled separately, the potentially disappeared fraction of species is the sum of disappeared species in each taxonomic group.

4. Results

The characterization factor proposed here to quantify the impacts of the introduction of terrestrial IAS on ecosystem quality. The characterization factor predicts the species richness lost from the modeled region in the unit of the potentially disappeared fraction of species. The CF has two components, a fate factor model predicting the fraction of terrestrial IAS introduced and an effect factor model indicating the damages to ecosystem quality from unit introductions.

4.1 Fate factor model

The fate of alien species introduction in unit introduction per transportation type can be represented by Equation 5.

$$FF_{i,j,x,t} = P(ps)_{ixt}.S_{ij}.(1 - H_{ij}) \tag{5}$$

Where 'i' represents the invasive alien species, 'x' represents the native region of the IAS, 'j' represents the invading eco region and 't' represents the type of transportation method the FF is modeled for. P(ps) represents the Propagule size factor of the IAS i in-unit invasive species per transportation of type t, between ecoregion x and j. S represents the species survival factor representing whether the IAS i can survive the challenges in alien ecoregion j and establish a population or not. H represents the human intervention factor indicating the policies exiting in the ecoregion j in preventing and removing IAS i. Guidelines to select the value of propagule size factor are given in section 2.3.1.1, the value for species survival factor S must be calculated from Equation 4 recommended in section 2.3.1.2, and the value for human intervention factor H according to the scoring criterion given in Table 4 of section 2.3.1.3. Fate factor of value 1 indicates that from the transportation activity of type t between the region x and the region j, a unit of terrestrial IAS i that can establish a self-sustaining population capable of damaging the ecosystem quality of region j is introduced.

4.2 Effect factor model

The damage to ecosystem quality indicated in PDF from the introduction of a unit of invasive alien species can be represented by Equation 6.

$$EF_{i,j} = \sum_{g} \frac{\sum_{a=1}^{n(g)} \beta_{a,i,j}.R_{a,j,g}}{R_{n(g),j}} \tag{6}$$

The total effect from unit species introduction is the sum of effects on each taxonomic group. The potentially disappeared fraction is the ratio of the potential number of species going extinct in the taxonomic group g ($\sum_a \beta aRa$) to the total species richness of the taxonomic group ($R_{n(g)}$) in the ecoregion. 'β' represents the scale of impact (Table 3) the modeled IAS have on each native species existing in the region. The ratio βS_a to S_n is in the unit PDF. The value for β is chosen according to the scoring criterion given in table 5 of section 2.3.2. EF indicates the potentially disappeared fraction of species in the ecoregion j, due to the event of the introduction of a unit terrestrial IAS i.

4.3 Characterization factor

The regional characterization factor for assessing the impact from the introduction of IAS i per transportation type t from the region x on ecosystem quality of the ecoregion j in PDF can be represented by Equation 7.

$$CF_{reg,i,j,x,t}(PDF) = P(ps)_{ixt}.S_{ij}.(1 - H_{ij}) \times \sum_{g} \frac{\sum_{a=1}^{n(g)} \beta_{a,i,j}.R_{a,j}}{R_{n(g),j}} \tag{7}$$

4.4 Impact calculation

The total impact from the introduction of invasive species throughout the life cycle of a product, process, or service can be assessed by multiplying the inventory results with the sum of individual characterization factors per type t and invasive species i, as in Equation 8.

$$Total\ Impacts_{reg}(PDF) = \sum_{t}\sum_{i} CF_{reg,t,i} \times transportation_t \tag{8}$$

The characterization factor developed can indicate the potential damage to ecosystem quality in terms of the potentially disappeared fraction of species from the activities leading to the unintentional introduction of terrestrial invasive species. While calculating the impacts from a process/product/service, multiple transport activities must be accounted for. This could be a different mode of transportation (different introduction pathways) or a different source and destination for the same mode of transportation. The CF must be calculated for each type of transportation involved and each possible IAS introduced in this transportation type (Figure 10). The total unintentional introduction of terrestrial invasive species. While calculating the impacts from a process/product/service, multiple transport activities must be accounted for. This could be a different mode of transportation (different introduction pathways) or a different source and destination for the same mode of transportation.

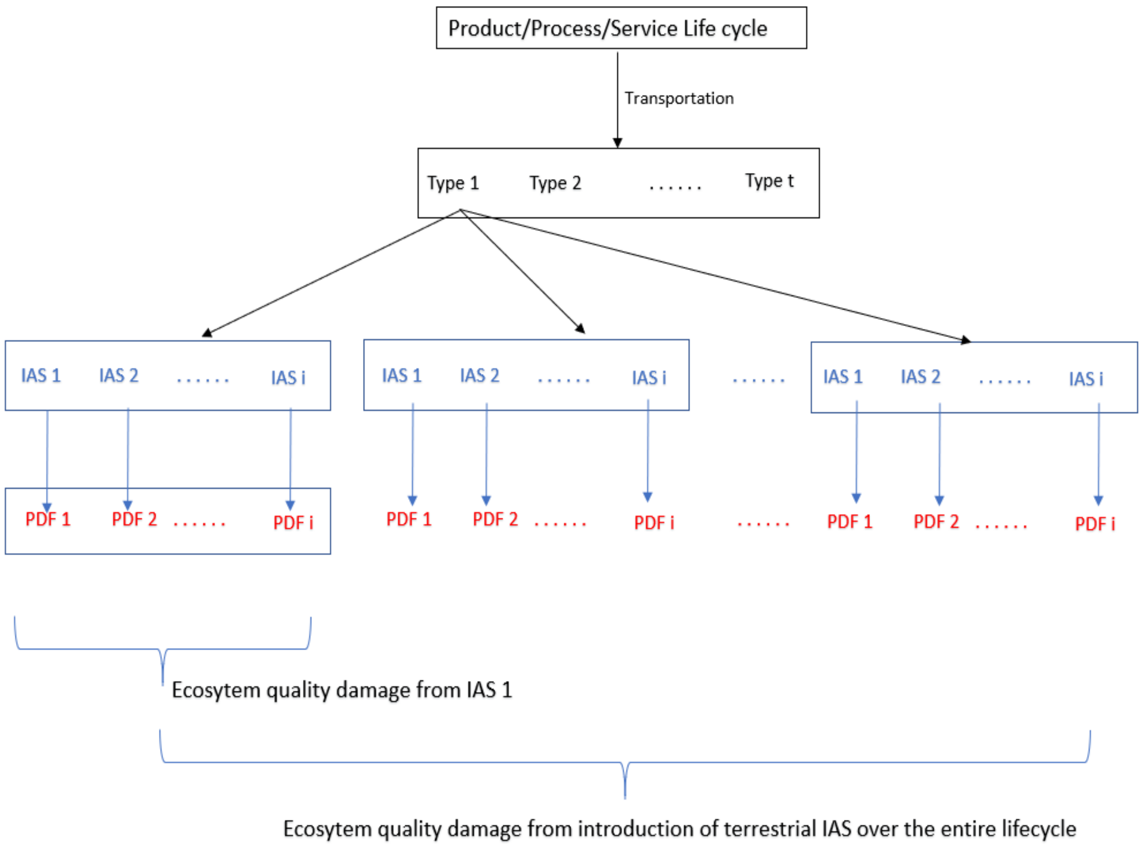

Figure 9: Steps involved in Impact calculation over the entire lifecycle from terrestrial IAS introductions.

The CF must be calculated for each type of transportation involved and each possible IAS introduced in this transportation type (Figure 10). The total impacts (damage to ecosystem quality from the product/process/service) will be the sum of all individual damages from the introduction of each invasive species i and transportation type t.

5. Discussion

5.1 Practical aspects and limitations of using the CF

The proposed characterization model involves many assumptions and ideal case scenarios which might be different in practice. The propagule size factor is predicted from previous records based on the guidelines provided in the method. Even if there is a very high frequency of previous occurrences, there are chances that the transported species may not be healthy or able to survive. It is very difficult to model these scenarios, but we cannot deny these possibilities. There is no operational database with information regarding propagule size, so for each case, the values must be chosen based on reports and studies. Similarly, the Human intervention factor is also based on assumptions that the policies existing are effectively implemented and no policy can prevent biological invasions. The unavailability of the required digitally assessable information (i.e., one or several databases) is undoubtedly the biggest limitation in realizing this model under the current LCIA framework. The CF quantifies the impacts in PDF indicating damage to ecosystem quality, which indicates a decrease in species richness of the modeled ecosystem. But a decrease in species richness does not wholly reflect ecosystem function loss nor damage to the ecosystem quality (Woods et al., 2018), therefore PDF may not be a perfectly suitable indicator to represent damage to ecosystem quality.

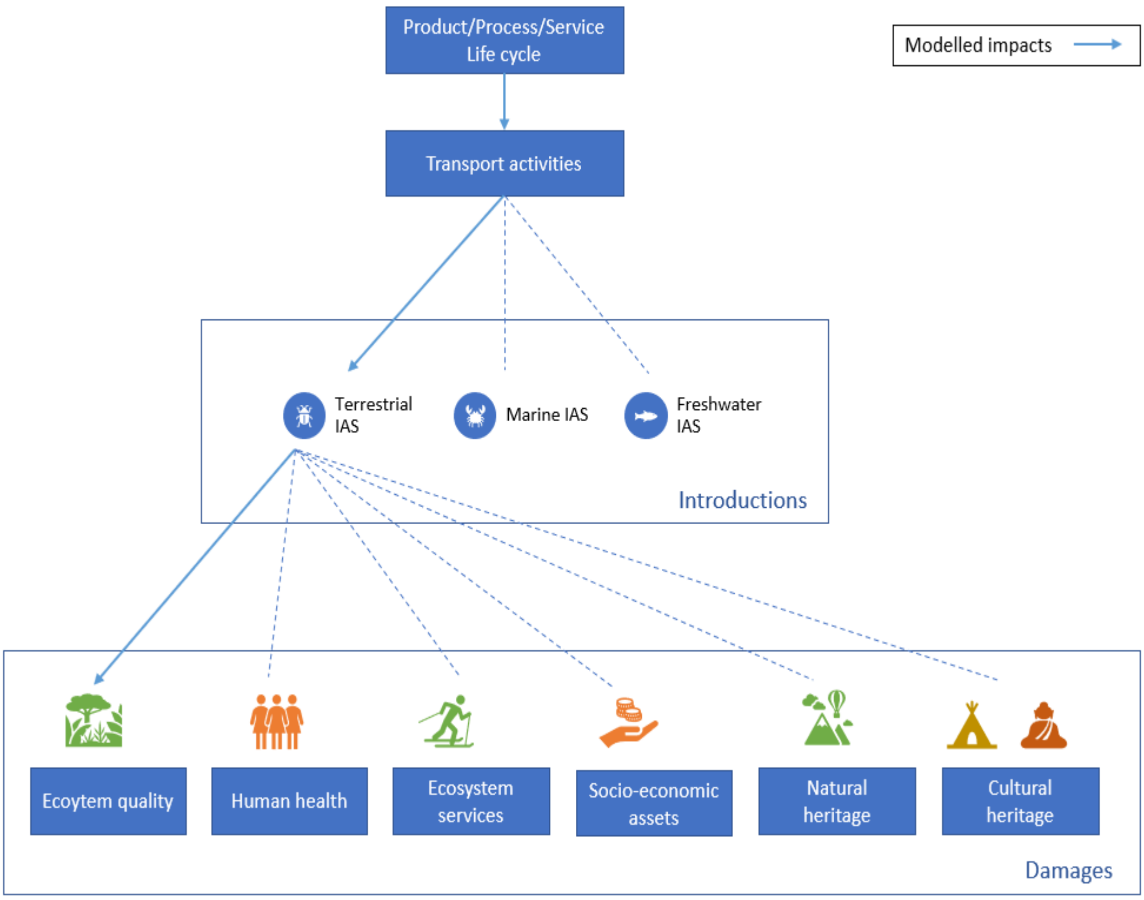

Figure 10: Quantifying impacts from terrestrial IAS introductions.

Terrestrial invasive species present a significant threat to global agriculture acting as pests (Paini et al., 2016). The current LCA framework lacks an operational indicator for socio-economic damage and hence some impacts from terrestrial IAS are overlooked by this model

(Figure 11). The same can be said for damages to cultural and natural heritage. Also, some species like the Asian tiger mosquito (Aedes albopictus) often serve as a vector for many diseases (Schaffner et al., 2009). The damages to human health from introductions also need to be modeled.

Another factor overlooked by the CF model is the propagule pressure factor, propagule pressure is a composite measure of introduction effort consisting of the propagule size and the introduction rate (Simberloff, 2009). Larger propagule size and increased introduction rate provide higher chances of the establishment (Drake & Lodge, 2006). Unless the introduction rates from all the introduction pathways and scenarios are modeled together, the propagule pressure is difficult to indicate accurately, instead, our model assumes if a unit IAS survives the challenges in the introduced region (species survival factor) the species damages the existing quality irrespective of the time frame in which it occurs.

Another factor overlooked by the CF model is the propagule pressure factor, propagule pressure is a composite measure of introduction effort consisting of the propagule size and the introduction rate (Simberloff, 2009). Larger propagule size and increased introduction rate provide higher chances of establishing a self-sustaining population (Drake & Lodge, 2006).

The CF quantifies the impacts in PDF indicating damage to ecosystem quality, which indicates a decrease in species richness of the modeled ecosystem. But a decrease in species richness does not wholly reflect ecosystem function loss nor damage to the ecosystem quality (Woods et al., 2018). Terrestrial invasive species present a significant threat to global agriculture acting as pests (Paini et al., 2016). The current LCA framework lacks an operational indicator for socio-economic damage and hence the impacts from terrestrial IAS are overlooked by this model. The same can be said for damages to cultural and natural heritage. As impacts from multiple IAS are calculated individually, there could be double counting i.e., the same native species could be affected by two (or more) IAS introduced during the lifecycle, and the affected species will be counted during quantification of impact from both IAS.

5.2 Research Outlook

The developed characterization model must be tested and validated with practical examples assessing the damage to ecosystem quality due to the introduction of IAS. As the CF only represents the damage to ecosystem quality, along with other limitations mentioned above, further research is highly recommended on improving the model. Characterization factors to include damages on human health and socio-economic damages are highly recommended. A database for terrestrial IAS with information components such as propagule type, survival rate, human intervention factor, and modification of the GISD database to include the recommended scale of impact needs to be developed. Further development to include an exposure factor to model the rate of invasion and a vulnerability factor to translate the regional losses to global loss is needed.

6. Conclusion

Trade and transport will continue to grow, so are the chances of species getting transported to new regions. The terrestrial biodiversity in the tropics is unmatched and global warming sets the perfect environment for many species to adapt to higher latitudes. This makes newer and newer regions prone to biological invasions. Terrestrial invasive alien species are already causing dramatic changes in many ecological systems worldwide, but we are lacking a methodology to quantify their impacts. The quantification of impacts of terrestrial alien taxa is necessary so that proper allocation of the impacts between products and services can be done. Like carbon footprint impact from IAS can also be allocated to different corporates and countries. This impact assessment can be used to form international regulations and can thereby help the financially weaker countries to fight invasion from the support of those who profit from the trade. Fate and effect factor models can indicate the potential loss of biodiversity in the invading region caused by the introduction of terrestrial IAS. The introduction, establishment, and impact mechanism of terrestrial IAS depend on many factors such as propagule size of introduction, the survival rate in the introduced ecosystem, the prevalence of policies to prevent and eradicate IAS, and the type of native species exiting in the region. Many assumptions had to be made while modelling the characterization factor due to lack of data availability, damages to ecosystem quality only indicate a fraction of the actual damage caused by IAS. Further models must be developed to include damages to human health, ecosystem services, socio-economic assets, cultural and natural heritage, etc. Even though large uncertainties and data deficiency hinder modelling damages from IAS, characterization models can still be developed, by putting in more time and effort.

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