NOVEL ECOSYSTEMS: Necessity, Revolution, or Laziness?

by

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Abstract

The earth's environment, climate, and natural systems are constantly changing, having little resemblance of ecosystems past. These new systems functioning in balance are termed "novel ecosystems" and have arisen as the new normal posing an important question in the restoration field as to how these systems should be approached. To address the state of novel ecosystems in the academic literature, I devised a matrix to assess variables of description regarding novel ecosystems and how they are expressed in the literature. Results showed a predominance of self-assembled systems with a disposition towards invasive species as a primary threat. Chemical, physical, and landscape data was severely lacking and most metrics for success were ecological. Data from the literature show a lack of research on designed novel ecosystems but shows promise for success given several examples. More research on novel ecosystems in restoration must be undertaken to fill gaps in aggregate data.

Keywords: Novel Ecosystems; Literature Review; Ecological Restoration

Dedication

I dedicate this dissertation to my grandparents, Adamantia and Konstantinos Floros. My years living with you were some of the best in my life.

Acknowledgements

I would like to acknowledge my supervisor, Susan Owen, for her guidance through each step of the process. She was instrumental in defining the path of this literature review, and for that I am extremely grateful. I wish to show my gratitude to program head, Anayansi Cohen-Fernandez for inspiring the topic of this study. I also would like to pay my special regards to my instructor Ken Ashley whose assistance proved invaluable through my years in this program. Thank you to all my instructors whose support was monumental during my years of study and for the completion of this project.

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Chapter 1.

Introduction

With an era of increased human impacts upon us, anthropogenic activities have a greater influence on ecosystems than they have in the past. These changes to environmental systems has resulted in ecosystem degradation and alterations to ecosystem function. In some instances, it is argued that the disruption to ecosystems has resulted in the emergence of novel ecosystems. This project evaluates studies of novel ecosystems in the context of restoration ecology.

To understand the impact of human activity on ecosystems it pertinent to understand ecological principles, such that we know what it is that we are attempting to restore. Most scientists would agree that ecology is the science which explores the relationships between organisms and their biotic and abiotic environments (Dice 1955). These environments and organisms interacting with one another to form complex food webs, nutrient cycles, and energy flows are together called ecosystems (Macdonald 2016). Ecosystems can take on a variety of functions including biomass accumulation, food production, herbivory, predation, decomposition, water filtration, soil formation, succession, and disturbance regime (Macdonald 2016). Having these functions kept intact is crucial to the strength and resilience of the ecosystem. Another important aspect of discussion is the form these ecosystems take. Form will be used as a descriptive word to describe the aesthetics of the ecosystem in terms of biotic and abiotic assemblages, whether native or exotic. Ecosystems may therefore come in many different forms, all carrying a variety of functions. Ecological restoration, therefore, is the practice of aiding recovery of these ecosystems and functions which have been disturbed, damaged, or demolished (Macdonald 2016).

Ecosystems can assemble through an assortment of processes. The dispersal and consequent colonization from neighboring species pools is essential, and follows an environmental filter of regional processes such as: local environment and habitat characteristics, and biotic/abiotic interactions which all have a great effect on the resulting community structure and function (Menninger & Palmer 2016). While natural ecosystems can self-assemble; in the context of ecological restoration some times intervention is required to support the assembly process. An example of this would be a designed ecosystem built from the ground up by restoration practitioners.

It is therefore of great importance when considering an ecological restoration plan, to consider these habitat connections, as restoration may be severely constricted when being removed from the surrounding gene pools (Menninger & Palmer 2016). It is possible for restoration ecologists to establish an ecosystem completely independent of the gene pools which nature provides us. However, it is of vital importance to consider the costs of doing so. The most pragmatic approach might be to consider ecosystem designs incorporating connectivity, such that the ecosystem can begin to assemble and begin recovery to a desirable state without constant human intervention.

1.1. What are Novel Ecosystems?

The idea of the novel ecosystem has become extremely popular as of late, sparking much debate in the ecological and restoration communities (Miller & Bestelmeyer 2016). The term was popularized in 2006 by Richard Hobbs and his colleagues, who argued that invasive species, land use changes, as well as climate change which have changed the earth's assemblages can shift towards a steady state. These newly created systems functioning in balance, would be dubbed "Novel Ecosystems" (Simberloff 2015) to acknowledge a transformation from a historical state to a newer and "novel" stable state. Much of the debate stems from fear that industry and corporations may use the idea of novel ecosystems as an excuse to reduce funding placed towards the restoration of ecosystems, while claiming the system is novel (Simberloff 2015). The debate around this approach stems from the fear that industry will use this newly created and loosely defined term as a "get out of jail free card", reducing the funding given to restoring or mitigating damages while claiming novelty within the system (Simberloff 2015).

1.2. Defining Novel Ecosystems

The first appearance of this term was in Chapin and Starfield (1997) who used novel ecosytems to describe an Arctic tundra transitioning to boreal grassland under an altered climate and fire regime. Through the years the term was loosely used to describe ecosystems with different biotic or abiotic factors having been adjusted from the original characteristics (Morse et al. 2014). Richard Hobbs and his colleagues in 2006 later popularized the term, however; it still lacked a concrete definition. Interest in this new topic compelled Hobbs to author a comprehensive book on the topic of novel ecosystems (Morse et al. 2014), and the definition by Hobbs et al. (2013) updated the previous loose definitions to the following:

> "a system of abiotic, biotic and social components (and their interactions) that, by virtue of human influence, differ from those that prevailed historically, having a tendency to self-organize and manifest novel qualities without intensive human management. Novel ecosystems are distinguished from hybrid ecosystems by practical limitation (a combination of ecological, environmental and social thresholds) on the recovery of historical qualities."

While this statement applies a much more specific and comprehensive definition to the term, it may be problematic as it does not account for certain anthropogenic factors, such as agriculture, agroforestry, or indirect human influence such as climate change, pollution, or other chemical stressors. Because of these reasons and because this literature review aims to be as inclusive as possible, I will be using the definition as proposed by Morse et al. (2014):

> "A novel ecosystem is a unique assemblage of biota and environmental conditions that is the direct result of intentional or unintentional alteration by humans, i.e., human agency, sufficient to cross an ecological threshold that facilitates a new ecosystem trajectory and inhibits its return to a previous trajectory regardless of additional human intervention. The resulting ecosystem must also be self-sustaining in terms of species composition, structure, biogeochemistry, and ecosystem services. A defining characteristic of a novel ecosystem is a change in species composition relative to ecosystems present in the same biome prior to crossing a threshold."

By using this definition, we can have a more detailed view on what makes an ecosystem novel. Differing human factors including agriculture, forestry, and climate change which have applied anthropogenic stresses causing ecological change can be viewed as novel ecosystems. This specificity of definition will also lead to a greater number of case studies and literature that will able to be included and analyzed within this review.

1.3. Why do Novel Ecosystems Matter?

As the world progressed and humans spread around the planet, we brought with us parts of the ecosystems from which we came. We are living in an era which has been termed “the Anthropocene epoch” (Steffen et al. 2007), with human activity having unparalleled impacts on nature unseen previously in history (Clement & Standish 2018). This phrase designates a new era in which human activities surpass the impacts of natural processes (Crutzen 2002). At least three quarters of the globe is recognized as anthropogenic biomes, or anthromes; which are landscapes changed and embedded within agricultural and settled landscapes which sustain human populations. The earth’s environment, climate, and natural systems are now permanently changed, and some estimate about half the world’s land mass is now dominated by novel ecosystems (Carter 2018). These novel ecosystems have experienced extreme degrees of change (Hobbs et al. 2006, 2013), and may be characterized by species changes accompanied by altered functions and interactions (Hobbs et al. 2014). These permanently altered systems often have little or no similarity to the historic ecosystems which resided there previously (Hobbs et al. 2013).

The representation of this novelty in our ever-changing ecosystems as the new normal has sparked much debate in the field of restoration over the revision of previously accepted restoration goals (Woodworth 2013). A reason for this dispute, is that novel ecosystems have often departed so substantially from their native compositions that restoration with historical accuracy may be impossible or require substantial resource contribution (Miller & Bestelmeyer 2016). New concepts have arisen recently in reaction to this task to conserve nature in an environment where biophysical conditions are constantly changing (Lennon 2017). Some focus on recreating past conditions (Taylor 2013) while others reexamine where value remains in our interactions with nature (Lennon & Scott 2014).

1.4. Invasive vs Novel Species

Regarding introduced species, the negative impacts are often focused upon, however; advocates of novel ecosystem approaches ask in which scenarios do novel ecosystems benefit native flora and fauna. Native biota can use novel ecosystems when they provide resources that historically were not present, when habitat and resources introduced resemble the previous ecosystems, and when the native habitats have limiting biotic interactions (Kennedy et al. 2018). In the right conditions, some native species can flourish in novel ecosystems, which could be perceived as a success. In fact, in certain cases non-native vegetation has been documented to have positive effects on amphibians, reptiles and birds (Packer et al. 2016). Therefore, when searching through the successes (or failures) in restoration, it is important to determine how success was defined, since the use of the term in this field could be quite subjective.

1.5. Novel Ecosystems through History

The structure and function of ecosystems having been affected by events through history has become evident to ecologists as of late (Foster et al. 2003). Natural and human-directed events have led system alterations having successional changes felt through hundreds to thousands of years (Dupouey et al. 2002). These ancient interactions can often become drivers of ecosystem function in landscapes of the present (Rhemtulla & Mladenoff 2007).

As discussed previously, we are living in an era considered by many to be the "Anthropocene Epoch" (Steffen et al. 2007). This may be true in terms of scale and the proportion of novel ecosystems compared to completely untouched landscapes, however; the core concepts of the novel ecosystem are not a new occurrence, and evidence of such can be seen through not only the historical record, but also in exceptionally old academia.

Although novel ecosystems are considered a contemporary topic, the presence of novel ecosystems can be seen throughout human history, and signs of their study can be seen in very early academic literature. In one early academic document, author Daines Barrington brought forth the hypothesis that sweet chestnut trees (*Castanea sativa*) were not native to Britain (Barrington 1769). This early citation from the 1700s is just one example of how the concept of novel ecosystems dates back centuries and may be a deeply integrated part of human anthropological history.

Human requirements leading to alteration of landscapes and ecosystems through agriculture, forestry, and other land use modifications are profoundly interlaced with changes in ecology throughout history (Szabó 2010). These previous alterations to ecosystem structure and function have been proven extremely important to management of modern systems, including the biodiversity of sites and landscapes (Kirby & Watkins 2015). Thus, while determining restoration goals and outcomes, it is important for us to recognize that our ecosystems are not simply remaining in a static and unchanging state, but rather in a state of constant fluctuation with human activities and nature co-evolving together.

Identifying the ongoing changes of temporal variability, and the effect of external stressors on ecosystems over the long-term finally can advise management approaches in the restoration of ecosystems to what is considered a pre-disrupted period (Isendahl 2016). The problem with this idea, is that applied restoration research deems any historical human activities as a type of intrusion (Isendahl 2016), and thereby our restoration goals of reaching a pre-human era as an end-goal may be unrealistic considering human activities and ecosystem structure have been together in flux throughout antiquity, and not merely recent human history.

1.6. Connectivity, Trophic Cascades, and Novel Ecosystems

Despite the deeply intertwined history of human activities and the ecosystems we interact with, we must be careful not to forget the extent we have spread, and our populations have grown. Even though the anthropocene epoch is upon us, and human impacts are much greater than they have been in the past. Habitat alteration by humans does change the spatial context in which species interactions ensue (Fahimipour & Anderson 2015). Our ever-expanding land use has dismantled habitat connectivity (Foley et al. 2005), resulting in food webs having altered exogenous quantities of resources (Stier et al 2014).

These changes in habitat connectivity, spatial habitat features, and other factors from a landscape perspective, are an important aspect for restoration as they manage critical resource supplies for food webs which can in turn disrupt patterns of ecological community structure (Dreyer & Gratton 2013). Trophic cascade equilibriums, which are characteristically a casualty of these connectivity disruptions occur when predator and prey dynamics in the food chain are broken, creating disturbances which “cascade” down to the lower trophic levels (Fahimipour & Anderson 2015). In other words: major alterations, whether natural or anthropogenic in source, which occur at one trophic level will descend through the other levels of the chain (Rao 2018). This ecological theory suggests major changes in ecosystems can occur through the changes and abundance of single species (Estes et al. 2011)

This concept of trophic cascading shows the many levels by which simple alterations can have drastic effects on ecosystems structure and function. These cascading effects have strong impacts on ecosystem dynamics and can even control varied ecosystem processes such as wildfires, disease, carbon-sequestration, biodiversity, invasive species, and biogeochemical exchanges among Earth’s soil water, and atmosphere (Estes et al. 2011, Rao 2018). Given these factors of how small changes can influence a large portion of ecosystem structure and function, in combination with the permanency of exotic species, important consideration must be accorded to traditional goals and outcomes as well as restoration values. In determining restoration goals and identifying what may be deemed success raises questions about the level of resource required to satisfy the traditional objective of restoring what is considered pristine by way of a reference ecosystem. For example, is it it more important to sink resources into continuously fighting an uphill battle of weed removal to achieve an historical reference state or is it more pragmatic and cost effective to focus our goals on restoring ecosystem function over form, by analyzing the underlying issues causing function to remain degraded, and focusing on the few aspects or species which develop the greatest amount of impact? When considering novel ecosystems, it may be pertinent to understand the driver of degradation and focus on the key species which might carry a significant influence.

1.7. How Important are Keystone Species when considering Restoration in a Novel Ecosystem Context?

As spoken of above, the species responsible for carrying the greatest amount of impact are known as keystone species and are vital components to ecosystem functionality by holding up interaction networks (Lins et al. 2017). The functional aspects of the ecosystem, including ecological function, processes, biodiversity, and ecosystem maintenance are all determined in part by these biotic interactions (Valiente-Banuete et al. 2015). Elimination of these functional aspects will in turn affect the entire biological community (Power & Mills 1995).

Due to reasons of interconnectivity, and the importance of certain individual species, it is vital to strategically consider elements of landscape perspectives such as keystone species when undertaking restoration initiatives to ensure reestablishment of ecosystem function (Lins et al. 2017). When considering novel ecosystem restoration, exotic species removal may seem like the obvious choice for a starting point. These species are easily noticed and identifiable, and justification for their removal will be straightforward when stating that they do not belong in the system as per the reference ecosystem. This may be true, and in the case of noxious weeds and destructive invasive species this might be an important repair, however; there are cases where exotics actually have positive effects (Packer et al. 2016). In these cases of exotics having positive or neutral effects, it may be more beneficial to consider allowing the system to remain as a novel ecosystem and instead determine which key elements are missing which would allow succession to be driven towards a more functional ecosystem.

1.8. Passive Restoration and Novel Ecosystems

As discussed previously, one goal of restoration may seek to drive ecosystems towards a more desirable state of increased functionality, without the constant need for human interventions. This type of restoration is referred to as passive ecological restoration, which is a type of natural regeneration or unassisted restoration, where the recovery process occurs without active human interventions (Zahawi et al. 2014). Passive restoration can often be accomplished through removal of specific disturbances (Melo et al. 2013) and can be as effective at achieving restoration goals such as increasing biodiversity and ecosystem services (Jones et al. 2009). When compared to traditional and more hands-on restoration techniques, passive restoration can be considered a cost-effective alternative, or sometimes even completely free (Holl & Aide 2011).

In the context of novel ecosystems, exotic species can be seen in some case to stimulate self regeneration, as seen in this one example where retired pastures in eastern Australia were aided towards a state of recovery by first being colonized by non-native trees and shrubs (Catterall 2020). With the possibility of non-native species being useful in helping restoration practitioners achieve their goals, and the idea of key species being crucial towards the promotion of ecosystem self recovery, it is conceivable that an adjustment of restoration concepts and goals/outcomes may be necessity.

1.9. Adjusting Restoration Goals and Outcomes

With the acquired knowledge of our world's ecosystems in a state of constant flux, with human and natural interactions deeply intertwined through the centuries, and landscape factors such as keystone species and connectivity being critical to the health and recovery of our ecosystem functions, it is logical to reconsider traditional restoration goals of recreating a reference ecosystem. Novel ecosystems have been present throughout anthropological history, and academic literature from antiquity have documented such systems (Barrington 1769). Problems in defining what is considered "natural" and "pristine" are arising, and this could be from our inability to accept ecosystems as dynamic (Hilderbrand et al. 2005). Goals for restoration aiming to achieve a perfect replication of previous ecosystems is considered a myth by some (Hilderbrand et al. 2005). Creating cost-effective measures of restoration by using ecological processes and frameworks such as connectivity for natural assembly, and trophic cascades to direct ecosystems to a higher desirable state of ecosystem function will be highly beneficial as we begin to accept the permanency of introduced species.

Chapter 2.

Goals, Aims, and Objectives

The goal of this review is to examine the use of novel ecosystems in current restoration literature and to contribute to current scientific debate by analyzing how studies and their authors present the attributes and outcomes of restoration in novel ecosystems, and to identify whether if it could ever be appropriate to deviate restoration strategy from historical conditions. Focus will be placed on peer-reviewed articles of case studies showing in-situ results of restoring sites with an aspect of novelty, and what benefits or detriments are experienced by the species of the system. The aim of this analysis will be to quantify when (or if) novelty is acceptable as a strategy to be included in restoration programs.

2.1. Research Question: How are Novel Ecosystems Understood in Restoration?

This review aims to explore whether taking a novel ecosystem approach to restoration is effective and reasonable, given the permanency of introduced species and changes in ecosystem's structure and function. Novel ecosystem approach refers to a method of restoration which does not merely aim to meet historical conditions but also takes into account the possibility of a new stable state different from the past. It aims to quantify the relationship between projects defining novel ecosystems and characteristics in terms of habitat degradation, biodiversity, and ecosystem services. It also aims to pinpoint what criteria is currently being used in the literature to delineate a success in the context of novel ecosystems and characteristics in terms of restoration. Ultimately, the overarching goal is to explore the contribution and modification of novel ecosystems to as a strategy to evaluate restoration outcomes. To accomplish this, the following objectives were proposed:

1. To develop a method to evaluate the goals and outcomes of ecological restoration projects that focus on novel ecosystems.

2. To classify and describe what type of ecosystems are being studied and restored in a novel ecosystem's context.

3. To evaluate the relationship between novel ecosystems and habitat degradation by using a modified version of the Recovery Wheel within the International Standards for the Practice of Ecological Restoration, to specifically determine their trajectory of recovery.

4. To evaluate how success is defined within projects and case studies taking place within a novel ecosystem environment.

Chapter 3.

Methods

I systematically reviewed the empirical literature on Novel Ecosystems from 2006 until December 2019. The starting year was chosen because this was when the phrase "Novel Ecosystems" was popularized (Hobbs 2006) and started gaining traction as a concept, so using this year as a starting point allowed for a search with the broadest scope. I used a comprehensive strategy and searched using the SCOPUS, JSTOR, Web of Science, and BioOne search engines which allowed data retrieval from a wide array of academic journals. Using the specific search terms ["novel ecosystem" +restoration+ "case study"], I initially retrieved 89 empirical articles that mentioned case studies in ecological restoration and novel ecosystems. After review of these articles and discarding of articles that were not case study focused a final dataset of 20 were identified for analysis. All literature had to be peer reviewed to be considered.

As there has been limited previous evaluation of the goals of ecological restoration projects with novel ecosystems, I had to develop a matrix that would allow a systematic evaluation of the case study literature. The categories in this matrix were informed by the method used in the systematic literature review of Evers et al. (2018) and by the categories that have been established by the Recovery Wheel given by the Society for Ecological Restoration (SER) within the document "International Standards for the Practice of Ecological Restoration" (Figure 1).

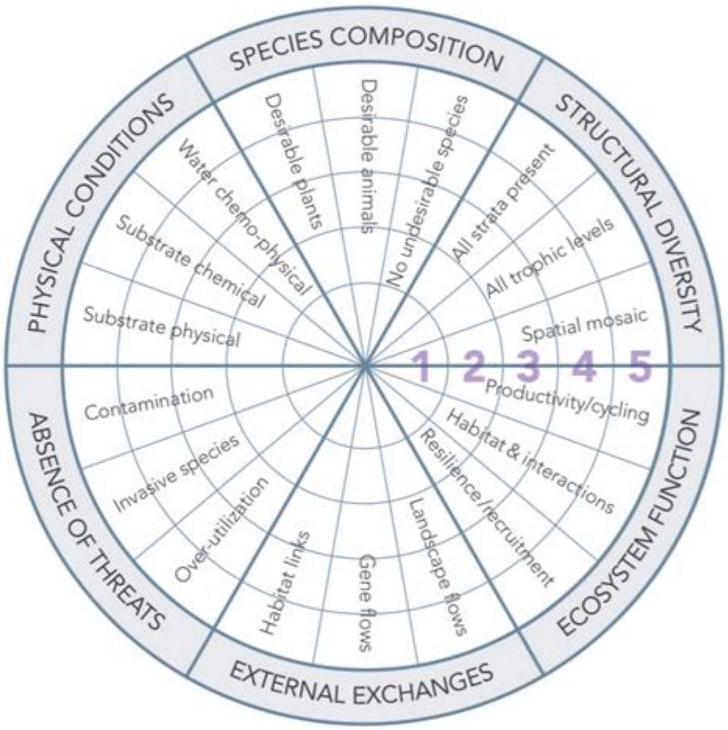

Figure 1: Recovery Wheel as shown in SER document (Macdonald 2016)

This Recovery Wheel delineates a five-star system to evaluate an ecosystems trajectory of recovery. The Recovery Wheel includes several environmental categories to be evaluated, including physical conditions, species composition, structural diversity, ecosystem function, external changes, and absence of threats. This approach provided a systematic evaluation of how the biophysical elements of case studies were discussed and presented in the literature. The wheel was designed for field application and I modified the criteria of this wheel to better suit the data which is found in the literature. The reason for modification of the data was that it could sometimes be incomplete and not focused towards the original goals of the evaluation methods. This combined matrix (Table 1) then allowed for a review of the database of literature that encompassed a qualitative assessment of the sites and a review of the relevant biophysical elements of the restoration projects. Completed matrix and wheel are included in the appendix (Table A1-A2, Figure B1-B20).

Table 1: Matrix used for review of database literature.

Metric	Categories
Location	Country or Region
Biome (historical)	Forest; Grassland; Aquatic; Urban
Methodology	Qualitative or Quantitative
Baseline	Historical; Abandoned; Modified
Threats	Invasive Species; Climate Change; Over-utilization; Etc.
NE assembly	Designed; Self-Assembled; Hybrid
Management recommendation	Manage for Novelty; Manage against Novelty; Tolerate Novelty
Ecosystem metric	Biodiversity; Provisioning; Regulating; Cultural; Etc.
Language Describing Success	Biological/Ecological; Financial/Economic; Cultural
Desirable Plants	Ranking System of 1 - 5
Desirable Animals	Ranking System of 1 - 5
No Undesirable Species	Ranking System of 1 - 5
All Vegetation Strata	Ranking System of 1 - 5
All Trophic Levels	Ranking System of 1 - 5
Spatial Mosaic	Ranking System of 1 - 5
Productivity/Cycling	Ranking System of 1 - 5
Habitat and Interactions	Ranking System of 1 - 5
Resilience/Recruitment	Ranking System of 1 - 5
Habitat Links	Ranking System of 1 - 5
Gene Flows	Ranking System of 1 - 5
Landscape Flows	Ranking System of 1 - 5
Contamination	Ranking System of 1 - 5
Invasive Species	Ranking System of 1 - 5
Overutilization	Ranking System of 1 - 5
Water Chemo-Physical	Ranking System of 1 - 5
Substrate Chemical	Ranking System of 1 - 5
Substrate Physical	Ranking System of 1 - 5

I also undertook a content analysis in order to determine the description of success in each of the case studies within three broad categories of success: ecological, financial-economic, as well as social-cultural. This analysis was done by ranking language used in each peer reviewed case study across the three categories in a binary fashion for presence, as well as marking down which was the primary motivator for the restoration. Results were tabulated and compared to see if any patterns arise while using the wheel of recovery to determine the recovery trajectory or perception of success within novel ecosystems.

Finally, I performed basic descriptive statistics. Calculations of frequency and proportion were tabulated and included for all the above parameters. The mode for the ecosystem recovery wheel rank was included where applicable.

Chapter 4.

Results and Discussion

This section will be approached in a segmented manner, going over objectives two through four sequentially. Key points of interest will be divided into their own sections. This will be done by giving each objective its own subsection for the results and then going over the discussion in a later subsection. This style of formatting was done to increase the clarity of this document. The first objective was satisfied through the methods and creation of the matrix (Table 1), thus in this section I will begin discussing the second objective. Basic descriptive statistics are also included.

4.1. Classifying and Describing Ecosystems Restored and Studied in a Novel Ecosystem Context

In order to satisfy the second objective. The research articles were analyzed, and a number of key environmental conditions classified. The ecosystems were characterized by biome, primary threat, novel ecosystem assembly, as well as the management recommendation discussed or intervention implemented. These factors give an interesting overview of what kind of novel ecosystems have been studied in the literature, what the primary sources of degradation are, and how they are being restored or recommended to be restored.

4.1.1. Biome Results

Ecosystems were classified by biome to determine if there was a predominance of ecosystems type within the cases studied. The classification of projects by biome was undertaken using four major categories of urban, forest, aquatic, and grassland. The classification revealed that of the 20 articles, about half were within a forested biome (nine articles, 45%), with five (25%) taking place within an aquatic biome, five (25%) in a grassland biome, and one article (5%) within an urban biome (Figure 2).

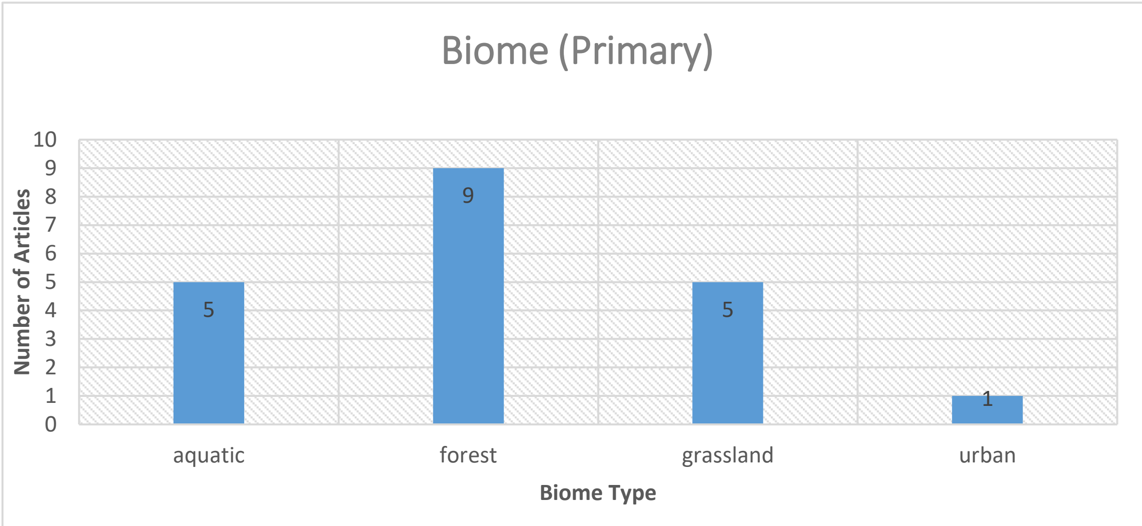

Figure 2: Chart showing the number of articles which cited each biome type.

4.1.2. Primary Threat Results

The novel ecosystems studied were characterized by a range of ecological perturbations, all happening to fall within three distinct categories when describing which was either causing the primary damage or would be the focus of study: invasive species, overutilization, and climate change. These primary threats were determined by review of the article's language towards which ecosystem disturbance was causing the most damage or was the main interest for removal. In review of the data set invasive species were identified as the greatest primary threat with 11 articles (55%) citing and acknowledging invasive species as the main disturbance to sites. The invasive species included both plant and animal species, as described by the articles. The threat of over-utilization was observed as a key issue in seven studies (35%). Over-utilization was variously identified as an over-exploitation of the land for human use. Climate change was only explicitly mentioned as a threat in two studies (10%) (Figure 3).

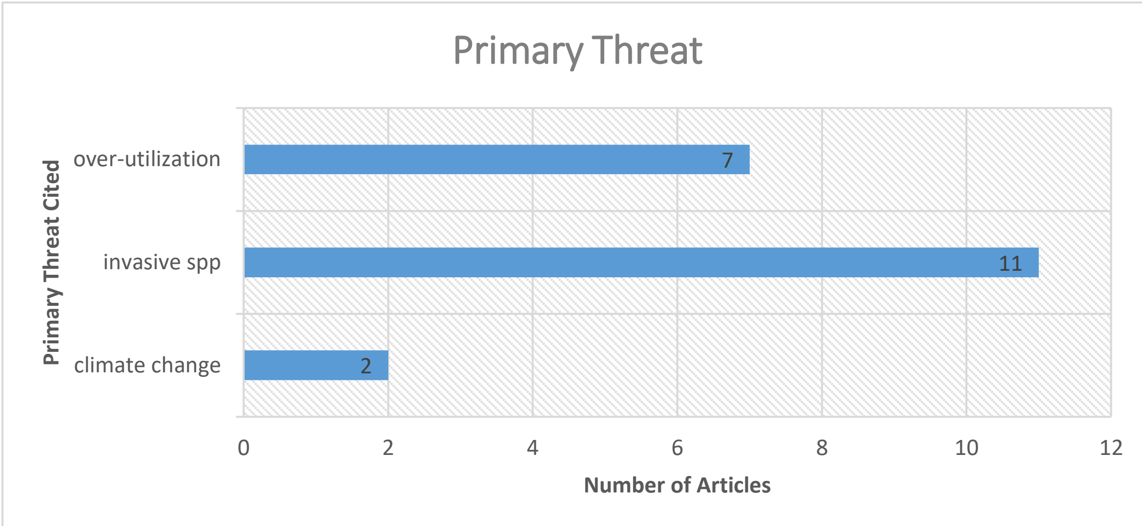

Figure 3: Chart showing the number of articles which cited each disturbance as the primary threat.

4.1.3. Novel Ecosystem Assemblage Results

Ecosystems were categorized by the manner in which the species of the system had assembled. This analysis divided the projects into three categories of system assembly: designed, self-assembled, and hybrid. Designed systems had their species assemblages placed there strategically by the individuals creating the ecosystem. Self-assembled systems were ecosystems which were left to assemble by natural means, either by neighboring seed banks or migration. Hybrid assembled systems were ecosystems which had become created through a mixture between the two previous methods, having had species both purposefully placed, and additional species dispersed through natural means. The analysis revealed that most cases had their ecosystems self-assemble, with 15 of the 20 articles (75%) assembling in this manner. Only three (15%) were designed, and two (10%) were a hybrid of design and self-assembly (Figure 4).

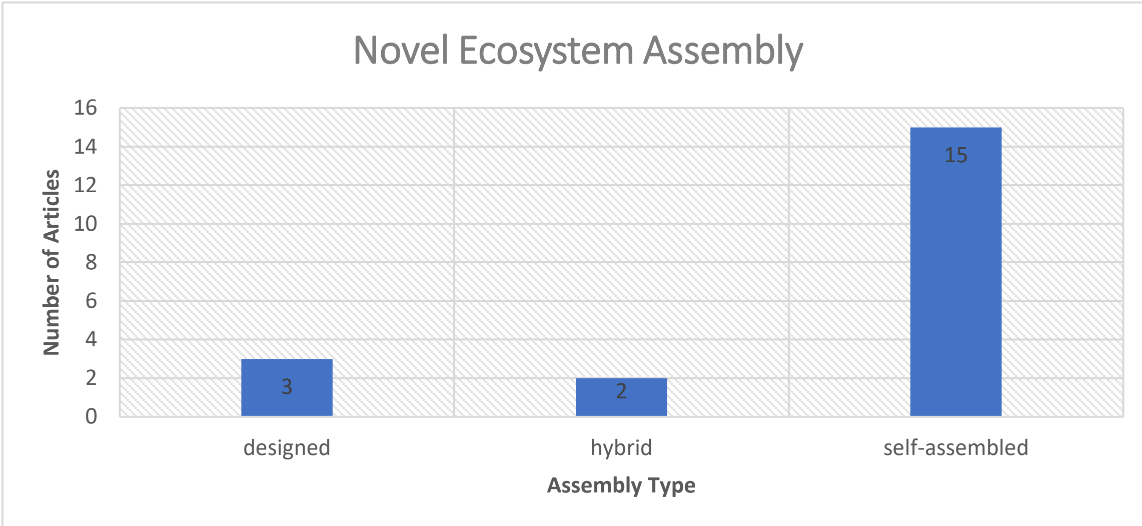

Figure 4: Chart showing the number of articles citing each assembly type.

4.1.4. Ecosystem Services Results

Ecosystems were categorized by the type of ecosystem service they primarily provided. The analysis divided the services into three categories: biodiversity, provisioning, and cultural. Biodiversity meaning the primary metric for measuring services was ecological, provisioning ecosystems were primarily useful for human consumption, and cultural ecosystems are used for other human usages such as recreation. Half of the articles cited provisioning as the primary ecosystem metric (10, 50%). Seven of the articles (35%) cited biodiversity, and three (15%) cited cultural as the main metric (Figure 5).

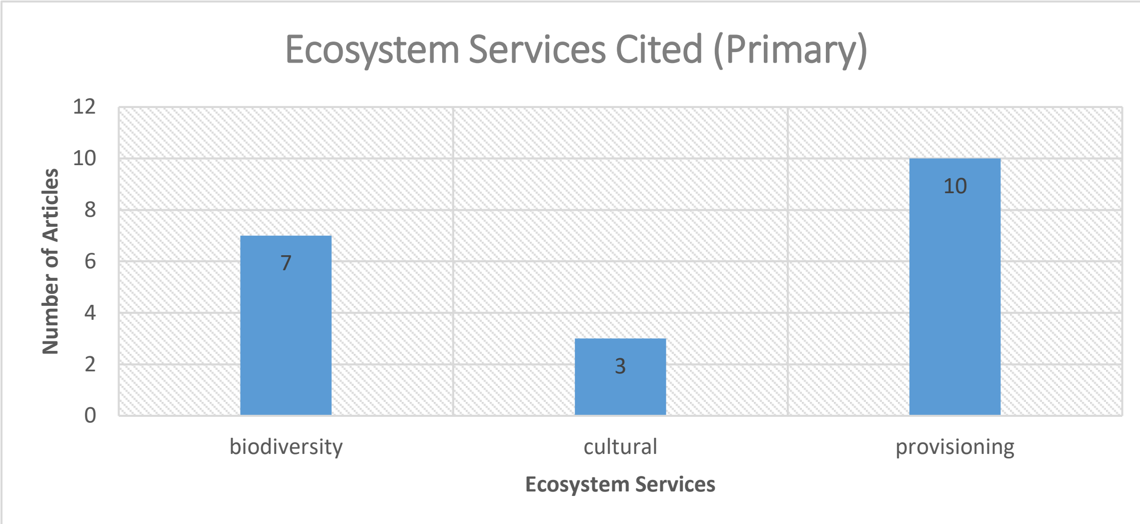

Figure 5: Number of articles citing each primary ecosystem service.

4.1.5. Management Intervention or Recommendation Results

Articles were also categorized by the management interventions or recommendations they were citing. Tolerating novelty was an intervention which neither removed nor accentuated the existing novelty of the system but allowed novelty to exist. Managing against novelty were cases which explicitly stated goals to remove said novelty. Finally, managing for novelty cases were articles including novelty in their restoration plans. This was including urban or human land use systems such as agriculture. Two of the articles (10%) were found to tolerate novelty, nine articles (45%) had managed or recommended to manage against novelty, eight (40%) recommended or managed for novelty, while one article (5%) was found to be not applicable for this section (Figure 6).

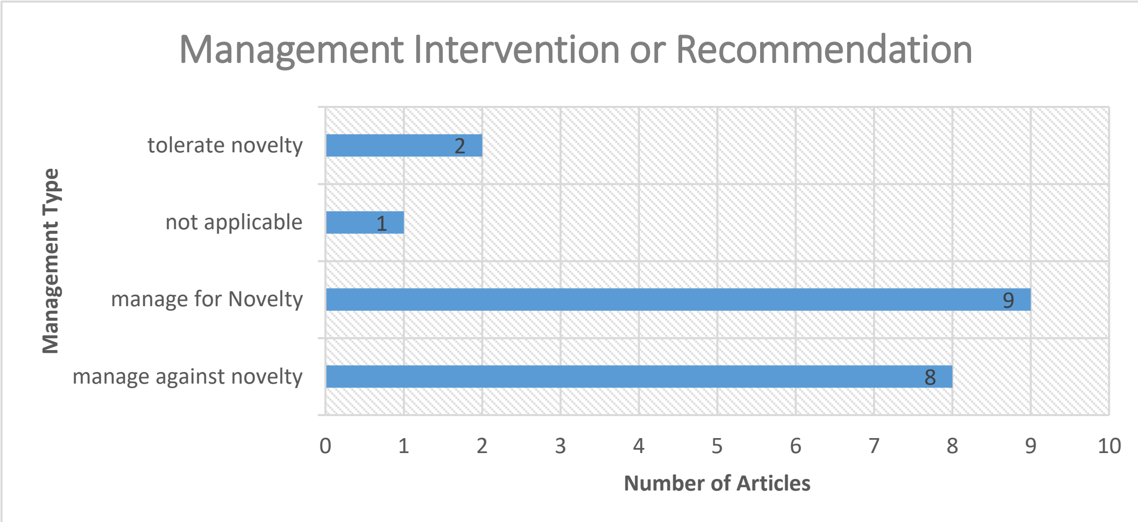

Figure 6: Number of articles citing each management recommendation or intervention.

4.1.6. Discussion: Classifying and Describing Ecosystems Restored and Studied in a Novel Ecosystem Context

Most work in the studies reviewed was done on previously modified systems, for the use of human provisioning services. Invasive species seems to be the primary threat, followed by over utilization. Most system's assemblages have been "self-assembled" as opposed to designed, even in modified systems. The number of articles advocating managing for and against novelty were approximately equal. This finding of management recommendation is interesting considering not many systems were designed. It seems researchers in this review were split down the middle on opinions if the self-assembled systems should be left or repaired. An interesting finding is of one designed system (Meadows et al. 2018) which was a case where financial gain was the primary goal for restoration, for example to increase property value, and ecological success followed. Sometimes novelty is included for aesthetic reasons, for perceived financial gain.

Within many of these novel ecosystems, the major threat was that of invasive species. This result is to be expected as ecosystems left to assemble in the presence of invasive seed banks will inevitably be dominated by the invasives. This shows the importance of connectivity and for dispersal and colonization (Menninger & Palmer 2016), even in the case of invasive species. These examples may not be the best example for how novel ecosystems can be used in restoration efforts, as invasive species by definition have a negative impact within the ecosystems they invade, as opposed to non-invasive novel species. The current research and case studies on ecosystems designed to be novel are few and far between, and therefore further cases must be studied in the future to have a better assessment of their viability.

Of the ecosystems that were designed or hybrid assemblages, one was suggesting an assisted migration of a native species in anticipation of climate change (Palmer & Larson 2014). The assisted migration involved moving species further North purposely, in anticipation that during future times of warmer temperature, these plants would be more stable in a cooler Northern climate. Climate change has substantial effects on many species, and many are already moving North unassisted as a response (Palmer & Larson 2014). That being said, the argument is that many will be unable to move on their own and therefore face a risk of extinction (Palmer & Larson 2014). Moving these species to new habitats beyond their natural range could then alleviate some of the extinction risk, by moving them to novel habitats (Palmer & Larson 2014). This form of restoration takes an interesting turn on the novel ecosystem concept, where the restorationist is not restoring the system with new species but moving a species into a new system.

Assisted migration wasn't the only reason for using novel species, but something interesting of note is that the novel species used were not necessary for the restoration projects in the sense of being needed to enhance the biological value of the ecosystem, and could be utilized for financial purposes. The vast majority of these cases were for agriculture or other human provisioning projects, but one interesting example (as mentioned above) was to promote an increase in property value (Meadows et al. 2018). With the primary aim to make their homes and properties more aesthetically appealing, certain Australian property owners sought to restore their land in a scientifically uninformed manner (Meadows et al. 2018). Most species used during this "do it yourself" approach were native species, but the property owners opted to use multiple non-native flowering species in order boost the colour and optical appeal of the area as well (Meadows et al. 2018). The end result was a duality of gardening and restoration which both benefited the property owners as the aesthetic appeal and financial value of their property increased, as well as a provision of additional habitat and corridor creation for the surrounding ecosystems (Meadows et al. 2018).

Many of these types of landowners undertake restoration efforts on their own due to a strong sense of stewardship and biodiversity conservation (Barr 2009). New forests established by landowners can have mixed outcomes for local biodiversity depending on species used and ongoing management implemented (Cooke & Lane 2015). This lack in the consistency of outcome comes from a gap between desire and knowledge and may be corrected with assistance and persuasion (Meadows et al. 2018). Although some of these “do it yourself” landowners had an aversion to governments and authority, choosing to source their information from tree planting and gardening stores (Meadows et al. 2018). Sometimes the actions of the landowners actually threatened the local environment, with aesthetic exotics spreading to neighboring areas (Meadows et al. 2018). Due to an aversion to authority, peer-mentoring may be an effective tool for the transferring of knowledge in these cases (Meadows et al. 2018). This type of case study shows promise in the field of restoration by taking advantage of property owner’s desire do their part for the local environment, while persuading them to invest money into the project through the prospect of increasing property value.

As stated earlier in this review, it is not a new phenomenon for humans to alter habitat for their own whether it be for provision or aesthetics. This type of behavior has been observed for hundreds of thousands of years (Dupouey et al. 2002). Keeping this in mind, it may be permissible to include exotic species in restoration programs so long as they have not been proven to be noxious or invasive. Therefore, identification of which underlying interactions are causing disturbance, rather than focusing on what is natural or unnatural may be the restoration option of greater importance.

4.2. Novel Ecosystems and Habitat Recovery on the SER Recovery Wheel

In order to satisfy the third objective, the articles studied were analyzed via a modified ranking system of the recovery wheel by the society for ecological restoration. The wheel contains several biotic and abiotic factors to be ranked, which were rated qualitatively on a scale of one through five. The case study projects vary in the trajectory of recovery in many of the ranked aspects shown in the wheel.

4.2.1. Biophysical Parameter Results from the Recovery Wheel

The biophysical parameters of the studies were measured in three distinct categories: water chemo-physical, substrate chemical, and substrate physical. The main outcome from exploring all three of these factors together is to view one commonality between them, which is a lack of results. Water chemo-physical had 11 articles (55%) with no information, substrate physical also had 11 (55%), while substrate physical had 10 articles (50%) with no information (Figures 7-9). Of the articles that provided this information the mode was rank four.

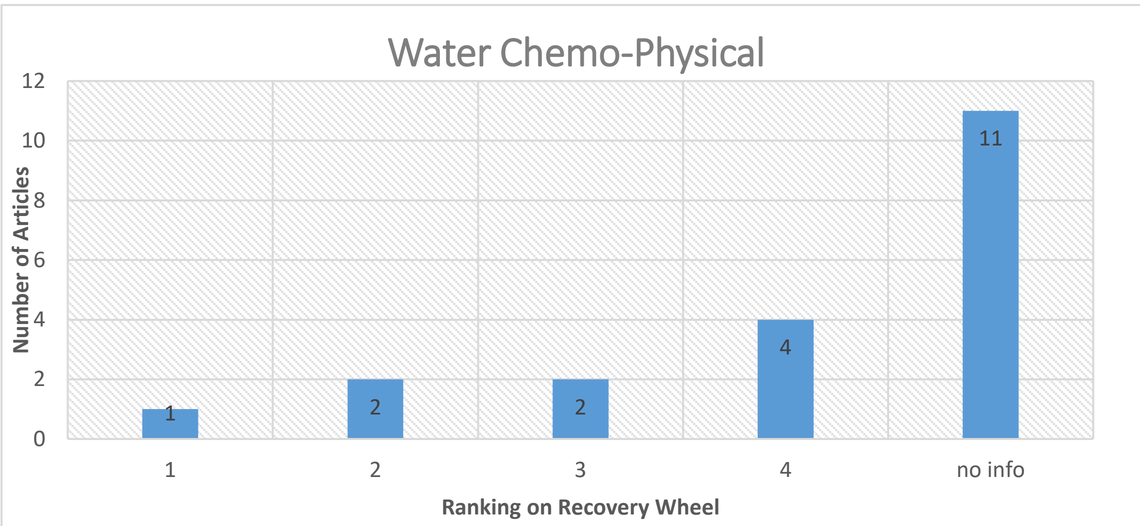

Figure 7: Chart showing the number of articles of each ranking in the parameter of water chemo-physical.

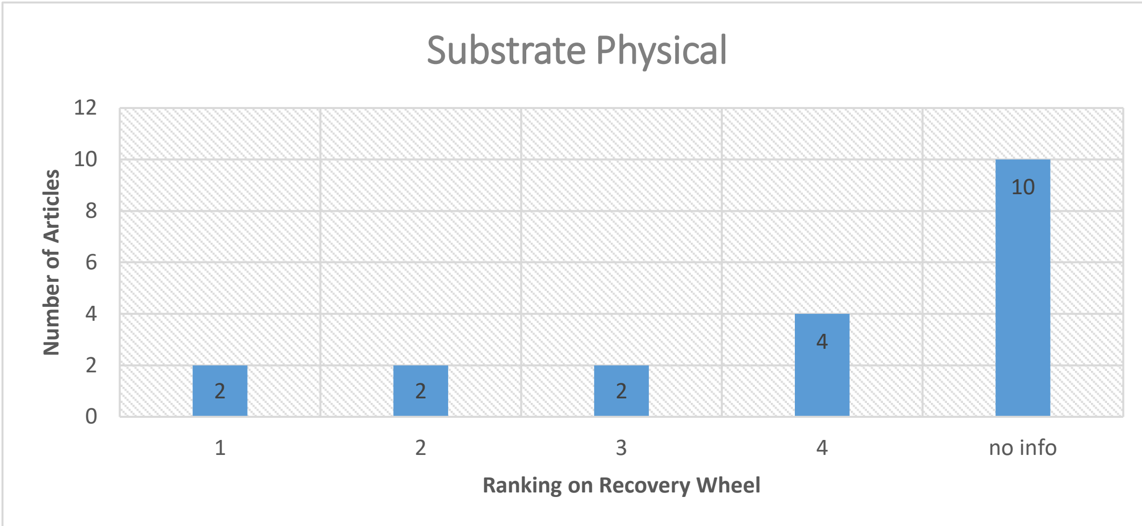

Figure 8: Chart showing the number of articles of each ranking in the parameter of substrate chemical.

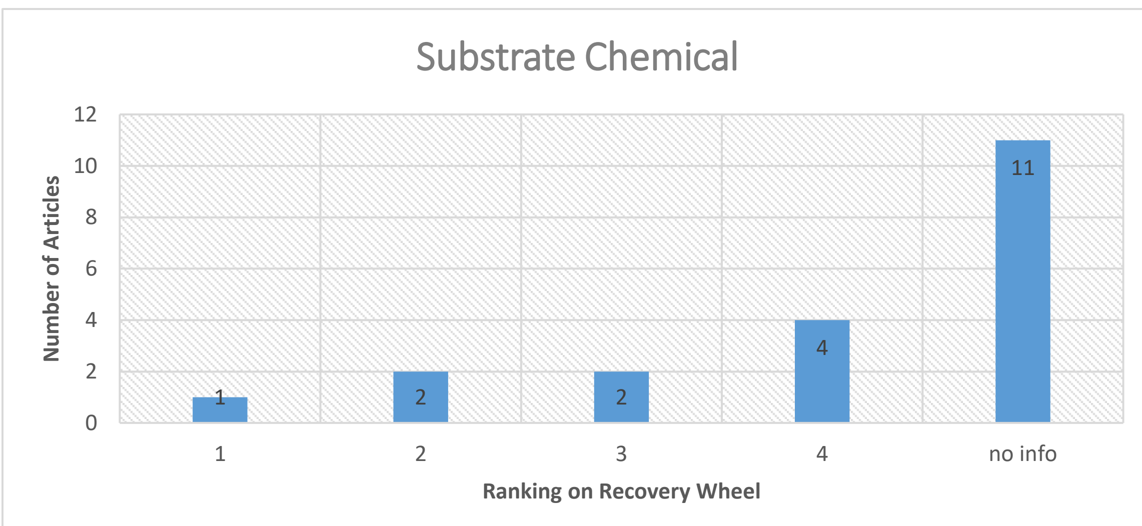

Figure 9: Chart showing the number of articles of each ranking in the parameter of substrate physical.

4.2.2. Landscape Connectivity Results from the Recovery Wheel

Several measures of ecological connectivity were evaluated including landscape flows, gene flows, habitat and interactions, resilience/recruitment, and habitat links. Due to similar outcomes, productivity/cycling will be discussed in this section as well. These different parameters allowed for scrutiny of the projects to gain a better understanding of what attention was placed on the role of the novel ecosystems in the wider environment as well as the relevance of genetic material being managed. Lack of information was again a common attribute of this section, with landscape flows, gene flows, habitat interactions, and habitat links all having seven articles (35%) with no information (Figure 10). Resilience/recruitment had six articles (30%) with no information and productivity/cycling having eight articles (40%) without any information (Figure 10). Of the articles that provided information on ranking on the recovery wheel, the modes were rank three for the following: landscape flows, gene flows, productivity/cycling, resilience/recruitment, and habitat links. Habitat and interactions was bimodal at rank three and four.

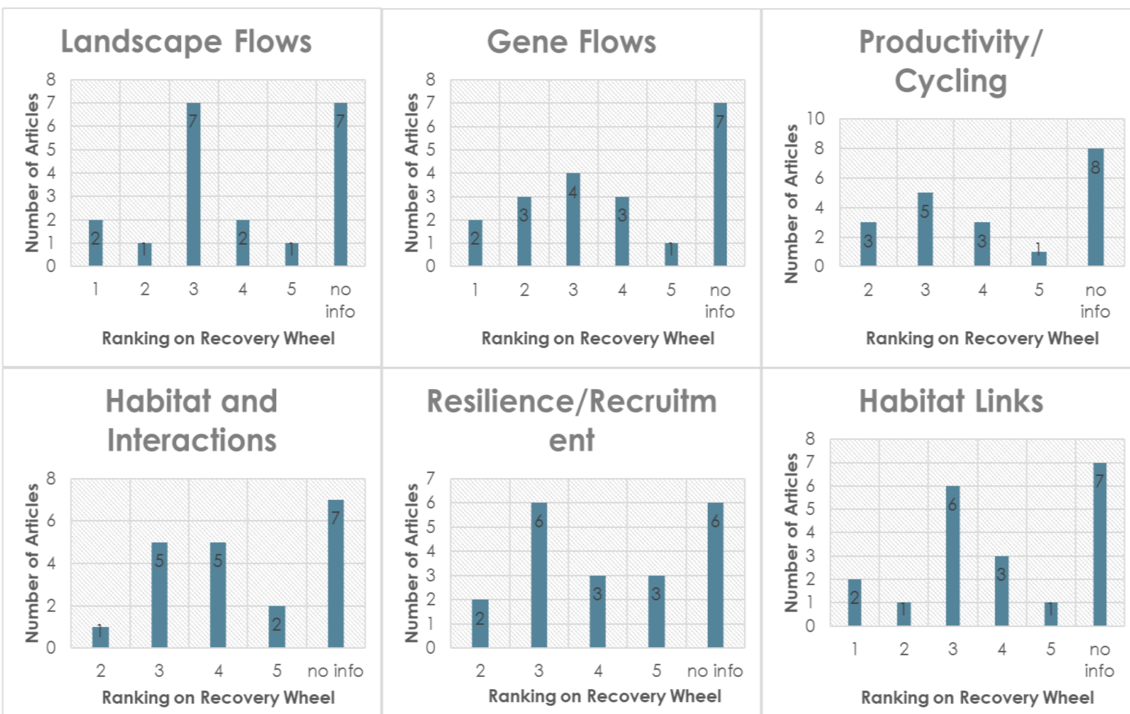

Figure 10: Charts showing the various landscape context results from each article on the recovery wheel.

4.2.3. Habitat Degradation from Threats results from the Recovery Wheel

The habitat threats of invasive species and over-utilization were also ranked as per the criteria of the recovery wheel. These two characteristics were already cited as the two primary threats in objective two, thus it was pertinent to see how the scoring ranked on the recovery wheel. Threats are well accounted for and spoken of in most of the case studies, and rankings tended to be quite low (the mode being rank one). Eight of the articles (40%) ranked as a one in overutilization, and 13 (65%) ranked as a one in invasive species (Figures 11-12). It is unsurprising how low these scores were, as invasive species was the primary threat cited by most of the articles with overutilization coming in second.

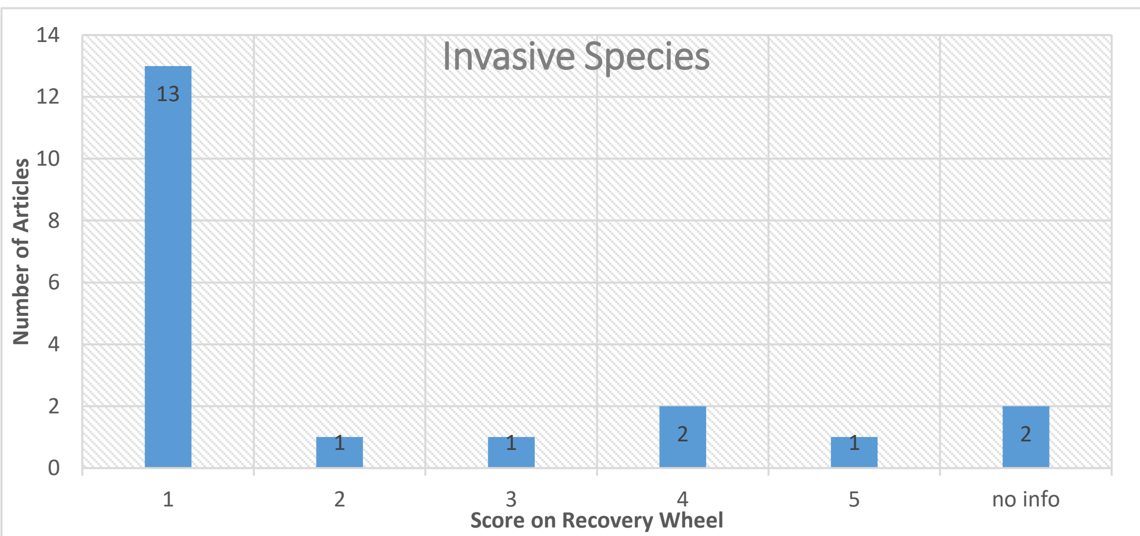

Figure 11: Chart showing the ranking of the invasive species parameter on the recovery wheel.

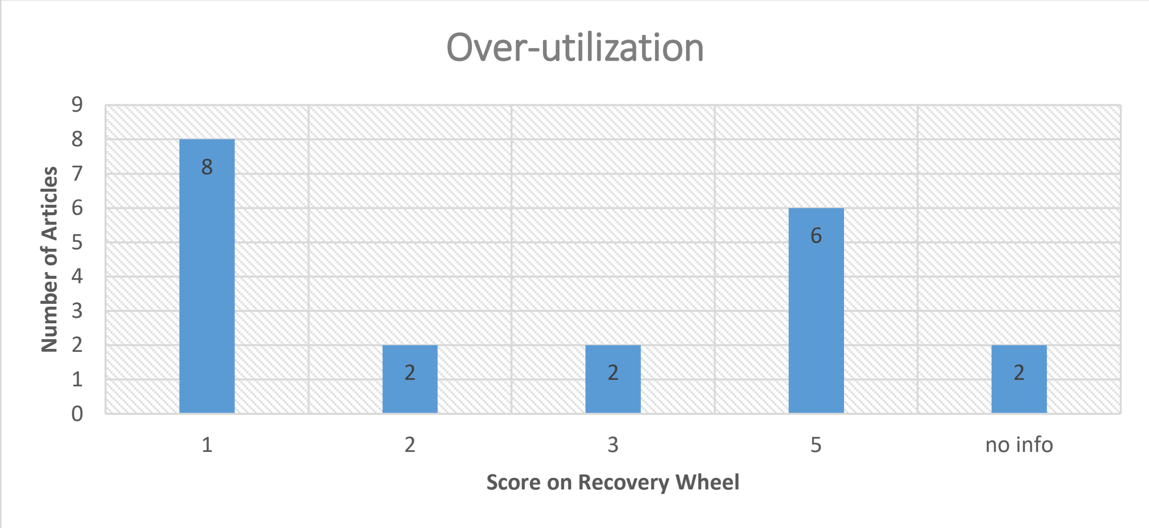

Figure 12: Chart showing the ranking of the over-utilization parameter on the recovery wheel.

4.2.4. Discussion: Novel Ecosystems and Habitat Recovery on the SER Recovery Wheel

The analysis of the biophysical elements of the case studies, informed by the attributes from the SER recovery wheel, show very dispersed results in terms of ecosystem trajectory for recovery over the various categories, but one commonality across all systems is the lack of information when it comes to chemical or physical data. Reporting on the surrounding systems is also lacking. Aggregate data seems to be exclusively biological, which leaves a huge gap within the research. When looking at the physical conditions of the case studies, only half of all the studies showed info, and when they did offer some information it was mostly lacking or difficult to tease out.

Information on habitat linkages, gene flows, landscape flows, and factors from a landscape perspective were greatly lacking as well. Only approximately half the articles carried this information, and again any information they did have was not very clear and fleshed out. This is unfortunate since a great deal of the success of a restoration project can be placed on the importance of the surrounding areas, whether there is opportunity for connectivity and migration or surrounding seed banks for invasive species.

When undertaking restoration plans, it is vital to consider these habitat connections, as restoration may be severely constricted when being removed from the surrounding gene pools (Menninger & Palmer 2016). These factors from a landscape perspective are also important for managing critical resource supplies for food webs which can then disrupt patters of community structure (Dreyer & Gratton 2013). Unless we want our restoration projects to require constant maintenance, we need to start making these types of observations mandatory as part of a restoration initiative.

Removing invasive species and returning the historical disturbance regime is a common control strategy (Firn et al. 2013). The model is based upon traditional ideas of succession, and assuming the continuum progresses towards a final state for the plant community (Firn et al. 2013). This idea assumes the continuum can be reversed and sent towards the historical state, however our understanding of this is that it is not always true (Perring et al. 2013). The issue is that the original community is not always restored, even when the disturbance is removed and instead, we end up with a novel assemblage of species (Booth et al. 2003). The novel ecosystem approach to managing invasive species has not been tested much, and applying this approach has potential to result in efficient and cost-reducing management techniques (Seastedt et al. 2008).

4.3. Defining Success in Novel Ecosystems Restoration Projects

A frequent question in ecological restoration science is the definition of success of a restoration project. Measures of success in each project were derived through a content analysis to identify whether success was defined using a habitat or ecosystem services perspective, though financial objectives or by meeting cultural or social success criteria. This analysis was undertaken to satisfy the fourth objective.

4.3.1. Categorizing Success

The primary metric for success in 18 of the articles (90%) was ecological, while only one article (5%) cited financial and one (5%) cited cultural (Figure 13). These metrics were decided qualitatively through analysis of the language used, and the cited purpose of the conducted research. Often the language used was poorly defined or ambiguous. The authors of the articles often wrote in a matter which assumed the reader knew that the most important goal of the project was ecological.

Figure 13: Pie chart showing the number of articles citing each of the three metrics of success.

4.3.2. Discussion: Defining Success in Novel Ecosystem Restoration Projects

The identification of ecological goals as a primary measure of success likely reflects the sampling strategy. The science-based nature of the academic search engines used in this study may have resulted in a sample that was biased towards ecological method and values. Often, when conducting an ecological restoration program there is one goal in mind, such as creating habitat for a specific endangered species, or removal of one problematic invasive species. A wider review of databases that also encompassed social science literatures may have captured studies that identified social or cultural goals defined as primary measures of success.

However, ecological goals were also associated with other types of goals, with projects seemingly targeting multiple agendas. As stated earlier, one interesting case of restoration occurred when property owners took it upon themselves to restore habitat strictly for aesthetic purposes (Meadows et al. 2018), while increasing ecological value as a side effect. This example is an important way one goal can serve two purposes.

Financial gain is a great motivator for investment in restoration activities, and it would be interesting to see more projects in this fashion come to fruition in the future. In the majority of cases it takes funds to restore habitat, and for an individual to know they will gain equity can be a good incentive.

Where non-native species were used as flowering or gardening plants, there may be an opportunity for education if alternatives were presented to the population before-hand. Mostly, novel plants were chosen because the restoration was done by the general populous who were not scientifically informed. These amateur restorationists, may be easily convinced into switching to a native species if the information is readily available.

Projects that focused on agricultural environments were another sector that commonly defined several aspects of success. One study used strategically applied grazing to manage invasive plant species in novel grasslands (Firn et al. 2013). They found that the optimal strategy for controlling invasive species and moving novel ecosystems to a more desirable state (in systems damaged by grazing) was not to remove the disturbance but to manipulate the timing, intensity, and spatial distribution of the grazing (Firn et al. 2013). In this restoration challenge, the system moves towards a desirable state, while maintaining profits from the cattle produced.

A fascinating way to consider this case, is as an example of a designed keystone species. As a reminder, keystone species are responsible for a great impact on ecosystem functionality by holding up interaction networks (Lins et al 2017). By introducing and managing an introduced keystone species (in this case, the cattle), the ecosystem was able to be pushed towards a more desirable state and invasive species are removed. This is also a far more cost-effective measure than manual removal of the invasive species.

Economic decision makers often overlook the dependency between ecology and economy, when economic activity is critically dependent on natural resources and ecosystems (Patterson et al. 2011). The benefits provided by natural resources, and therefore their protection and restoration does not come with a market value (Patterson et al. 2011). Because of this lack of a price tag, it is beneficial to look into examples such as this which are cost effective and be seen to enhance the environment in a way that supports robust ecological function and shows enhanced market value on an accountant's balance sheet.

Chapter 5.

Conclusion

Restoring ecosystems, and therefore the complex relationships between organisms and their environment, as well as the intricate food webs, nutrient cycles, and energy flows are crucial for bringing back function and resilience to the nature we cohabitate with (Macdonald 2016). These ecosystems assemble through a variety of processes, with connectivity and landscape features being considered vital for the dispersal and colonization of the areas from neighboring genetic sources (Menninger & Palmer 2016). Unfortunately, our ecosystems have gradually been disturbed or destroyed due to anthropological impacts throughout many centuries, and undertaking restoration to fix these issues is essential to return ecosystem function, as well as the ecosystem services from which our society derives great benefit.

As invasive species, climate change, and other large-scale changes occur across the planet, the appearance of novel ecosystems is becoming increasingly common as the earth's ecosystem assemblages attempt a shift towards a new stable state (Hobbs 2006). These systems, through human influence, now differ greatly from their historical counterparts and express many novel qualities (Hobbs 2013). As the idea of the "novel ecosystem" increases in popularity, debate amongst the scientific community has grown around the potential usefulness and application of this concept in the field of ecological restoration (Miller & Bestelmeyer 2016).

The permanency of these changes, due to the unequaled influences of humans in recent history (Clement & Standish 2018), has led us into an era of the "Anthropocene epoch" (Steffen et al. 2007). In this era of human history, three quarters of the planet are dominated by anthropogenic biomes, and roughly one half of all the world's land mass is now considered to be novel ecosystems (Carter 2018). These novel ecosystems may bear little to no resemblance to the ecosystems of the previous bygone era (Hobbs et al. 2013).

Although these novel ecosystems can be considered a contemporary topic, there presence can be seen throughout antiquity, even in the early academic literature (Barrington 1769). Natural and human-directed changes and alterations have had successional changes felt through the centuries (Dupouey et al. 2002), and these ancient interactions have had influence on ecosystem function and landscapes of the present (Rhemtulla & Mladenoff 2007). Humans and the ecosystems we interact with are always in a state of fluctuation, and it has been like this through antiquity.

With our planet in a state of frequent flux, and novel ecosystems emerging as the new normal, restoration goals are currently in consideration and amendment by multiple experts within the field (Woodworth 2013). These new possibilities for alternate restoration goals are currently of great importance, especially considering how novel ecosystems may have strayed from their past equivalents so significantly that reaching a historically perfect state may no longer be feasible (Miller & Bestelmeyer 2016).

Due to the permanency of the introduced exotic species, and the changing climate, it may be necessary to re-evaluate the traditional restoration goals of replicating a reference ecosystem. Another possibility which must be considered is the acceptance of novelty in our ecosystems, and a focus on restoring ecosystem function rather than form. Once understood, many underlying ecosystem frameworks such as connectivity, trophic cascades, and keystone species, can be manipulated in order to drive the ecosystem towards a more desirable state. These methods of more passive restoration could be considered a far more cost effective alternative, and sometimes could be completely free (Holl & Aide 2011).

In view of the potential for restoration goals to evolve towards adopting novel methodologies, and the prospect of a novel ecosystem state being acceptable of restoration end goals. I aimed to explore these ideas and concepts, and how they are being approached and considered in the current academic literature. To explore the way restoration projects were being undertaken in novel ecosystems, I devised a method of evaluation by creating a matrix to analyze novel ecosystem restoration projects published in peer reviewed literature. This matrix was adapted from a method used by Evers et al. (2018) to undertake a systematic review of ecosystem services in novel ecosystems and the method used the Society of Ecological Restoration to evaluate ecological recovery. With this method I described what type of novel ecosystems were assessed within the sampled empirical literature and evaluated them based on the characteristics afforded by the SER recovery wheel. Finally, from the language used by the articles, criteria for success was tabulated to discover how researchers are determining the values of a successful project.

My first objective of creating a matrix of evaluation was satisfied through my methodology, where I combined and modified existing tables from the literature to complete my literature analysis. This required flexibility and refinement to account for incomplete information or varied presentation of information from the empirical studies.

The second objective was focused on better understanding the nature of the environments that were the focus of the restoration activities in the sampled articles. Most of the research was completed within previously modified systems, which had been modified for human use. Self-assembly was the primary form of ecosystem formation, which was disappointing in the sense that a designed system would be the true test for the purposeful restoration by means of a novel ecosystem-oriented goal. This means of self-assembly without intervention may have contributed to the predominance of invasive species as a primary threat in the literature. It is unfortunate that as systems are left to assemble in the presence of seed banks with aggressive invasive species, they will inevitably be dominated by invasives.

The matrix was also used to evaluate the biophysical and other ecological parameters that inform progress in ecological restoration projects. These results to inform objective three highlighted gaps in the way data was measured and communicated in these studies. The categories describing chemical and physical characteristics of the substrate and water were overwhelmingly under reported. Further, the categories describing habitat linkages, connectivity, and any information on surrounding landscapes were also lacking, this was disconcerting as much of a project’s trajectory for recovery is dependent on a greater landscape context.

The ways success is defined in these novel ecosystem projects can help better understand how restoration are goals are operationalized. As discussed, success in restoration projects have often been considered when a historical ecological state has been restored (Taylor 2013). The challenges presented by restoration of novel ecosystems are how success is defined and what it means in terms of structure and function of these systems. Success in these studies was predominantly categorized as ecological success. This overwhelming result should have been expected considering the search engines used were all ecological in nature. Furthermore, restoration ecologists often restore environments with one single goal in mind, whether it being protecting or creating habitat for a key species or removing a particular disturbance. This methodology of approaching restoration would explain the tremendous inclination towards ecological success as the prime driving force.

5.1. Implications for Restoration

The field of restoration has much to anticipate as novel ecosystems spread and become the new norm. Research on novel ecosystems is new and therefore not as robust as many other time-tested concepts. However, there is much promise for their use as an end goal from the many anecdotal cases which have arisen and used novel ecosystem concepts with success (Firn et al. 2013, Meadows et al. 2018, Palmer & Larson 2014). Evidence for use of novel ecosystems in restoration can be seen in several case studies, including those sampled for this research. Review of this work allows for evaluation of how these projects have been approached as well as presenting opportunity for critique of the research methods used to evaluate the restoration outcomes. By seeking a greater intersect with the ecosystem principles of restoration literature with the new challenges to manage change and function in novel ecosystems it is possible to better align the outcomes of the projects alongside more traditional restoration goals.

One of these examples can be seen in a recommendation for an assisted migration of a tree species further North to cooler temperatures in anticipation of climate change (Palmer & Larson 2014). If proven to be successful, this type of restoration, through the addition of an introduced keystone species, may show promise to alleviate extinction risk of species which would otherwise be affected by climate change (Palmer & Larson 2014). Considering our climate is warming, and these changes are permanent, it is important to look into creative solutions such as this, to move sensitive species which are unable to migrate on their own (Palmer & Larson 2014).

Other case studies of note include an example where landowners attempted amateur restoration in an attempt to increase property value (Meadows et al. 2018). Implications for independent property owners who show a sense of stewardship to undertake restoration efforts on their own could greatly improve connectivity and habitat linkages. This method for restoring small plot acreages could be made to be more restoration centric (as opposed to gardening) through distributing of information and peer-mentoring systems (Meadows et al. 2018).

Agriculture and other areas where humans share land use with the natural environment may benefit from examining the possibility of novel ecosystem concepts. Just as the example of strategic grazing being used to control invasive species (Firn et al. 2013), other imaginative solutions could benefit the revival of ecosystem services without being detrimental to society's economic demands. If private industry can be looked upon as ecological partners, as opposed to destroyers perhaps innovation can occur whereby both can exist simultaneously with mutual benefit.

This example of agricultural manipulation for restoration can be considered a manipulation of a human-introduced keystone species. This is one example of many possible solutions to restoration issues which can rely on the underlying ecosystem frameworks and concepts. By understanding how ecosystems work, we can find more of these methods of creating drastic results through minimal intrusions. Creative solutions such as this human-manipulated keystone species will be crucial to managing a greater range of novel ecosystems in the future.

Not many of the examples studied in this paper were designed explicitly to be novel. The two that were designed in this manner, experienced some levels of success. It will be important for future restoration projects to consider designing such systems, to ensure that self-assembled systems which may be assembled by destructive neighboring invasive species do not continue to dominate the novel ecosystem research.

5.2. Recommendations for Future Research

Although the implications for restoration are promising; promise is not enough to bank the success of our future restoration projects upon. Further research upon many of the lacking areas is necessary to fill specific gaps and build certainty in this new and emergent field. It would be of interested to see what other ways financial gain could become a primary motivator, in order to prompt restoration without being considered a burden on funds. This may create opportunities for industry to take initiative and restore systems for their own benefit, and increase habitat, biodiversity, and restore ecosystem services as a side effect.

This study highlights that there are few peer reviewed articles that explicitly discuss empirical approaches to restoration in novel ecosystems. Despite the growth in literature debating the contribution of novel ecosystems in the context of restoration there is limited application of what the goals of such projects may meaningfully be and how they may be undertaken in practice. The review of the data in this research has revealed that those projects that are contributing to our understanding reveal very limited insights into fundamental biological and physical variables. Data is severely lacking in any chemical or physical categories of the water and substrate, and information such as habitat linkages or potential for gene flow in a landscape context is not there. While this information is extremely important for the creation of a functional ecosystem that can be self-sustaining, as discussed above; research on systems designed to be novel is also lacking, and it would be of interest to see if many of the problems with invasive species could be mitigated by including this as an approach.

5.3. Concluding Remarks

As the world continues to progress towards a warmer climate and further spread of species occurs (Hobbs et al. 2006, 2013), our ecosystems will continue to trend towards increasing changes which are accompanied by altered functions and habitat interactions (Hobbs et al. 2014). These changes are here to stay and may bear little resemblance to the systems that once were (Hobbs et al. 2013). There is much promise in the field of restoration to adapt to these changes and continue to produce creative and innovative solutions to these problems, while persisting to consider the adjusting and challenging of the traditional end goals of historical accuracy in our ecosystem. By harnessing the potential of the core ecosystem frameworks of assemblage, trophic cascades, keystone species and many others, it is possible to push ecosystems towards a state of passive restoration. Changing our views on the traditional goals and outcomes of ecological restoration may therefore be necessary, to focus on the restoration of the underlying functions, rather than focusing on the form of the reference ecosystem. Due to the newness of this burgeoning field, much more research is to be done if we are to fill in the gaps and continue to test novel ecosystems as a viable restoration approach.

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Appendix A.

Complete Matrix as Reviewed from Database Literature

Table A1: Completed table of ecosystem descriptive variables.

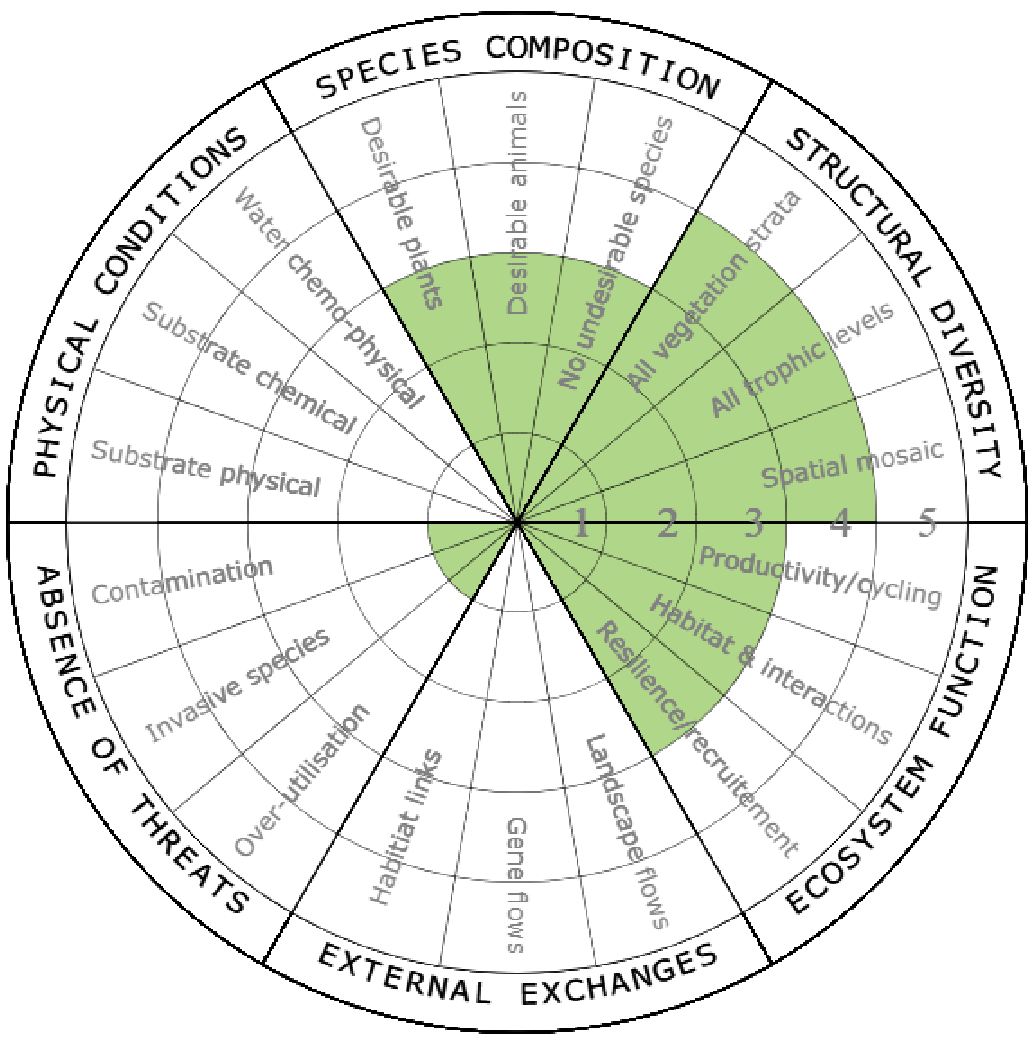
Article	Article	Biome (Secondary)	Methodology	Baseline	Primary Threat	Secondary Threat	NE assembly	Management recommendation	Ecosystem metric (Primary)	Ecosystem Metric (Secondary)	Primary Language	Secondary Language
Australia	grassland		quantitative	modified	invasive spp		designed	manage for Novelty	provisioning		ecological	none
Australia	forest		qualitative	abandoned	invasive spp	soil compaction, erosion	hybrid	manage against novelty	biodiversity	cultural	financial	ecological
Hawaii	forest		qualitative	modified	invasive spp		self-assembled	manage for novelty	biodiversity	regulating	ecological	none
Western Cape Province South Africa	forest		quantitative	modified	invasive spp		self-assembled	tolerate novelty	biodiversity		ecological	none
China	aquatic		qualitative	modified	over-utilization		self-assembled	tolerate novelty	provisioning	cultural	ecological	none
Mona Island, Puerto Rico	forest		quantitative	modified	invasive spp		self-assembled	manage against novelty	biodiversity	provisioning	ecological	none
Darling Basin, Australia	grassland	forest	quantitative	modified	over-utilization	invasive spp	hybrid	not applicable	provisioning		ecological	none
Madrid, Spain	urban		quantitative	modified	over-utilization		self-assembled	manage for novelty	provisioning		ecological	none
Lincoln, Nebraska	forest		quantitative	modified	invasive spp		self-assembled	manage against novelty	cultural		ecological	none
Boulder County, Colorado	grassland		quantitative	modified	invasive spp		self-assembled	manage against novelty	cultural		ecological	none
Arizona	aquatic		quantitative	modified	invasive spp	over-utilization	self-assembled	manage against novelty	cultural		ecological	none
Targhee National Forest, Wyoming	forest		qualitative	modified	climate change		designed	manage for novelty	biodiversity		ecological	none
Multiple locations	aquatic		qualitative	modified	invasive spp		self-assembled	manage against novelty	provisioning		ecological	none
Madrid, Spain	grassland		quantitative	modified	over-utilization		self-assembled	manage for novelty	provisioning		ecological	none
Chesapeake Bay	aquatic		qualitative	modified	over-utilization		self-assembled	manage for novelty	provisioning	cultural	cultural	none
Northeastern Alberta	forest		quantitative	modified	over-utilization		designed	manage for novelty	provisioning	biodiversity	ecological	none
Lake Naivasha, Kenya	aquatic		quantitative	modified	invasive spp		self-assembled	manage against novelty	provisioning	biodiversity	ecological	financial
Willamette Valley, Oregon	forest		quantitative	modified	over-utilization		self-assembled	manage for novelty	provisioning		ecological	financial
Santa Cruz Island, California	forest		qualitative	modified	climate change		self-assembled	manage for novelty	biodiversity		ecological	none
Mandan, North Dakota	grassland		quantitative	modified	invasive spp		self-assembled	manage against novelty	biodiversity		ecological	financial

Table A2: Completed table of recovery wheel variables.

Desirable Plants	Desirable Animals	No Undesirable Species	All Vegetation Strata	All Trophic Levels	Spacial Mosaic	Productivity/Cycling	Habitat and Interactions	Resilience/Recruitment	Habitat Links	Gene Flows	Landscape Flows	Contamination	Invasive species	Overutilization	Water Chemo-Physical	Substrate Chemical	Substrate Physical
3	3	3	4	4	4	3	3	3	no info	no info	no info	1	1	1	no info	no info	no info
3	5	1	4	5	5	3	4	4	4	4	4	5	1	5	no info	no info	1
3	no info	1	4	3	3	no info	no info	no info	no info	no info	no info	5	1	5	no info	no info	no info
3	5	3	4	4	4	no info	4	5	no info	no info	no info	5	1	5	no info	no info	no info
no info	3	1	no info	3	3	no info	no info	no info	1	1	1	no info	1	1	no info	no info	no info
4	no info	1	3	3	3	no info	no info	3	3	3	3	no info	1	5	no info	no info	no info
1	2	1	1	1	1	no info	no info	no info	no info	no info	no info	5	1	1	no info	no info	no info
4	4	4	4	4	4	3	3	4	4	4	3	5	1	1	4	4	4
4	4	1	4	4	4	3	3	3	3	3	3	5	2	5	3	3	3
1	1	1	2	1	1	2	2	2	2	2	2	5	1	5	2	2	2
3	3	3	5	5	5	4	4	3	3	3	3	5	1	1	no info	no info	no info
3	3	3	3	3	3	no info	no info	no info	3	2	3	no info	no info	no info	no info	no info	no info
no info	2	no info	no info	no info	no info	no info	no info	no info	no info	no info	no info	no info	1	1	no info	no info	no info
2	no info	5	2	2	2	2	5	5	5	5	5	5	5	2	1	1	1
4	4	2	4	4	4	4	4	4	4	4	4	5	4	1	2	2	2
no info	no info	no info	3	3	3	5	5	5	no info	no info	no info	no info	no info	no info	4	4	4
2	2	1	3	3	3	2	3	3	3	3	3	2	1	2	3	3	3
4	4	4	4	4	4	4	4	2	3	2	3	5	4	3	4	4	4
3	3	3	3	3	3	no info	no info	no info	1	1	1	5	3	3	no info	no info	no info
1	1	1	2	2	2	3	3	3	no info	no info	no info	5	1	1	4	4	4

Appendix B.

Recovery Wheels



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 1: Australia

Figure B1: Recovery Wheel of Article 1.

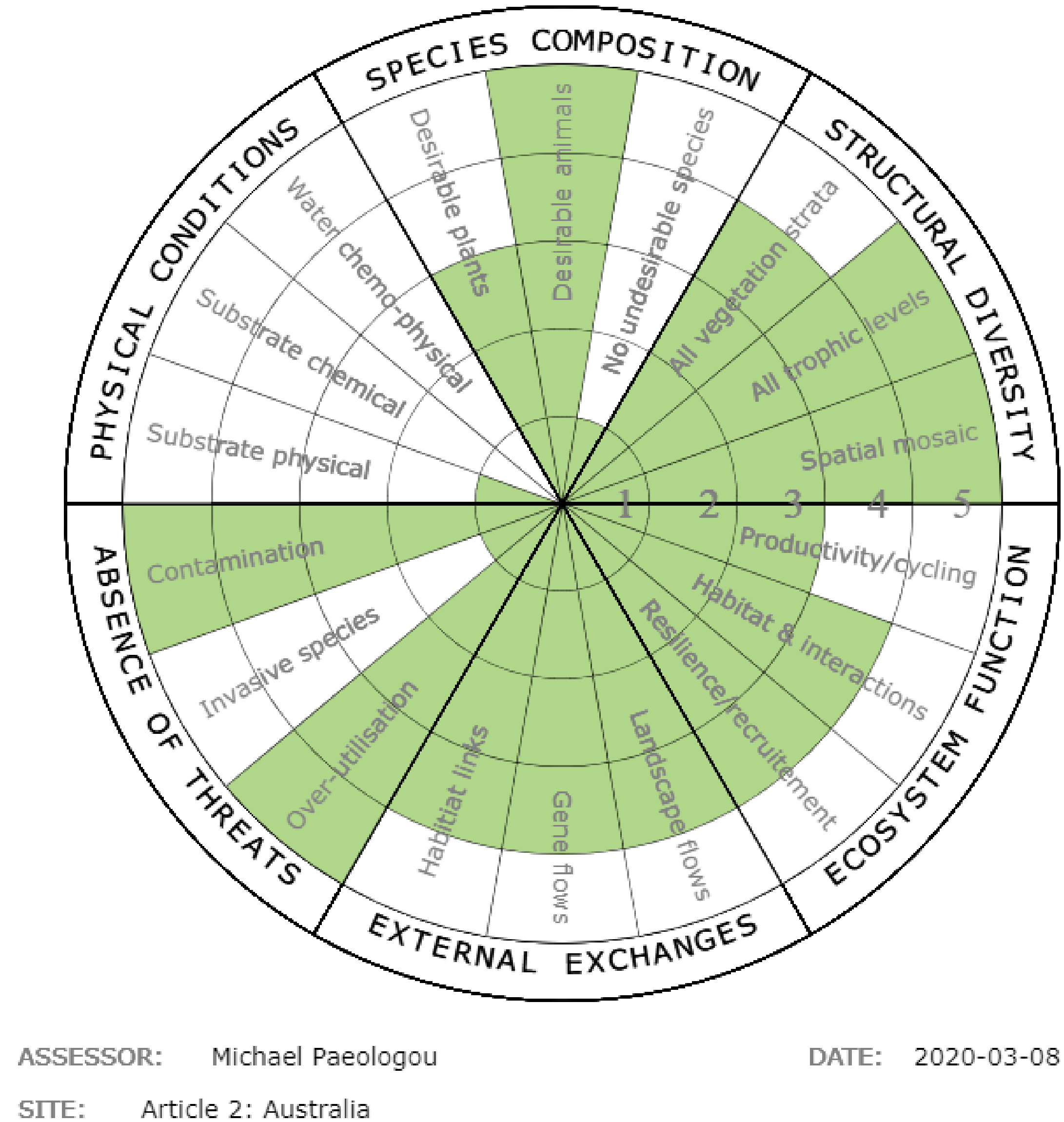
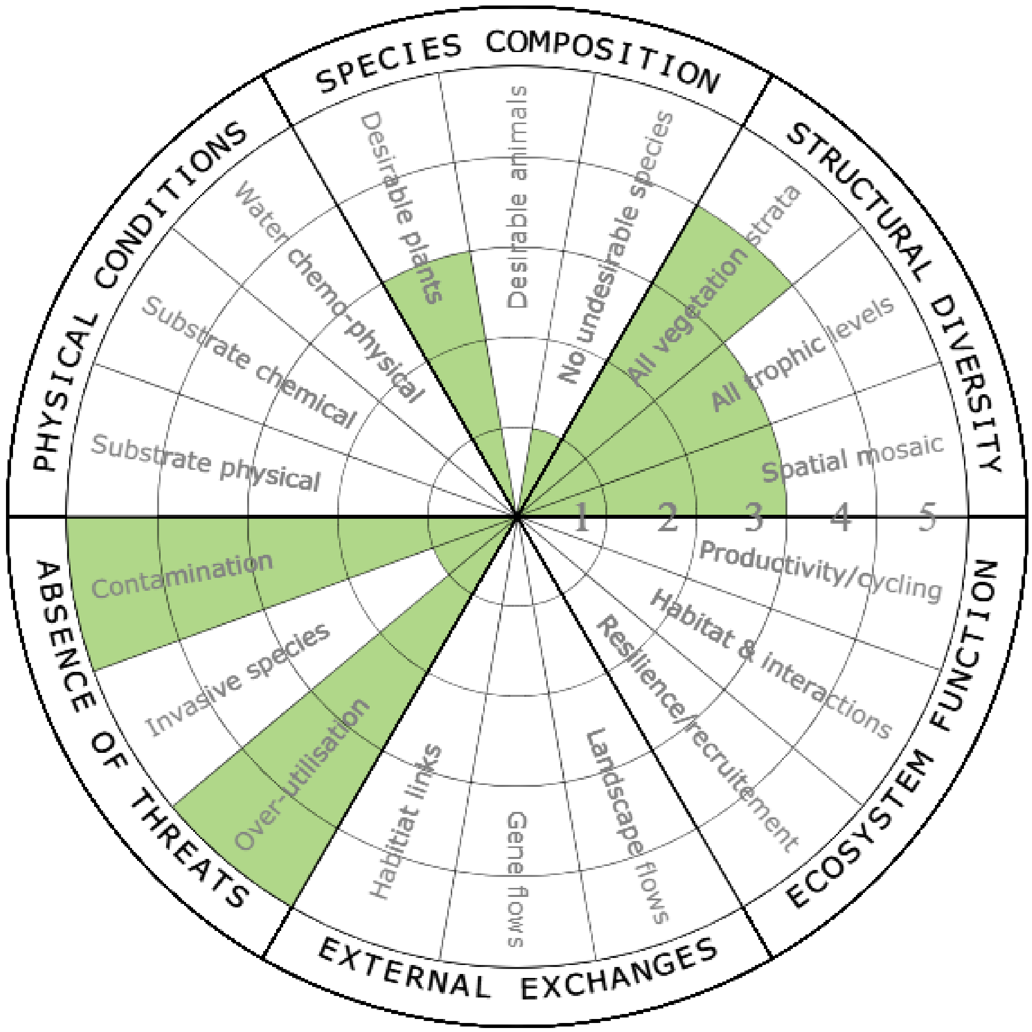


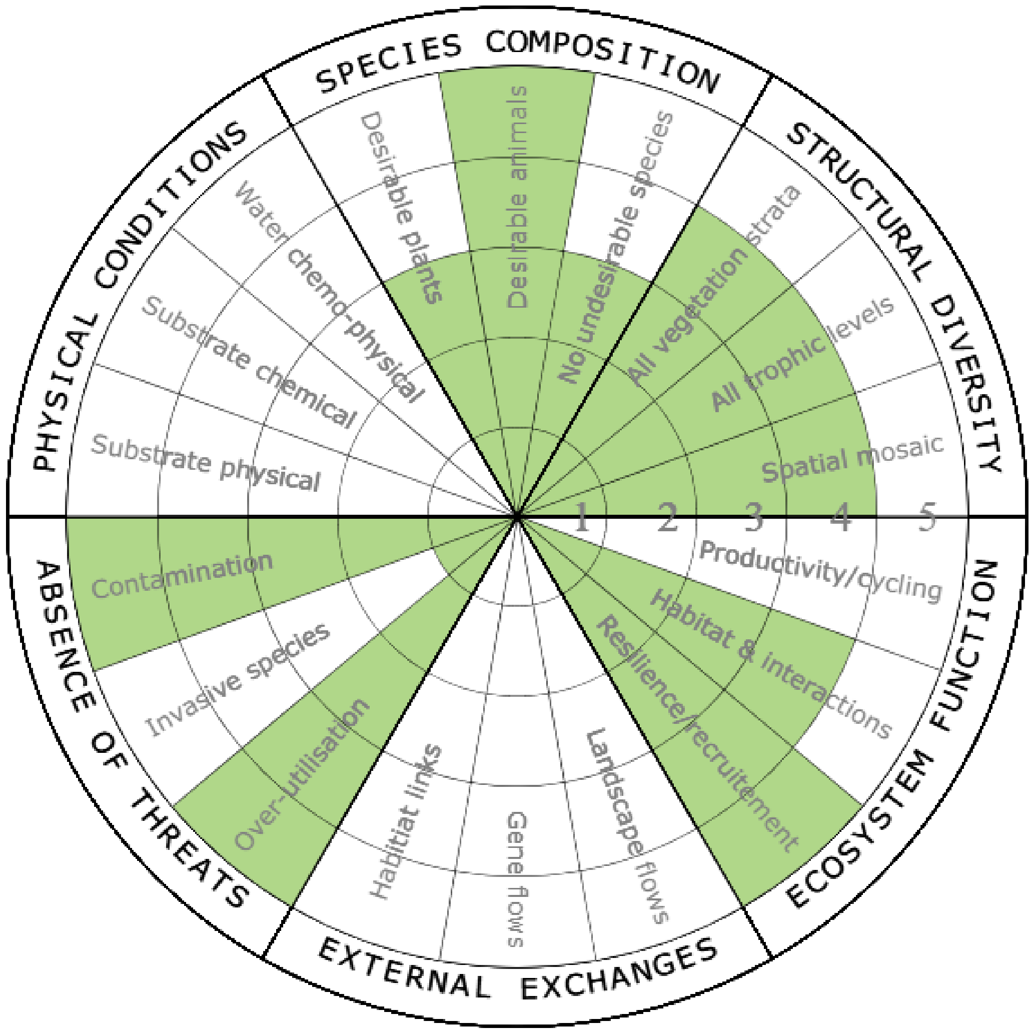
Figure B2: Recovery Wheel of Article 2.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 3: Hawaii

Figure B3: Recovery Wheel of Article 3.



ASSESSOR: Michael Paeologou DATE: 2020-03-08

SITE: Article 4: Western Cape Province South Africa

Figure B4: Recovery Wheel of Article 4.

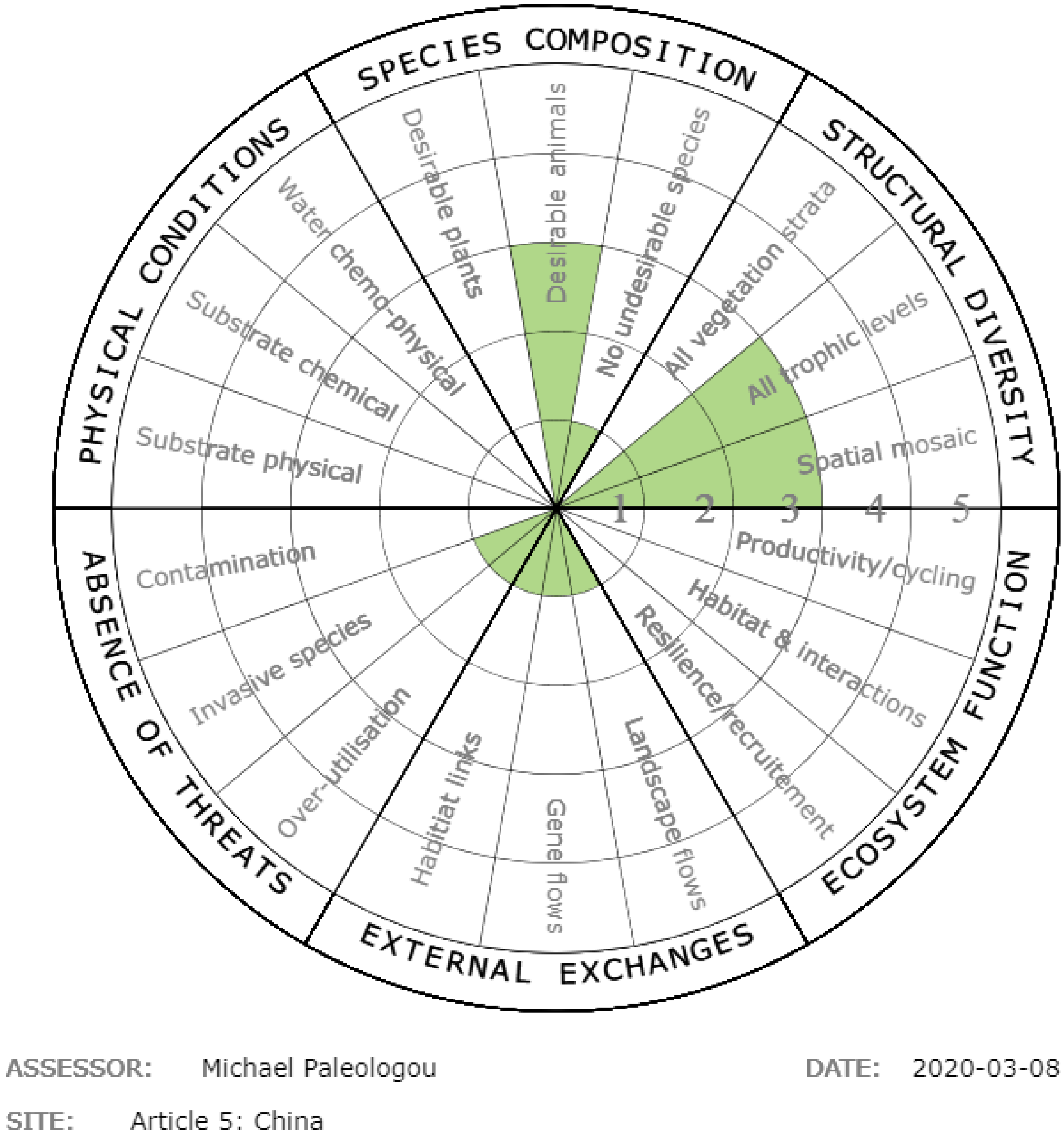
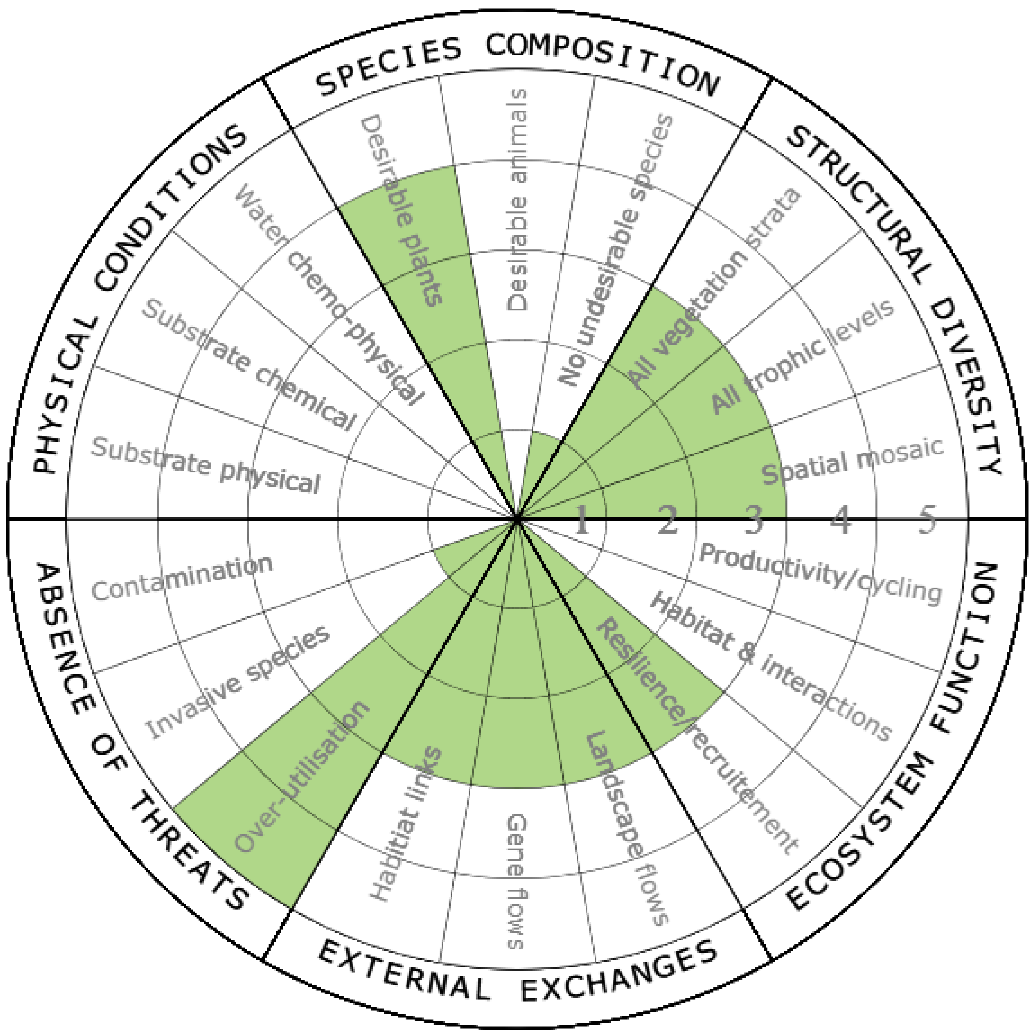


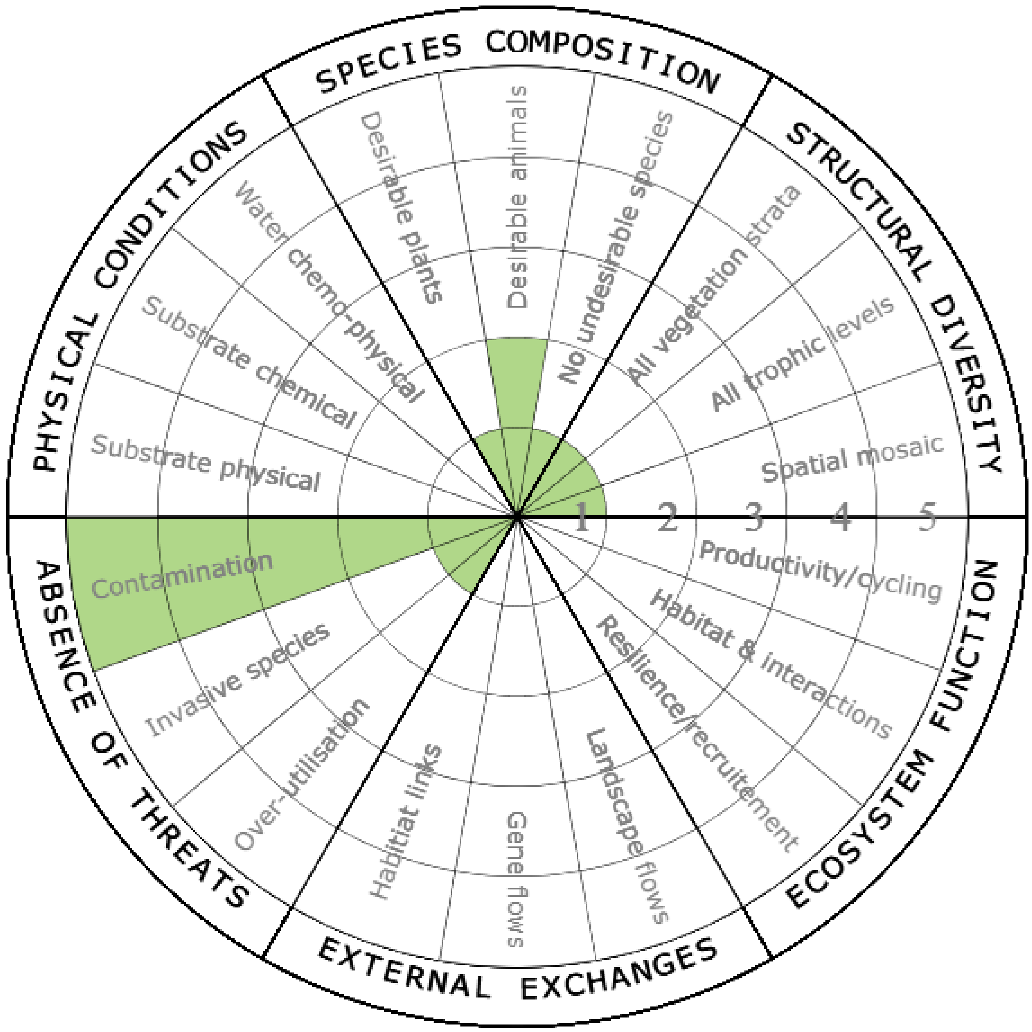
Figure B5: Recovery Wheel of Article 5.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 6: Mona Island, Puerto Rico

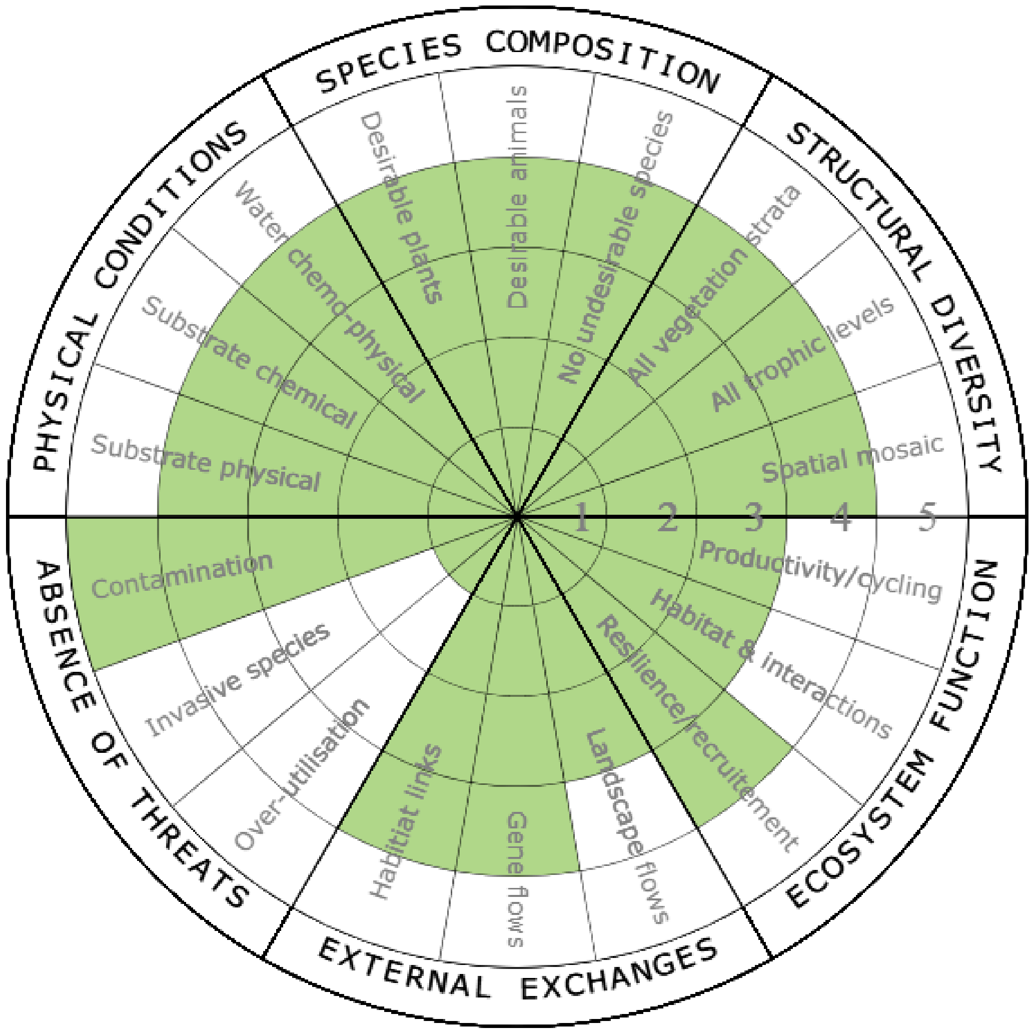
Figure B6: Recovery Wheel of Article 6.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 7: Darling Basin Australia

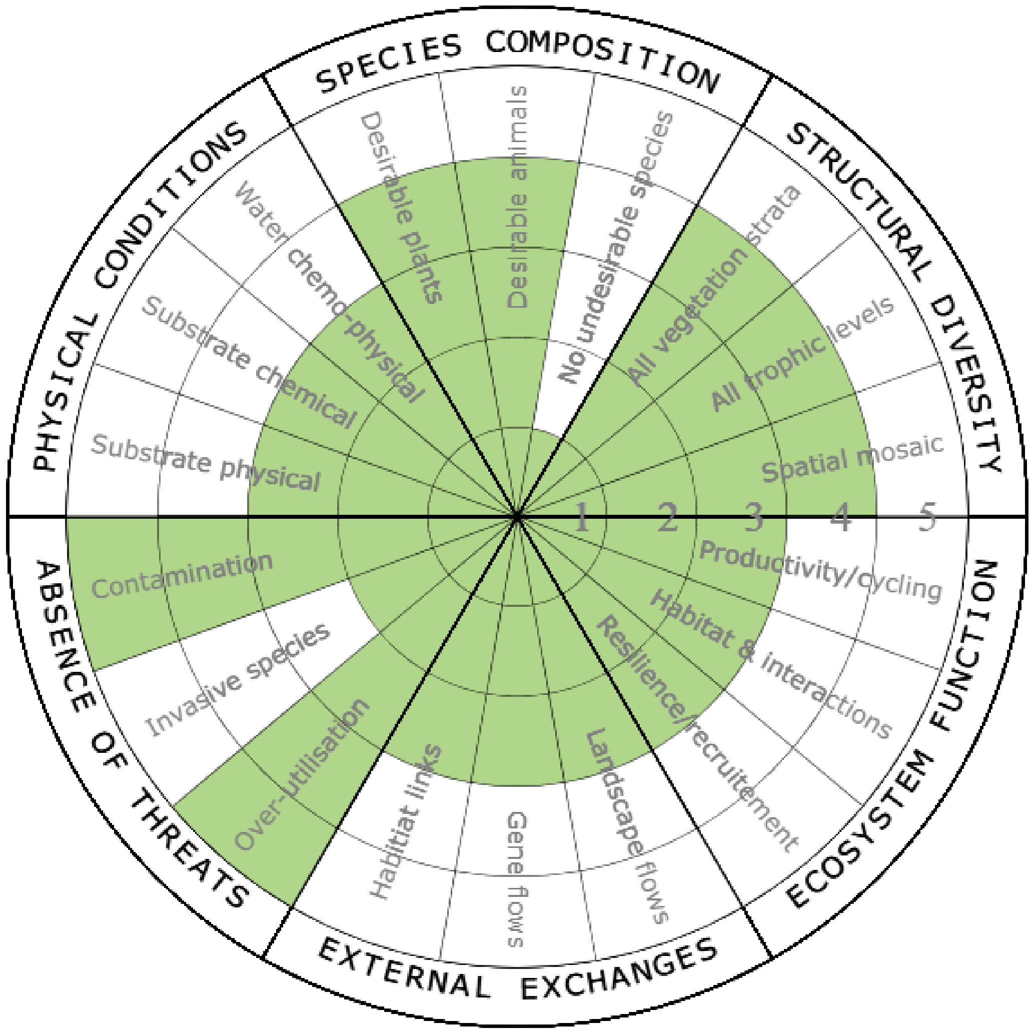
Figure B7: Recovery Wheel of Article 7.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 8: Madrid Spain

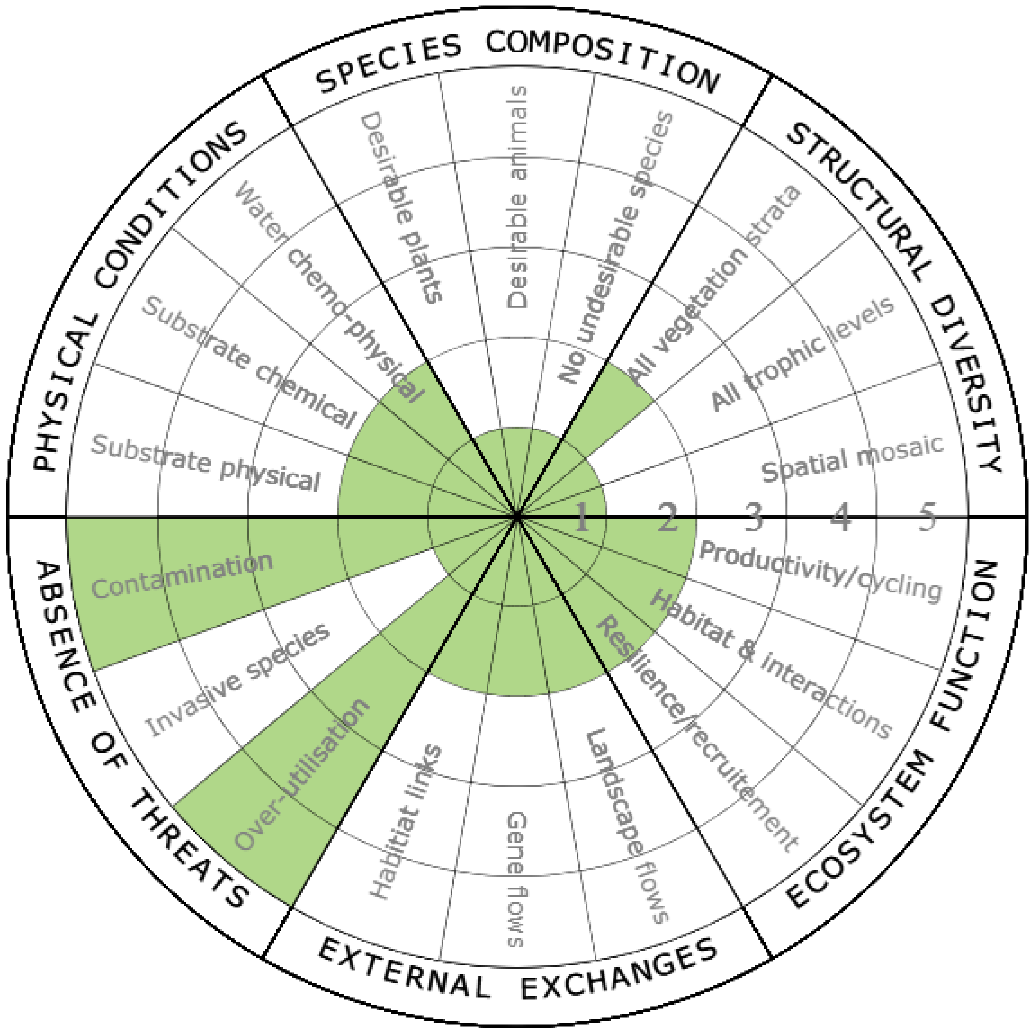
Article B8: Recovery Wheel of Article 8.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 9: Lincoln Nebraska

Figure B9: Recovery Wheel of Article 9.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 10: Boulder County Colorado

Figure B10: Recovery Wheel of Article 10.

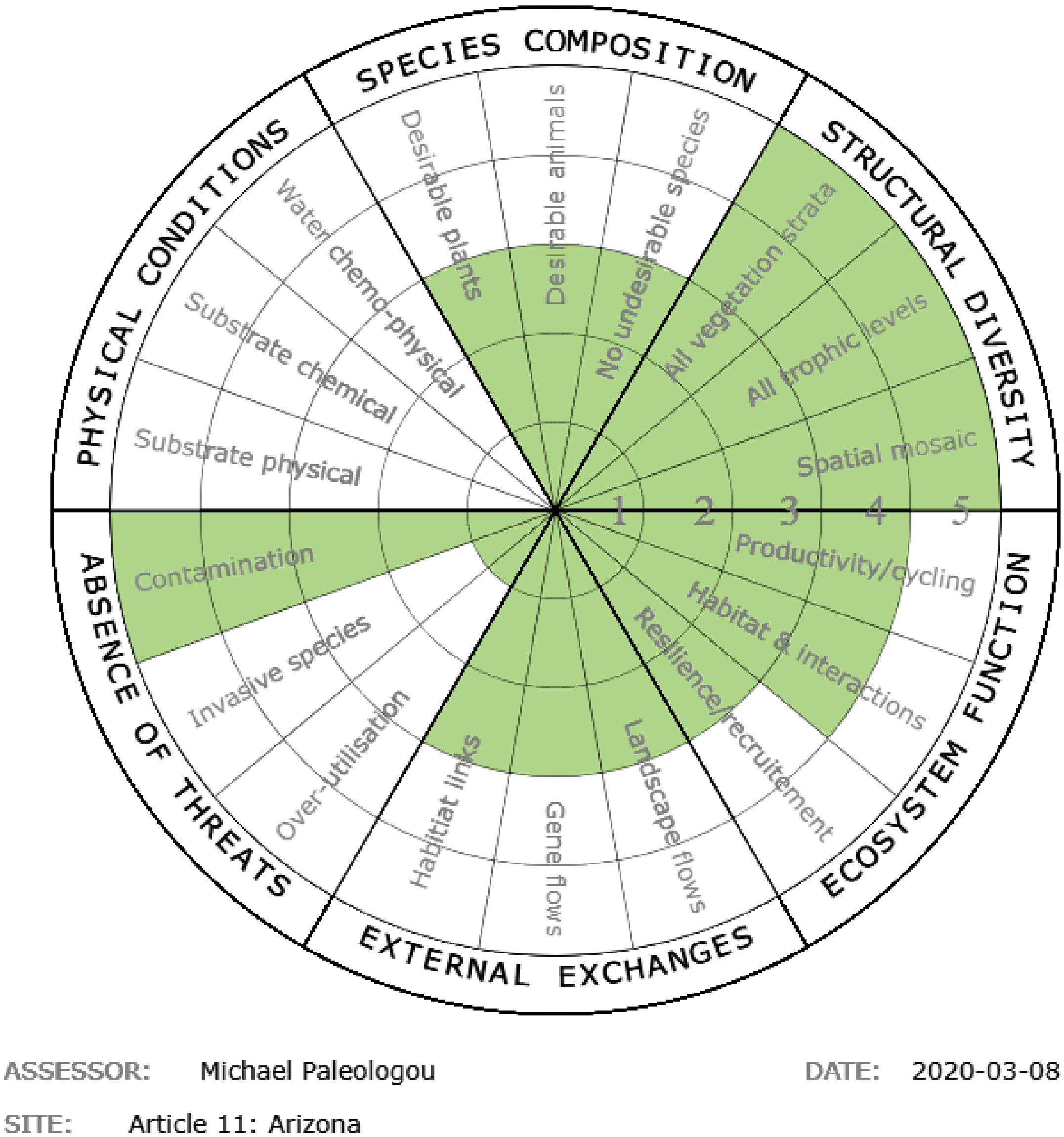
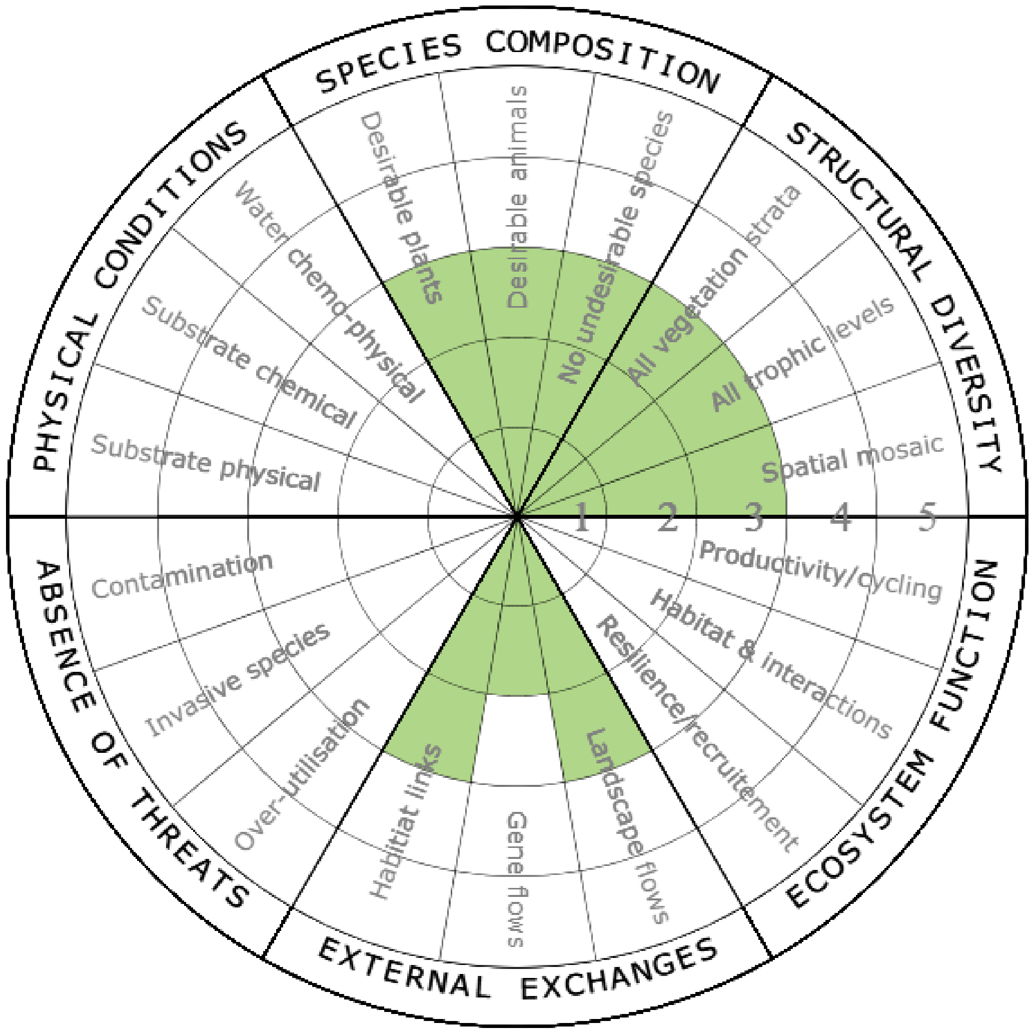


Figure B11: Recovery Wheel of Article 11.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 12: Targhee National Forest, Wyoming

Figure B12: Recovery Wheel of Article 12.

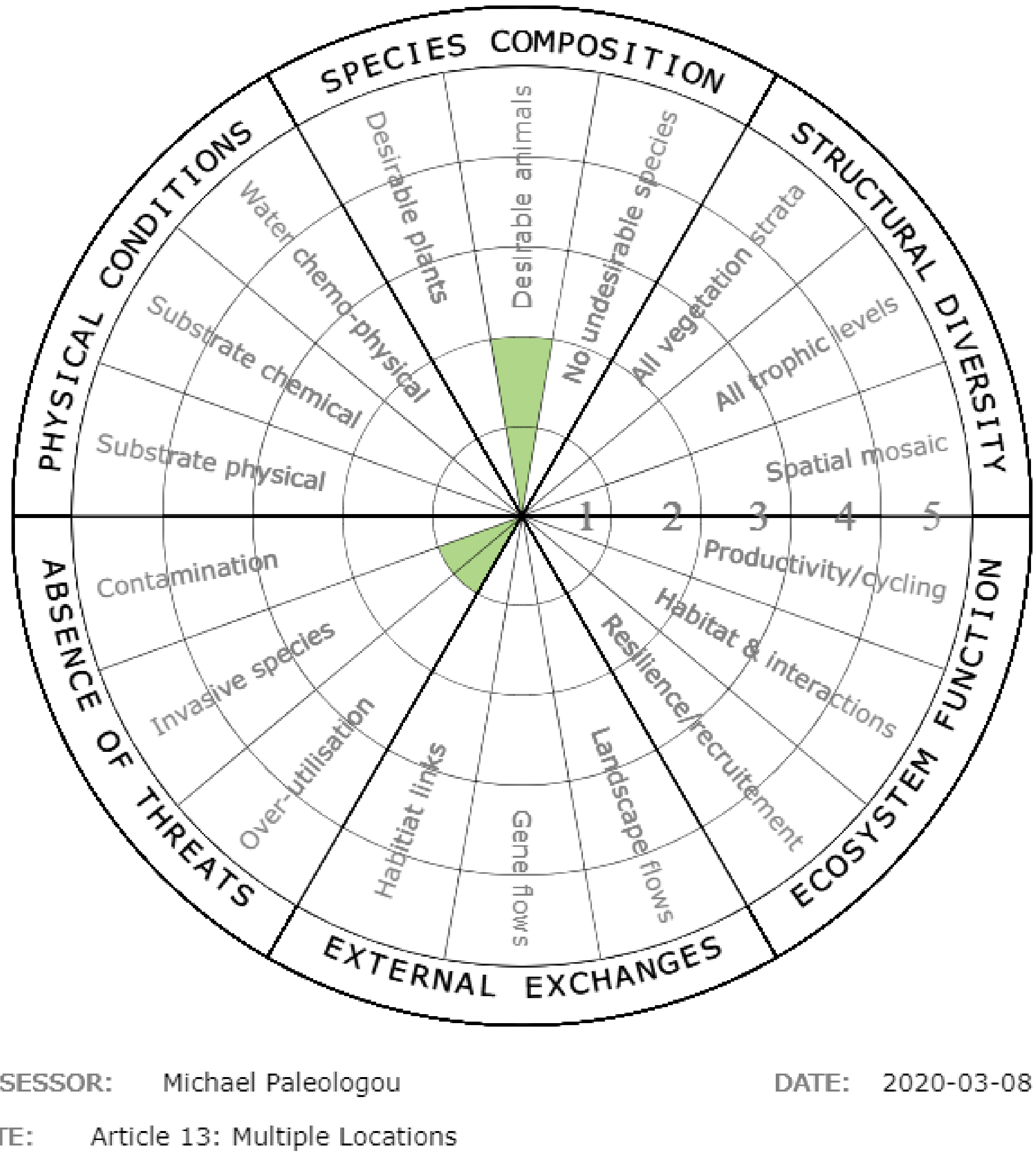
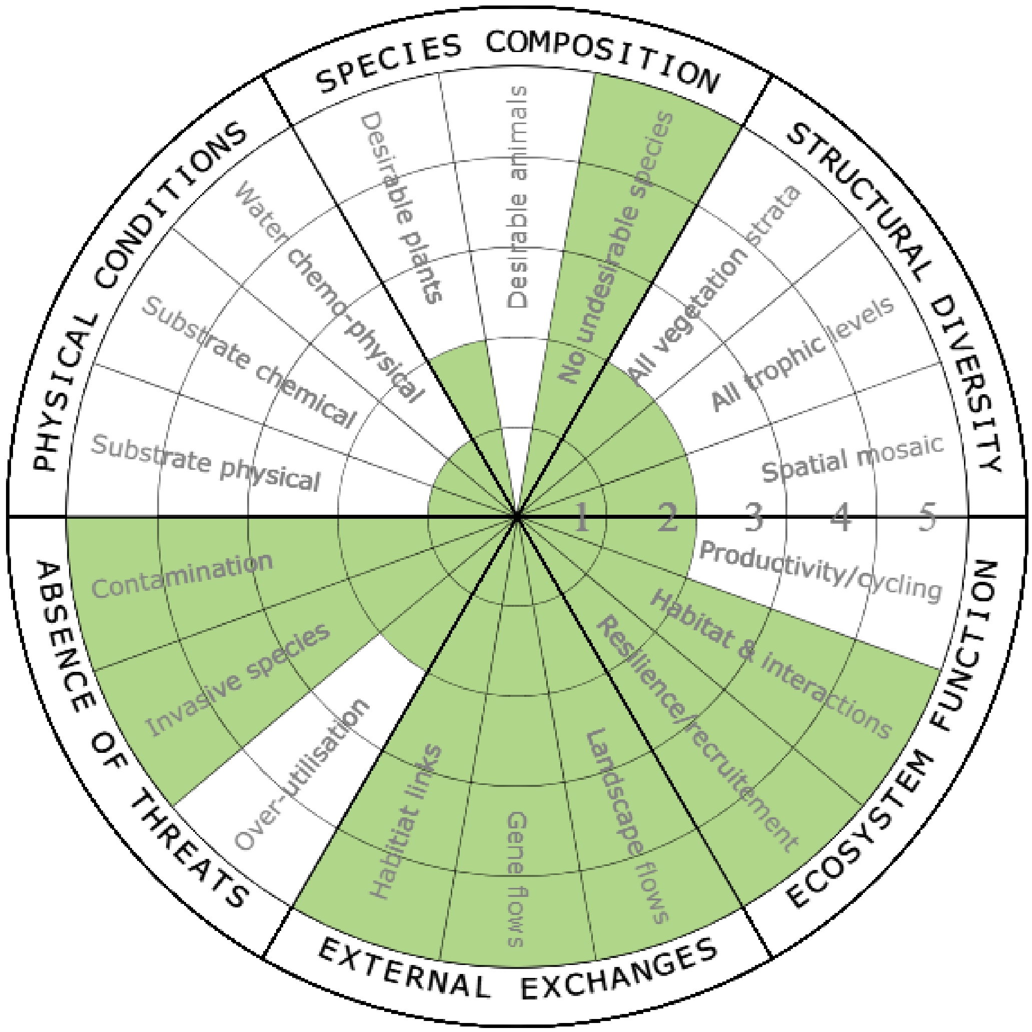


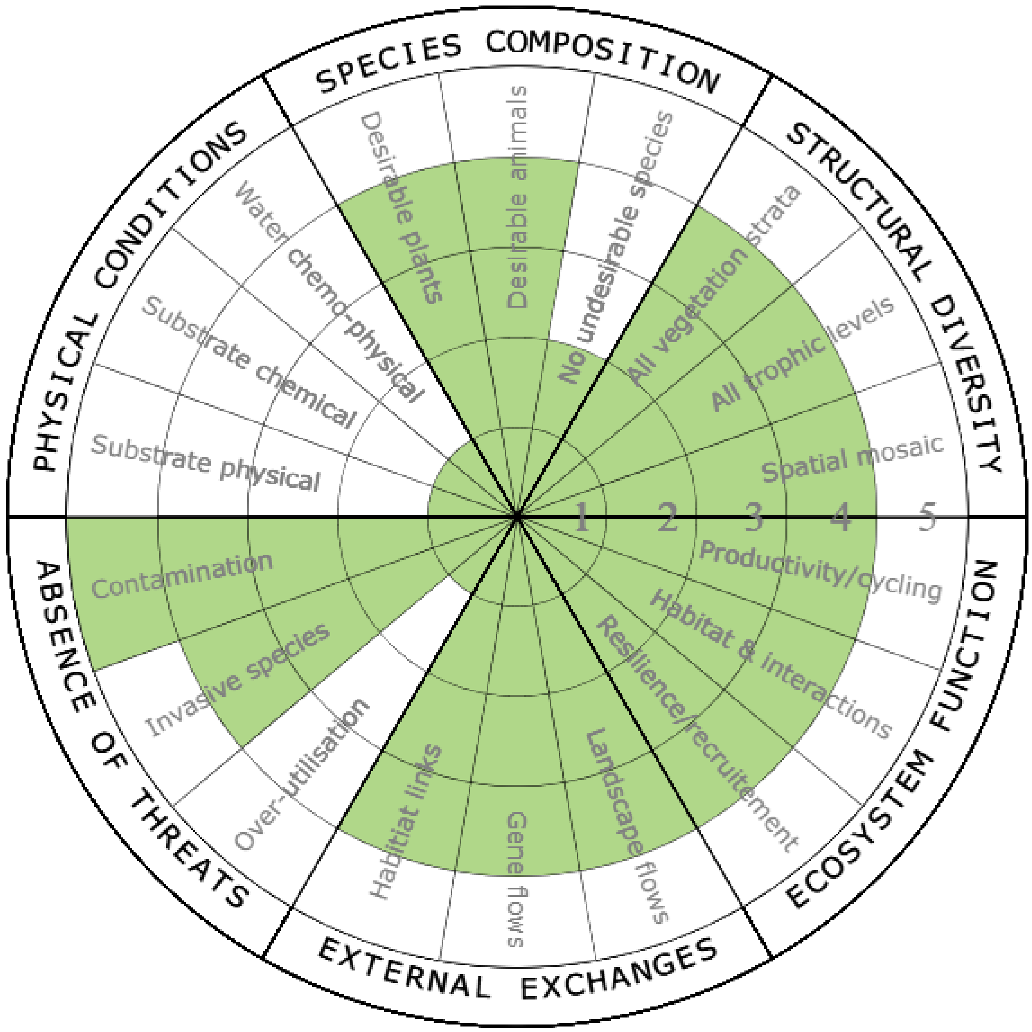
Figure B13: Recovery Wheel of Article 13.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 14: Madrid, Spain

Figure B14: Recovery Wheel of Article 14.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 15: Chesapeake Bay

Figure B15: Recovery Wheel of Article 15.

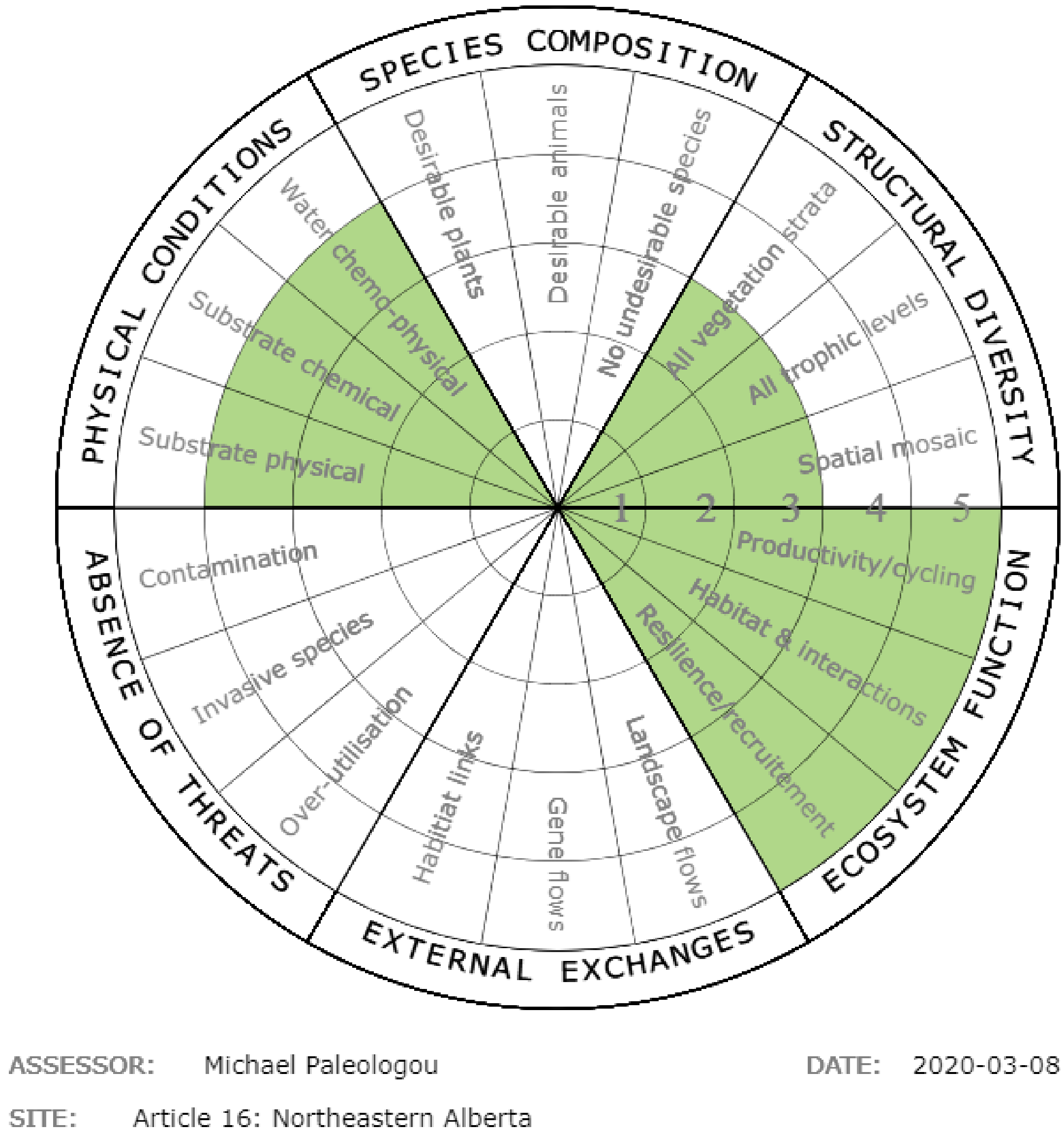
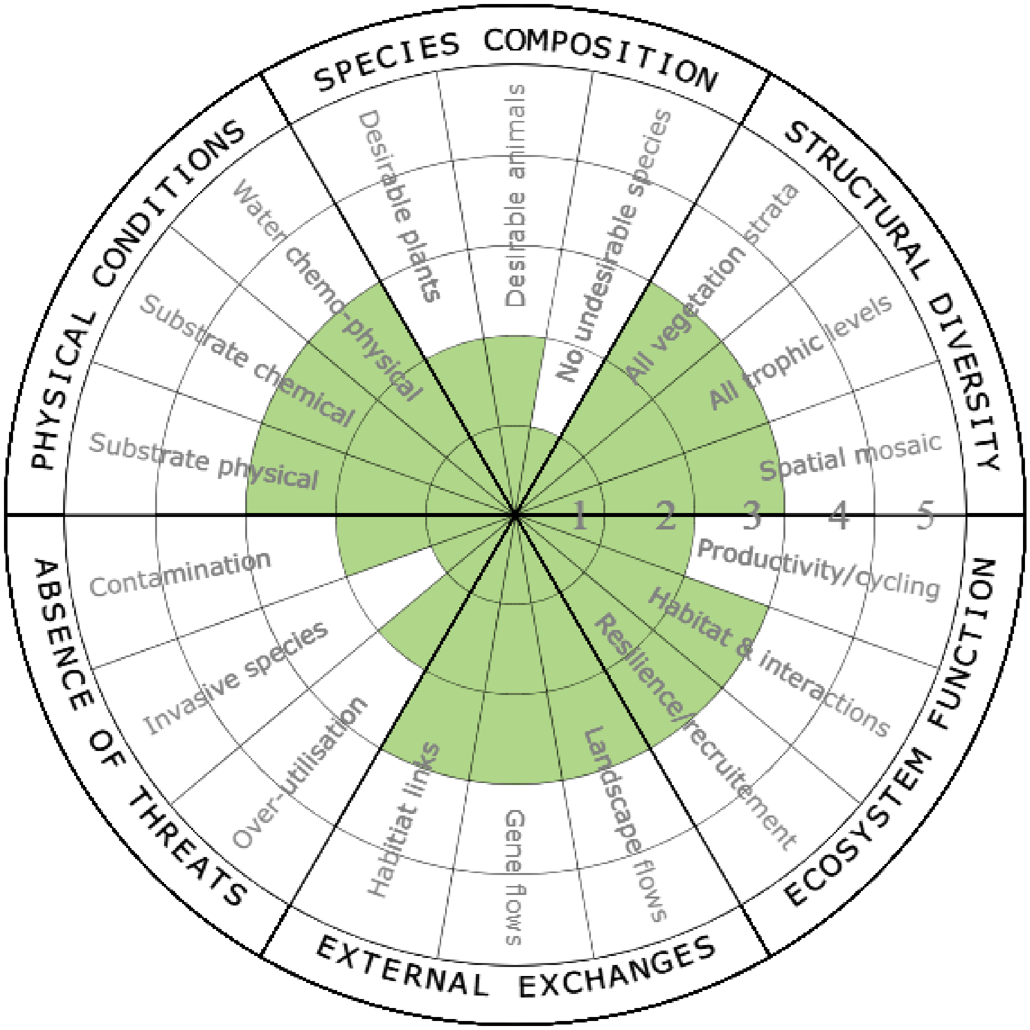


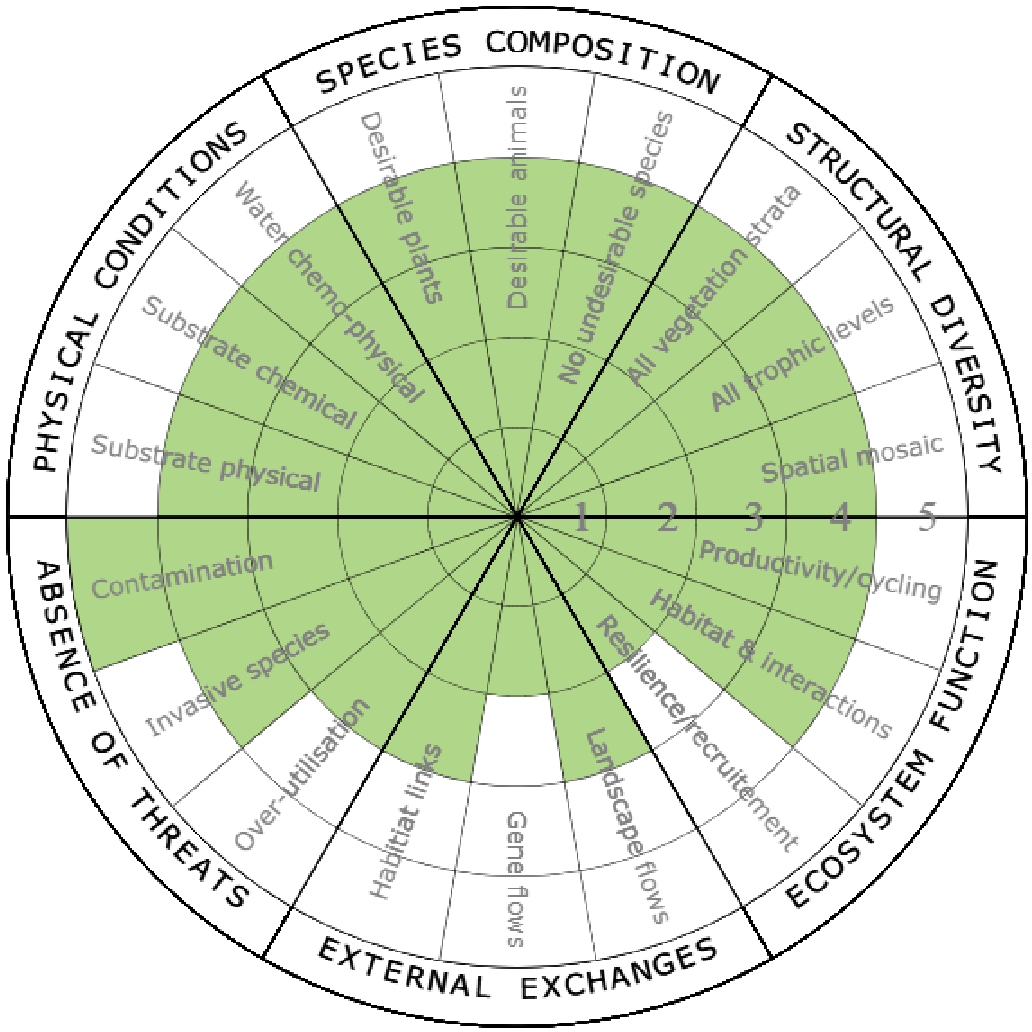
Figure B16: Recovery Wheel of Article 16.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 17: Lake Naivasha, Kenya

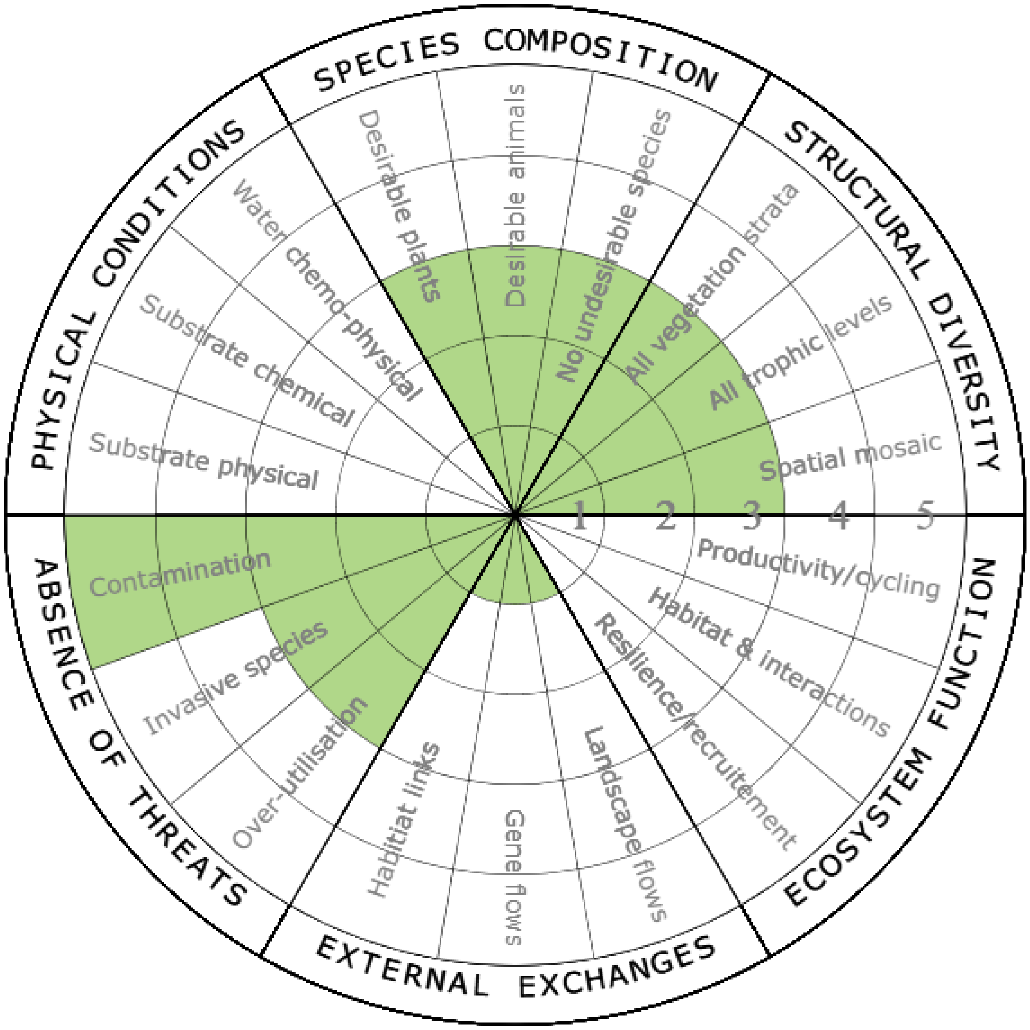
Figure B17:Recovery Wheel of Article 17.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 18:Willamette Valley, Oregon

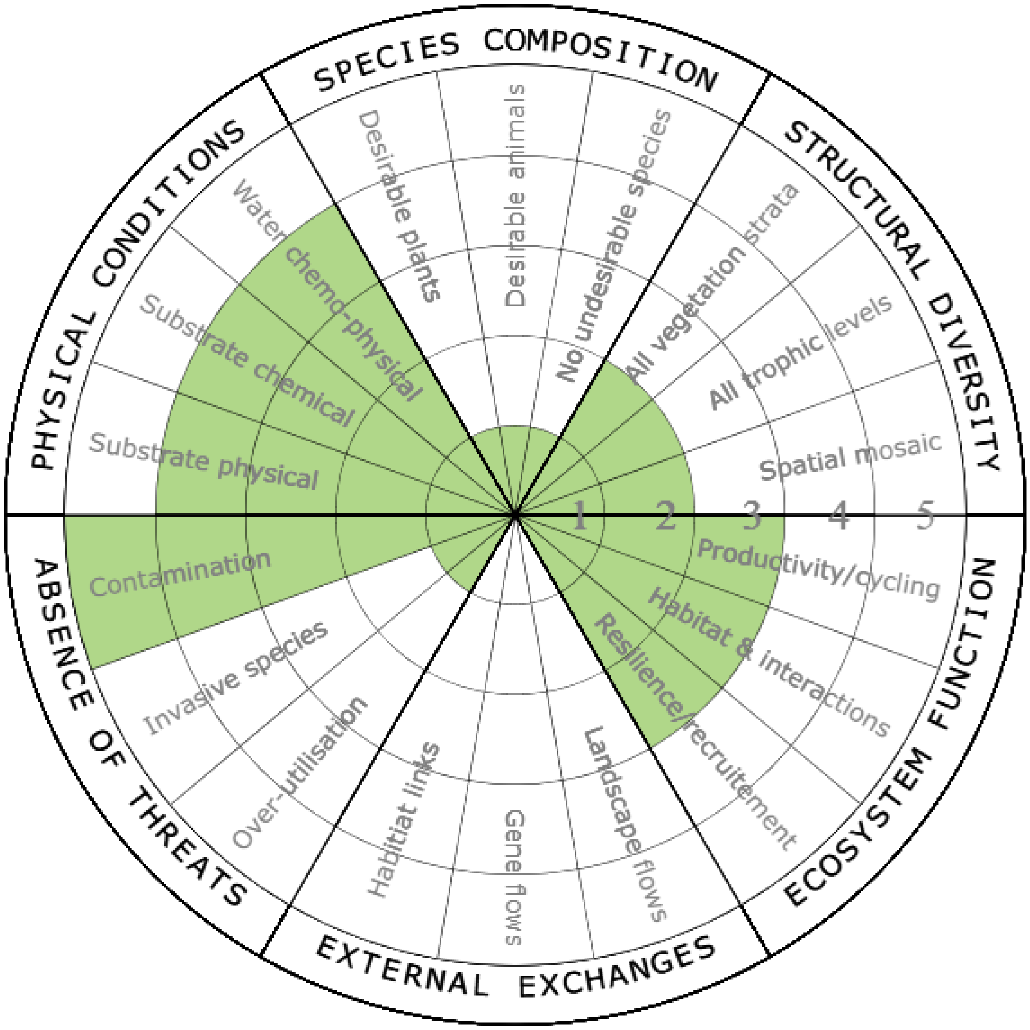
Figure B18: Recovery Wheel of Article 18.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 19: Santa Cruz Island, California

Figure B19: Recovery Wheel of Article 19.



ASSESSOR: Michael Paleologou DATE: 2020-03-08

SITE: Article 20: Mandan, North Dakota

Figure B20: Recovery Wheel of Article 20.