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REVIEW

Realizing UN decade on ecosystem restoration through a nature-based approach: A case review of management of biological invasions in protected areas

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Abstract

As the influx of different invasive species and their spread to new areas increases, there is a need for a rigorous and relevant scientific evidence-based control and restoration (EBCR) approaches to inform practical decisions and policymaking. While evidence-based decision is gaining popularity in science and policy, its potential for transformative change especially in the management of invasive plant species remains unexplored. Control and restoration of areas invaded by invasive plant species in natural and protected ecosystems require such decisions. Here, we provide a framework to guide how EBCR can contribute to transformative change and we argue that upscaling existing EBCR practices in areas invaded by invasive plant species (especially in protected areas (PAs)) requires coalitions of interdisciplinary science, public, private, and civil society actors with a common goal. Since actors' roles and stakeholder interactions are dynamic, to achieve durable impacts, the upscaling process must continually engage and involve actors, while maintaining a balance of incentives among them. Social and cultural dimensions of local communities as well as their indigenous and local knowledge need to be incorporated. Pathways to upscaling EBCR may involve leveraging adaptive governance, integrating successful initiatives and lessons into public policy and practices, or reinforcing governance and management-led change with private efforts. We identify general lessons from (complex) PAs for successful upscaling of EBCR and illustrate the components of our framework through a novel application of a nature-based approach (NbA) in PAs invaded by invasive plant species.

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In brief: A decade on ecosystem restoration

The UN Decade on Ecosystem Restoration, guided by Resolution 73/284 adopted by the General Assembly on 1 March 2019, aims to prevent, halt, and reverse the degradation of ecosystems on every continent and in every ocean (https://www.decadeonrestoration.org/). With the world facing multiple crises, experts from various disciplines are using various strategies, tools, and approaches to help to revive damaged ecosystems, end poverty, combat climate change, nutrient pollution, and prevent undesirable consequences arising from this, including mass extinction of both plants and animals. And as the year 2021 is marked as the beginning of the

UN decade of ecosystem restoration, restoration and rewilding is on the radar of everyone involved in ecosystem and nature conservation. As environmental pressures intensify and efforts to restore and rewild expand, there is an urgent need for a rigorous and relevant scientific evidence base of restoration and rewilding to inform decisions and policymaking in various ecosystems.

This paper seeks to use a novel evidence-based control and restoration (EBCR) approach developed with specific context and relevance to protect area settings to support the UN ecosystem restoration efforts that aim at reviving ecosystems damaged among other factors, by now-extensive populations of invasive plant species. Such approaches as the EBCR are urgently needed, particularly in protected areas (PAs) that are currently being negatively impacted by degradation drivers and whereby mitigation practices commonly practiced in other land use types such as farmlands are not recommended. Thus, the use of EBCR in restoration efforts in such natural ecosystems is the key as they are built on the framework that seeks for generality from empirical data and aims to develop and enhance best practices that can aid the damaged ecosystems bounce back to their original state. We further argue that the effectiveness of EBCR will depend on its integration in the 4 pillars; adaptive governance, management of pathways, drivers, and a good understanding of invasive and noninvasive plant species ecology and biology, whose details are discussed in the subsequent sections of this paper.

One of the main responses to halting biodiversity losses caused by anthropogenic pressures has been the establishment of PAs [1,2]. About 15% of the Earth's landscape is currently under protection for biodiversity conservation [1], with Convention on Biological Diversity (CBD)'s latest target set at 17% and 10% for terrestrial and marine areas, respectively, to be under effective management by 2020 [3,4]. PAs have been classified by the International Union for Conservation of Nature and Natural Resources (IUCN) into 6 major categories (https://www.iucn.org/theme/protected-areas/about/protected-area-categories). Generally, categories I to III consist of areas where human intervention is restricted, and in this study, we refer to them as fully protected areas (FPAs).

Despite national and international efforts to conserve biodiversity through FPAs establishment, better planning for long-term conservation requires first recognizing that ecosystem degradation is happening even in FPAs, through habitat loss caused mainly by invasive plant species, and anthropogenic activities that are altering the planet in diverse ways at faster rates than ever before [5,6]. Unfortunately, the myopic lens of rewilding and restoration efforts just outside protected areas, for example [7], under the assumption that PAs are immune to degradation, may continue to accelerate biodiversity loss in FPAs and diminish and distort our understanding of the biodiversity crisis in these areas. Absence of restoration efforts in FPAs can lead to biodiversity loss through plant invasions' impacts [8].

Rewilding and restoring FPAs using EBCR approaches such as a nature-based approach [9] as a means to generate solutions to halt habitat and biodiversity loss should be opted as a matter of urgency. While international agencies such as UN's Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), CBD and researchers increasingly advocate the accelerating efforts of rewilding and restoring degraded ecosystems, little attention has been given to the consideration of practical application protocols in the context of management of biological invasions in FPAs. This can be explained by the inadequate EBCR approaches and innovations in the body of knowledge that have undesirable consequences on environment and biodiversity in FPAs. The rates of biodiversity losses in FPAs are on the increase and sometimes even higher than other conservation areas [10]. This calls for evidence-based solutions to invasion threats that can reduce the impacts of invasive plants. While the principal drivers of species extinctions vary by taxonomic group and location, evidence shows that anthropogenic factors (habitat loss, land use change, and deforestation) are leading in reducing biodiversity in PAs compared to adjacent areas [11]. Many developing nations exploit their natural resources to achieve economic development targets and alleviate poverty [12], and as a result, rates of anthropogenic habitat conversion are increasing alongside PA establishment [6]. Expanding human population requires infrastructure development, often at the expense of natural habitat resulting in habitat isolation, degradation, and loss [13,14].

Some consequences of habitat loss and fragmentation to biodiversity include increase of unpalatable invasive plant species in PAs, and this has higher extinction risk [15], particularly of large herbivores. Moreover, habitat loss and fragmentation constrain animal dispersal, reducing the size available for subpopulation and the possibility of regular genetic exchange [16]. There is evidence to suggest that land use/cover change, particularly those influenced by plant invasions in PAs, negatively affect species persistence in many ecosystems of conservation importance. For example, predictions by [17] suggest that about 49,000 species per every 1 million species in tropical forests are likely to become extinct by 2060 due to the ongoing habitat conversions globally. Similarly, [18] shows that about 86% of globally threatened mammals on Earth are at risk from habitat change; [10] on the other hand, provides evidence for halving in the abundance of large mammals within African PAs between 1970 and 2005. More generally, a recent study revealed that 62.0% of species listed on the IUCN red list are endangered by loss of habitat through anthropogenic activities, making habitat loss the number one cause of extinction risk today [19].

Primary forests contain the majority of the global terrestrial biodiversity [20] and are known to contain over 50% of the world's terrestrial species [21] as well as the highest rates of endemism [22]. However, the ongoing deforestation and degradation of these forests contribute 12% of global anthropogenic greenhouse gas emissions each year [23,24]. Earlier work by [25] revealed that the impact of anthropogenic land use change on biodiversity will have a much greater effect on tropical countries because species in the tropics tend to have smaller home ranges than those at higher latitudes due to higher diversity of habitats in the tropics. An unregulated conversion of habitats forms the majority of global deforestation and continues to be a course of concern for wildlife conservation in many tropical counties [22,26]. However, it is unclear exactly how fast past and recent changes that have been around the PAs have negatively affected wildlife habitat as well as loss of biodiversity in these areas.

To save biodiversity and reverse degradation of habitats (such as those caused by plant invasions in protected and conservation areas), we must tackle habitat destruction and ecosystem restoration in these areas, rather than just believing that the establishment and protection of PAs will solve the problem of biodiversity loss. Our review brings together an evidence-based framework that explores the design, implementation, management, and outcomes of restoration in FPAs degraded by invasive plant species that use an NbA to generate nature-based solutions that are lacking in these types of ecosystem conservation settings. The framework also includes lessons drawn from a range of stakeholder views that integrate social and natural science approaches to understand, improve, and scale up restoration and rewilding in PAs during the UN Decade on Ecosystem Restoration and beyond. The idea of "nature-based solutions" (NBSs) is now being used to reframe policy debates on biodiversity conservation, climate change adaptation and mitigation strategies, and the sustainable use of natural resources, among other issues. While interesting and potentially useful for those debates, an NbA is a concept that still needs to be fully integrated into restoration actions in FPAs; its use is not confined to discussions about ecosystem services and natural capital [27].

Fig 1. Invasion of invasive plants *Bidens schimperi* (a) and *Gutenbergia cordifolia* (b) in Ngorongoro Conservation Area (www.ncaa.go.tz) northern Tanzania (*Source*: *Own field pictures*).

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Biological invasions' management dilemma revisited

Biological invasion process has strategies that influence the invasion potential for the invading species, therefore, enabling them to colonize novel environments (e.g., Fig 1) and outcompete native counterparts [28]. These include capacity to produce abundant seeds [29,30], rapid germination and growth rate, high survival rate, early or late flowering after germination [30,31] long seed dormancy and allelopathy [30,32].

Following their establishment in the recipient ecosystem, invasive plant species displace native plant species and reduce the ecosystem's productivity [33,34]. Most invasive plant species use allelopathy to suppress germination, growth, and development of native plants by releasing allelochemicals into the environment [35–37]. This results in a change in the vegetation structure of the recipient ecosystem through loss of diversity [30,38], and therefore, creates pasture scarcity for inhibiting herbivores.

For over decades, invasive plant species management, especially in farmlands have been mostly through chemical herbicides (http://ucanr.edu/blogs/blogcore/postdetail.cfm?post). While this reliance in synthetic herbicides has been well developed among farmers, the consequences of the practice have been noticeable [39,40]. The impacts of synthetic herbicides on biodiversity and the cost implications associated with them have recently been under discussion [39,40]. This has fuelled a discussion on the applicability of synthetic herbicides in managing invasive plant species, especially in FPAs [41,42].

While as late as 1800s, invasive plant species management in agricultural lands was mainly through mechanical removal (http://ucanr.edu/blogs/blogcore/postdetail.cfm?post); recently, ecologists started to advocate on the use of biological control and integrated pest management (IPM) as approaches needed to complement mechanical control for improved performance [43]. Although IPM approaches are successful in improving farmlands' productivity, their applicability in PAs is still a myth [41,42]. Fuelled by climate change and increased environmental degradation, management of invasive plant species in FPAs has become increasingly challenging. This will remain challenging due to 2 reasons: Firstly, the suites of invasive plant species are likely to change, and secondly, some invasive plant species are likely to become more invasive in the future [44].

The assumption underlying hesitation in utilizing both mechanical and biological control of invasive plants in PAs has been due to the invasion facilitative impacts of disturbance from mechanical control [45,46] and unintended consequences should a biological agent proliferate in the receiving ecosystem [47]. On the other hand, the major challenge over biological control of invasive plants have been a rising concern on the potential damage to both threatened and endangered native forage closely related to a targeted invasive plant [47]. It is in this caution that restoration ecologists started to rethink on the appropriate ways of addressing the problem [34,48,49], including adopting EBCR practices such as the nature-based approach [9,34,48,49].

The nature-based approach (NbA) for managing biological invasions in FPAs

While the majority of existing invasive species management options have been reported to be associated with some negative impacts to biodiversity [37], nature-based approaches (NbAs) for managing invasive plants [9] present an opportunity for successful management of invasive plants in PAs. As nearly half of invasive plants eradication efforts fail [50], there is a great need for improving the effectiveness of invasive plants control efforts such as NbA on a variety of fronts [51]. To achieve this, we urge that PAs managers should ensure collaborative efforts that account for complexities surrounding governance issues, recognizing and integrating local perspectives in development and implementation of invasive plants' pathway management plan. They should also possess a better understanding of drivers of ecological invasion, the biology and timing of invasive plant species phenology when managing biological invasions (Fig 2). These should act as pillars that support NbA framework to manage invasive plants in FPAs.

A better understanding of each of these pillars (Fig 2) can improve a protected and conservation area manager's ability to successfully use an NbA or any other eco-friendly invasive plants control method to manage biological invasions. Success in the control and restoration of invaded areas often hinges on the ability of managers to successfully control or eradicate certain invasive plants after establishment and spread. To be able to achieve this, authorities need to account for the 4 suggested pillars (Fig 2), as well as the adoption of the effective and

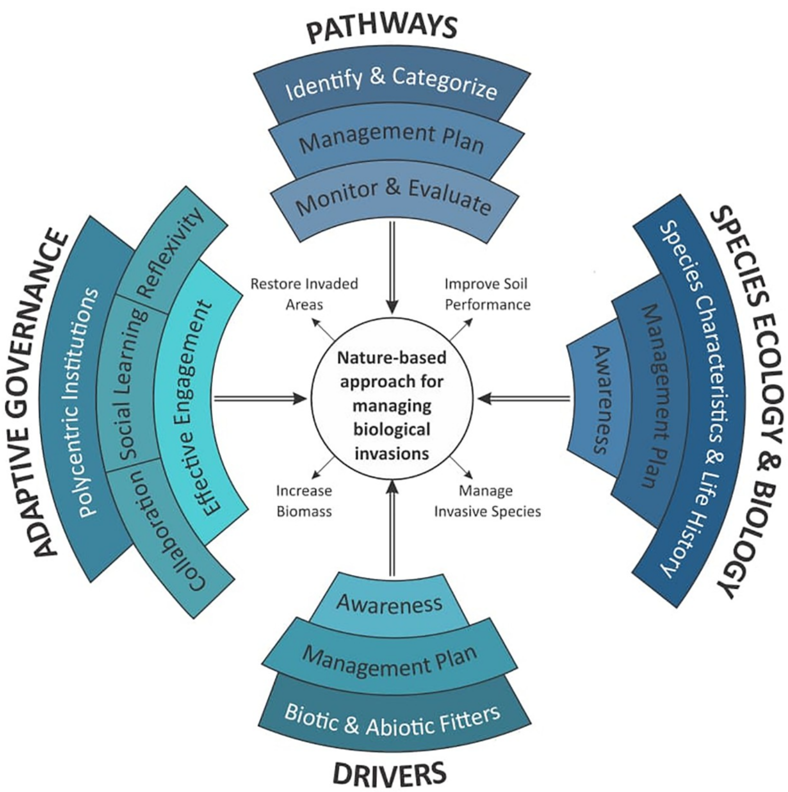

Fig 2. Effective management of invasive plant species in a PA is determined by 4 interacting pillars: Adaptive governance, management of pathways, drivers, and a good understanding of invasive and noninvasive species ecology and biology.

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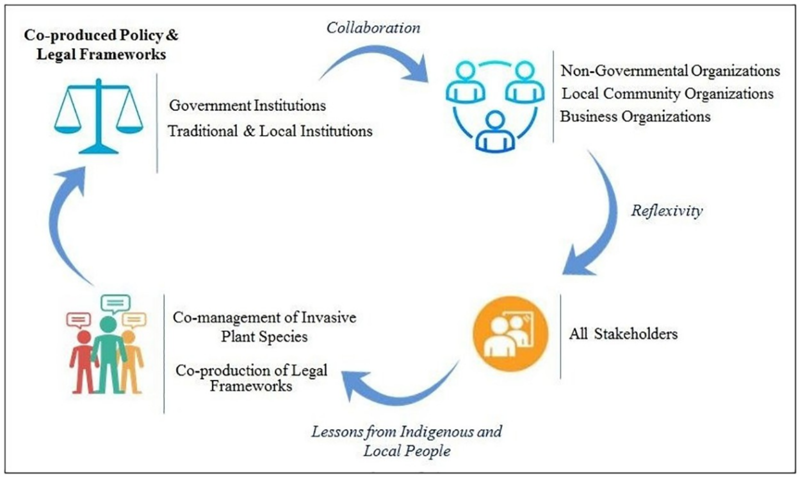

Fig 3. A proposed adaptive governance model for coproduction of policy and legal frameworks for managing invasive plant species: Polycentrism will ensure inclusion of traditional by-laws in preventing practices that facilitate ecological invasion. On the other hand, collaboration will ensure a better understanding by all actors and hence adoption of better agreed practices that will maximize the effectiveness of invasive plants management approaches such as the NbA. Meanwhile, reflexivity is essential for the institutional change needed to transition toward sustainability and success of invasive plant management efforts such as the NbA. Lastly, lessons learned from indigenous and local people will enable the sharing of different perspectives that can facilitate new understandings, trust, and knowledge coproduction and can lead to more mutually acceptable policy and legal frameworks for managing invasive plant species. The adaptive governance should be implemented and promoted as a cross disciplinary framework involving collaborations between scientists from various disciplines as it has been proven to work in situations driven by disease invasions such as emerging infectious diseases, including COVID-19. COVID-19, Coronavirus Disease 2019; NbA, nature-based approach.

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sustainable nature-based approaches when undertaking their management actions. We hereunder discuss these pillars (Figs 2–5) in detail, and for each pillar, we will recommend on how effectively it can be used to manage invasive plants in protected and conservation areas. However, effective management requires knowledge and actions on the interplay between actors, these management pillars themselves, their network topology, and management actions.

Adopting an adaptive governance approach

Conventional natural resources governance requires strengthening transformation frameworks that provide various options, such as ecosystem-based adaptation, that deliver multiple

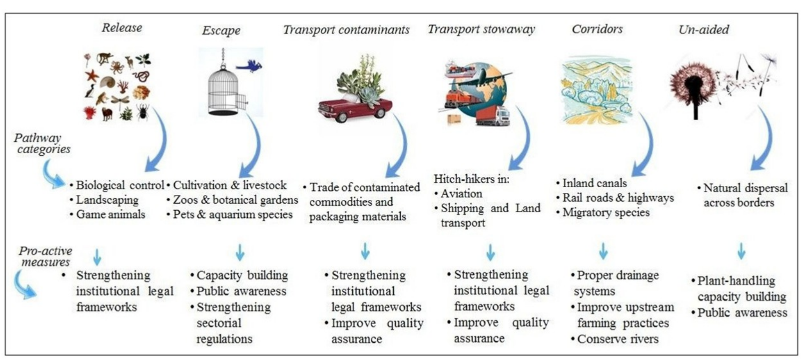

Fig 4. Common invasive species pathways as per CBD pathways classification framework [67] and their proposed management options (i.e., EDRR). CBD, Convention on Biological Diversity; EDRR, early detection and rapid response.

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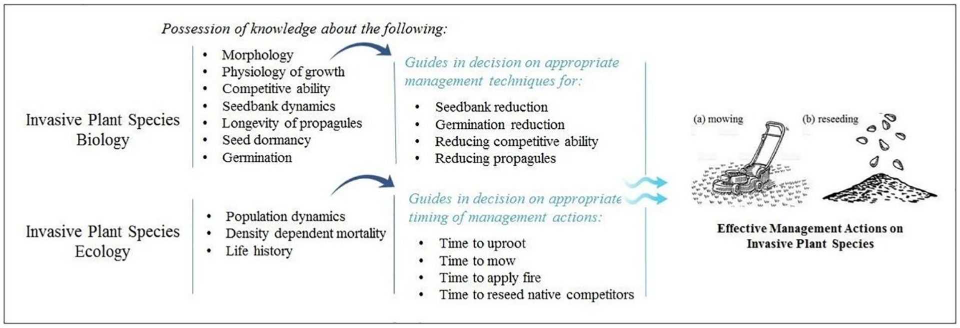

Fig 5. An illustration on how an understanding of invasive and other plant species' biology and ecology can be used for managing biological invasions in PAs.

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benefits to help address challenges that include inclusive governance [52]. In developing and adopting these transformative frameworks, it helps to utilize conservation and management synergies that could be obtained from spatial coordination of conservation efforts by different stakeholders, thus, achieving Sustainable Development Goals (SDGs) 14 and 15, which are focused on conservation and the sustainable use of natural resources in the context of contributions to human well-being (SDGs 1, 2, 3, 6, and 7). Understanding, recognizing and adopting the design, and implementation of novel governance structures and mechanisms explicitly designed to boost spatial coordination of conservation efforts is therefore of critical importance if we are to successfully manage invasive species in our natural ecosystems.

Effective landscape governance entails integration, coordination, and harnessing synergies between formal and traditional governance and managing emanating conflicts [53]. It further emphasizes on stakeholders' involvement in planning and implementation to reinforce coherence and positive impacts to ensure sustainability. Fortunately, over the last decade, there have generally been an increase in participatory techniques and greater use of formal accountability in managing PAs [54] but most PAs are still governed by rigid policies and regulations. Unfortunately, ecosystems are dynamic and therefore pose challenges in determining which governance can be effective to deal with future scenarios. Adaptive governance (Box 1; Fig 3) has been suggested as a way forward to deal with disasters [55] such as biological invasions that are increasingly occurring in PAs, especially during periods of abrupt environmental and land use change.

In principle, adaptive governance represents a model that aims at ensuring socioecological resilience [56]. It seeks to embrace cross-scale collaborations that allow for collective actions and ongoing learning on existing calamities [57] such as biological invasion. An adoption of adaptive governance therefore is of great importance in managing invasive plants where human nature interaction is intensive. As adaptive governance offers a great promise in disaster management and policy literatures [58], it also highlights on how it can be effectively applied in managing biological invasions in PAs that harbor biodiversity (Fig 3). While some scholars have identified certain principles conducive to adaptive governance [55], environmental legislation, as an important component of the governance system, is often misaligned with these principles, particularly polycentric institutions and collaboration. As a polycentric system involves the decentralization of some decision-making power to local governing bodies who have indigenous and local knowledge (ILK) and insight into the local context [52,59], it often fails to recognize the traditional institutions that tend to be highly respected by local

Box 1. The role of adaptive governance in managing invasive species in a PA: A lesson from "*Ngitiri*" silvo-pastoral system—Northwestern Tanzania.

Ngitiri is a silvo-pastoral system practiced in Northwestern Tanzania [60]; it involves retaining an area of standing vegetation from the onset to the end of the rainy season. The practice is mainly governed through traditional by-laws set by local communities that are involved in the practice. While effective proactive institutional policies and guidelines are of great importance in effectively managing invasive plants within PAs [61], traditional by-laws have indicated to be more effective in governing degraded communal complex landscapes [62]. This governance is through some traditional rangeland restoration and management practices, such as the common "*Ngitiri*" [62]. As the majority of local people are highly dependent on biodiversity and ecosystem services in most African complex landscapes where human and wildlife coexists, it is critical to incorporate traditional by-laws in policy decisions around the landscape management. PAs' management policies and legal frameworks are therefore likely to benefit much from inclusion of traditional by-laws in existing and new regulatory instruments. When such regulatory instruments are formed, they are likely to be received positively by local people as most of them feel possessiveness of the instrument [60]. Normally, decision-making in PAs management affects both social and ecological interests, therefore requires governance system that calls for stakeholders' collaboration to provide a consensus among them [63]. Such collaboration ensures for the availability of the best information to be used [64] for a sustainable management of invasive plants. Likewise, an adequate legal authority, effective administration, and planning increases the chance of managing invasive plants effectively through NbA. Formulating and implementing such adaptive governance instruments therefore, while applying the NbA (Fig 2), will maximize the effectiveness of such efforts.

people. The current polycentric system should therefore strive to ensure inclusion of traditional institutions to achieve successful management of invasive plants in existing PAs (Fig 3).

There is a need to link this pillar with effectiveness of the implementation of the NbA in FPAs to explore and understand how NbA is associated with other pillars of invasive plant species management can be framed, understood, and collectively implemented by different stakeholders to realize their effectiveness.

Identifying and managing invasion pathways

In order to realize the success of the implementation of the NbA, rigorous actions that identify, develop awareness, plan, and manage pathways of introduction of biological invasions must be in place throughout (Box 2). Pathways of introduction of biological invasion describe how a species is transported, intentionally or unintentionally, outside its natural geographical range [65]. Creating diversion of the pathways can aid in preventing invasive species dispersal and hence new introductions, likewise, managing dispersal pathways through awareness creation among stakeholders. These together with development and implementation of pathway management plan in FPAs have been recommended as among the crucial prerequisites for preventing new invasions [66]. We therefore argue that identifying the major dispersal pathways of

Box 2. The role of invasive species pathways in attaining effective management of biological invasions in FPAs: A lesson from Ngorongoro Conservation Area (NCA)—Northern Tanzania.

As human activities are the major contributor of invasive species dispersal [68] in human inhabited PAs, formulation of an invasive species pathways management plan is crucial. Such a plan needs to involve all stakeholders that are associated with the PA at stake. It should aim at preventing new introduction and further spread of the existing invasive species and should include EDRR mechanisms. While eradication at a later stage of invasion is challenging [69], management efforts such as NbA needs to be supplemented by efforts that ensure no more invasive species addition by existing pathways (Fig 4). Thus, the plan to be formulated should identify existing and potential pathways that might affect invasive species management efforts. Failure to formulate an effective plan while implementing invasive species management effort such as NbA is likely to impair their effectiveness. The success of NbA in managing invasive species in PAs such as the NCA in northern Tanzania, for example, requires an integration of all existing and potential invasive pathways (Fig 4). Within the NCA, several invasive species pathways have been identified, these include those related to escape (from agricultural and pastoral lands in the surrounding villages, trails of livestock movement), transport stowaway (from lodges and or hotels supply machinery/equipment), transport contaminant (attachment to vehicle tires, tourist's luggage), and corridors of large mammal's migration (seed attachment to animals). In this regard, for a management intervention such as NbA to be successful, there must be an invasive species pathways management plan. The formulation of such a plan needs to be participatory so that all stakeholders' views are included.

invasive species in a PA and developing their management plan is critical to limiting further spread and arrival of new biological invasions in the FPAs (Fig 4).

Effective management of biological invasions using an NbA calls for early detection and rapid response (EDRR) mechanisms to be in place [66] so that to ensure the eradication of an invasive species at an early stage. However, for this to be effective, an invasive species pathways management plan is necessary [66].

Given the consequences associated with invasive species, approaches that ensure prevention "proactive" rather than late actions "reactive" are highly encouraged [61]. These approaches that among others account for early detection and intervention of invasive pathways (Fig 4) are likely to be more cost effective and successful than existing reactive approaches [70,71].

Understanding and mitigating drivers of biological invasions

Due to increasing anthropogenic influences on land as fuelled by various drivers such as climate and land use change, both direct and indirect invasion drivers have been vivid [72]. Control of biological invasions depends on the collective decisions of resource managers across invasion zones. Regions with high land use diversity may be subject to severe invasions, for 2 main reasons; first, as land becomes increasingly subdivided, each manager assumes responsibility for a smaller portion of the total damages imposed by invasive species; the incentive to control them is therefore diminished. Secondly, managers opting not to control the invasion increase control costs for neighboring land managers by allowing their lands to act as an invader propagules source [73]. In calling for effective management of now-extensive populations of exotic plants in such complex land use area, it is required that integrated and collective effort with social, economic, and ecological interventions are needed.

Additionally, for an invasive species to establish, survive, regenerate, and disperse in a new area, it must negotiate several biotic and abiotic (climatic) filters [74]. Those filters that facilitate successful dispersal of an invasive species are referred to as drivers (Figs 2 and 5) that may be in various categories depending on context, region, and species. Recently, climate change and increased land use change such as clearing of forest for agriculture and industries, overgrazing, and urbanization have exerted pressure on most PAs that lead to species invasion [44,46]. Likewise, activities such as recreational activities, mowing, or inappropriate use of fire that leads to soil cover disturbance, if not well managed, might act as drivers for further species invasion [45,46]. Like it is for invasive species pathways, drivers of invasive species are equally important to be recognized so that to realize NbA' effectiveness in managing invasive species in PAs. Coordination among managers can help collective mitigation of these effects, but greater numbers—and a wider variety of land managers occupying a region if working independently, hinder collective action. We suggest that the incorporation of management mosaic dynamics into invasive species research and management is essential for their successful control and eradication. When dealt with this way, the attainment of the effective management outcomes of an NbA can be realized.

The challenges in managing invasion drivers in PAs lies on not only the fact that identifying such drivers is complex and requires collaborative efforts, but also lack of awareness about invasive species among stakeholders and the public [75]. Equally, different protection status and land/ecosystem management category depicts the type of management practices, including those of invasive drivers that are taking place. These ultimately affect the extent to which the effectiveness of invasive species management such as NbA can be realized. Since the underlying causes of the drivers of invasion in the landscape are human mediated, then the way in which the landscape is managed can influence the extent of invasive species management success as addressed through NbA (Fig 2). A mutual good understanding of invasion drivers needs to be well incorporated when applying management approaches for biological invasions such as an NbA. It is therefore important that PA's managers, relevant stakeholders, and the public be well informed on potential and available drivers of biological invasions in their vicinity for effective and timely EDRR, eradication, and control of the biological invasions (Box 3).

Knowledge of plant species' ecology and biology

Understanding both invasive plant species biology and ecology maximizes chances of successful management efforts ([76]; Fig 5) including effectiveness of the implementation of an NbA (Box 4). It enables development of the species-specific action plans that account for the species' characteristic and life history attributes to be incorporated into the management actions. Invasive plant species biology includes attributes such as morphology, seed dormancy and germination, physiology of growth, competitive ability, seed bank dynamics, and dormancy and longevity of vegetative propagules [77]. Ecology, on the other hand, includes but not limited to such aspects as population equilibrium, density-dependent mortality, and life stages that are particularly important in regulating population size [78].

Awareness of invasive species biology and ecology (Fig 5) can not only be used to better predict invasive plant species infestations, but can also be integrated into invasive plant species management approaches such as an NbA to enhance invasive plant species management strategies in the future. Knowing the biology and ecology of a native grass species *C. dactylon* and a

Box 3. The role of drivers of invasion in attaining effective management of biological invasions in FPAs: A lesson from Ngorongoro Conservation Area (NCA)—Northern Tanzania.

Human-induced disturbances have been among the drivers of most invasive species in a complex ecosystem [34,48] such as the NCA, which follow a multiple land model where human–livestock–wildlife coexists. As coexistence is important for survival, a good understanding of anthropogenic causes of environmental change is important to ensure a sustained coexistence. While PAs are facing a multitude of invasion drivers that are mainly human induced, an understanding of those drivers presents an opportunity for effective management of invasive plant species (Fig 2). For example, in a complex multiple land use area like NCA, when directing efforts in managing invasive species through the NbA such efforts become unrealistic if existing invasion drivers such as inappropriate use of fire for pasture management, increasing urbanization within the landscape and the governance system have not been taken care. A successful management of invasive plant species in a complex ecosystem such as the NCA therefore requires for the manager, other stakeholders, and the public to have a good understanding of the drivers and an ability to incorporate them during invasive plant species management intervention (Fig 2). Since most drivers of invasion that manifest in the landscape are human mediated, the way in which a PA is managed under different authorities influences the success of an NbA.

Box 4. The role of species ecology and biology in management of biological invasions in FPAs: A lesson from Ngorongoro Conservation Area (NCA)—Northern Tanzania.

As FPAs are very dynamic due to the impacts of different interacting factors that shape ecosystems, a better understanding of the species forming ecosystems is crucial for management purposes. For example, in a complex landscape such as the NCA efforts are being implemented to manage invasive plants using various approaches including the NbA. The management authority, the Maasai people who inhabit northern Tanzania and parts of Kenya and other stakeholders need to be aware of the biology and ecology of the target invasive species for effective management. Moreover, control measures should be timed to ensure maximum suppression of invasive plants; therefore, management strategies should be applied when the majority of invasive seedlings have emerged [80]. Such timing requires investments in terms of both money and time to ensure that monitoring to establish information on invasive plant's soil seed bank and the emerging time of a targeted invasive plant are known. For example, while mowing can be an effective strategy to manage problematic invasive plants as it is applied in NCA, it is required to be guided by a good understanding of the biology and ecology of the invasive plant to be managed. This understanding is crucial as it will inform the manager on the appropriate time to apply mowing as invasive plants management strategy. When this has been well established coupled with active governance, management of both pathways and drivers of invasive plant species (Figs 2, 4 and 5) are likely to maximize the effects of a control measure such as the NbA.

fodder crop *Desmodium intortum*, for example, has successfully aided in the formulation of an NbA that has proven to manage most of invasive plant species of the family *Asteraceae* [34,48,49,79]. While restoration of invaded areas calls for an adaptive approach that includes science-informed decisions, we are now more than ever witnessing the majority of control and management methods such as NbA that have been developed using science and technology (http://www.invasivespecies.gov/council/nmp.shtml) that relies mostly on the clear understanding of plant species involved.

While development of models that can provide prediction on timing and extent of invasive plant species emergence for effective invasive plant species management have been recommended [80], to do this an understanding of the biology and ecology of both native plant species and the respective invasive plant species to be managed is crucial. For example, knowing on the number of seeds per an invasive plant and seed dormancy tendency can guide in setting timeline for management actions of such plant when it comes to effective implementation of a successful NbA. This information is also crucial for estimating the magnitude of the problem. For example, the total number of seeds that an invasive plant is able to produce indirectly indicates the amount of invasive plant's soil seed bank in an invaded landscape is one such information that is of paramount importance for invasive plant species management. Thus, for effective management of biological invasions, acquisition of knowledge about the biological and other characteristics of different species that are key to driving invasion process, awareness creation among stakeholders, and development of various strategies and action plans are important (Box 4; Fig 5).

Concluding remarks and the way forward

Fully protected areas and conservation areas are vital to conserving nature and provide countless ecosystem goods and services, yet they face unprecedented challenges to their sustainability. With the utilization of an NbA within the framework of the 4 pillars (Fig 2), we provide a new pathway to managing biological invasions in these FPAs whose effective implementation will help realization of the targets set within the framework of UN's decade of ecosystem restoration. Effective implementation of an NbA in addressing the challenges of biological invasions within the framework of these 4 pillars will require policy and governance framework that are by themselves adaptive, stakeholders that are aware of invasion pathways and drivers, and a good understanding of biological invasions at stake. We argue that to enable NbA and other management approaches for biological invasion to work effectively, cross-scale partnership dialogues among researchers, stakeholders, and decision makers are key to jointly implement an NbA. These dialogues and their approaches will allow local stakeholders (and their perspectives), policymakers, researchers, and practitioners to jointly implement this NbA, while at the same time, learning the best practices to address the knowledge gaps and ensure that their relevance in spatial-temporal scales are being realized.

With the accumulating evidence of changing disturbance regimes becoming increasingly obvious, there is potential for disturbance ecology to become the most valuable lens through which climate-related disturbance events are interpreted [81]. Our proposed framework here opens an alternative avenue to improve each of the pillars and map the relative role of each in ensuring effective use of an NbA and/or other approaches for managing biological invasions in PAs.

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