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Managing invasive plants through a nature-based approach in complex landscapes

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Invasive plants are establishing in many protected areas where use of synthetic herbicides is prohibited. We introduce a nature-based approach (NbA) as an alternative to controlling invasives. The integration of NbA into ecosystem conservation provides potential to suppress invasive plants, improve soil cover, increase the diversity of native plants, and ultimately ensure ecosystem sustainability.

Complex landscapes: future protected areas?

Protected areas are mainly designed to protect natural features including wild fauna and flora, with the concepts of pristineness and wilderness often considered central. For example, under the 'Yellowstone model' for national parks, human inclusion in such protected areas has been strictly banned [1] mainly due to associated environmental **impacts** (see Glossary) and risks that humans may bring to both protected fauna and flora. The fundamental tenet is that the inclusion of humans in national parks can result in complexities in managing such protected areas, but is this always the case? Should we isolate people to achieve conservation goals? Or should people learn to coexist with biodiversity within these protected areas? These are very important questions that modern ecologists and conservationists need to answer.

While almost all the six International Union for Conservation of Nature and Natural Resources (IUCN)-protected area categories[i] allow for human intervention to some degree, they are all prone to influences such as introduction of invasive species. These protected areas are also at greater risk as a majority are closer to human settlements or are to some extent sandwiched between other forms of land use, resulting in the formation of **complex landscapes**. The increase in human population to 10.9 billion people[ii] soon after the end of the 21st century will enhance the potential for increased formulation of complex landscapes and colonization by invasive plants. Globally, invasive plants increasingly pose the greatest threat to biodiversity and their number continues to rise in most protected areas [2]. The Ngorongoro Conservation Area (NCA), a multiple land use area and one of the biodiversity hotspots in northern Tanzania for instance, has experienced a steady increase in human and livestock populations for over 60 years which might have facilitated the colonization of more than 25 invasive plants. Among these are the savanna African daisy (*Gutenbergia cordifolia*) and Bidens (*Bidens schimperi*), which occupy most of the main crater and other grassland areas of the NCA [3]. These two invasives are fire adapted and grow in pure stands or in patches with other native species (e.g., *Cynodon dactylon*), depending on site conditions and past disturbances such as fire, overgrazing, settlements, and precipitation.

Managing invasive plants in protected areas: an ecosystem manager's nightmare

There is growing appreciation that protected areas, like all **social-ecological systems**, face increased invasion due to global change [4]. In past decades control of invasive plants in areas that have been invaded by them outside protected areas has mostly relied on synthetic herbicides [5]; however, managing them inside protected areas has been difficult and challenging. Whereas most control methods are associated with adverse impacts to biodiversity [6–8], a **nature-based approach (NbA)** for managing invasive plants [3,9] is both environmentally friendly and sustainable. The fundamental principle underlying NbA (Box 1 and Figure 1) is the utilization of environmentally friendly techniques generated from native biota for managing invasive plants [3,9]. The use of such biota, as a nature-based management approach to control **biological invasions** in rangelands by suppressing invasive plants, has been reported to improve the diversity of native plants, facilitate the germination of native plants, and maintain and/or improve soil fertility [9]. Bond *et al.* [10], for instance, reported that with regard to forests' ability

Glossary

Adaptive governance: a mode of governance in which multiple actors are involved, interactions occur within and across states, private sector and civil society are key, and decisions require action(s) across multiple scales and levels.
Biological invasion: a process that occurs when individuals of a species arrive in an area with human assistance and establish and spread in new areas.
Complex landscape: unlike the contemporary 'Yellowstone model' national parks, complex landscapes are those protected areas that will likely harbor humans. A complex landscape exacerbates pressures on land due to its demands for land for settlements, recreation, food production, and transportation. As such, they are characterized by increased anthropogenic disturbances.
Ecological restoration: a practice that aims at initiating, recreating, or accelerating recovery of a disturbed ecosystem.
Impact: any significant change (increase or decrease) of an ecological property or process, regardless of perceived value to humans.
Nature-based approach (NbA): an ecosystem-based management and/or restoration procedure that relies on the direct utilization of native flora and fauna in addressing challenges arising from ecosystem degradation drivers.
Nature-based solution: an output generated through an NbA as a means to address challenges arising from ecosystem degradation drivers.
Social-ecological systems: complex adaptive systems, in which natural/ecological and human/social components interact to affect system dynamics. They reflect interconnected relationships between ecosystems and society.

to sequester carbon, if 350-Mha forest areas were naturally restored using native tree species, 42 gigatons of carbon (GtC) would be sequestered by 2100, compared with 1 GtC for the same area afforested with alien pines and eucalypts. This implies that restoring forests using native plants (NbA) have over 40 times more benefits than using alien plants (non-NbA).

Currently, **nature-based solutions** generated through NbA are used to address some global challenges including climate change and instability [11]. Here we highlight the use of NbA particularly in complex landscapes to ignite a broader discussion about a sustainable way of managing invasive plants in an era of increasing biological invasions. The use of NbA in controlling and restoring areas invaded by invasive plants is a process that utilizes native biodiversity-promoting elements to assist the recovery of an ecosystem that has been degraded, damaged, or destroyed by biological invasions. When choosing the native plant species (biota) that can be used under NbA, an assessment of existing plant communities in a given area is crucial, as this will allow for selection of native plants with desired characteristics such as those with a competitive advantage over invasives [9]. The use of solutions generated through NbA in managing invasive plants should, among others, consider the seasonality and aboveground plant biomass coverage of the area to maximize germination and growth of the native plants. Should there be excessive growth of invasive plants above the ground, clearance of the plant biomass in the area is recommended prior to implementation of NbA.

The effectiveness and success of any solution generated from NbA in managing invasive plants should be implemented and evaluated on the basis of adherence to three main pillars: (i) **adaptive governance**, (ii) management of invasive plants pathways and drivers, and (iii) a good understanding of invasive and noninvasive plants ecology and biology (Figure 1). In principle, adaptive governance represents a transformative, flexible, and multilevel governance model that aims at ensuring improved socioecological resilience [12]. It seeks to embrace multiscale collaborations across various levels such as governmental organizations, non-governmental organizations, local people, and individual actors to allow for collective actions and ongoing learning on managing existing invasive plants. Management of invasive plants' pathways and drivers, by contrast, involves early identification and detection of invasion pathways and drivers that aid in preventing invasive plants dispersal and hence lowers new introductions. A clear understanding of both invasive plant species' biology and ecology helps to maximize chances of successful management efforts by ensuring that species-specific action plans that account for both invasive and noninvasive plants' characteristic and life history attributes are incorporated into the invasive plants' management actions.

Box 1. Carefully planned NbA improves invasion management and restoration efforts

The NbA pilot program was employed for 2 years to control and restore areas invaded by *Gutenbergia cordifolia* and *Bidens schimperi* in the NCA. An NbA to manage the two invasive plants involved reseeding of competitive native fodders *Cynodon dactylon* and *Desmodium intortum*, and spraying *D. intortum* leaf extract in plots invaded by the two invasives [3,9]. Reseeding of the fodders displaced invasives *G. cordifolia* (Figure I) and *B. schimperi* (Figure II), leaving behind the grass stands (Figures IB,C and IIB,C). At the end of 2 years of NbA implementation, significant reduction in cover of invasives *G. cordifolia* and *B. schimperi*; and improved diversity of native grasses, soil seed bank, soil cation-exchange capacity, availability of phosphorus, and maintenance of other soil properties were observed (Figures IB,C and IIB,C). Ongoing monitoring and evaluation make this a valuable pilot site for similar invasive species control and **ecological restoration** using NbA in the region. The development of any NbA therefore must invest in research to assess and identify suitable native plants that can be used to bring back the desired ecosystem balance.

Figure I. A field experimental plot within Ngorongoro Crater in the Ngorongoro Conservation Area (NCA) demonstrating the effectiveness of the nature-based approach (NbA) (white circles = reseeding of 133 g/20 m^2 of *Cynodon dactylon* as the most competitive native fodder, red circles = reseeding of 50 g/6 m^2 of *Desmodium intortum*, and black circles = spraying of 100% *D. intortum* leaf extract from an allelopathic native plant). (A) Invasive plant biomass being cleared from the ground to maximize the effectiveness of the treatments, that is, before control experiment (brownish/purplish vegetation = an invasive plant: *Gutenbergia cordifolia*); (B) and (C) are fenced and unfenced plots, respectively, where research on the control of *G. cordifolia* was carried out for four (two wet and two dry) seasons for 2 years.

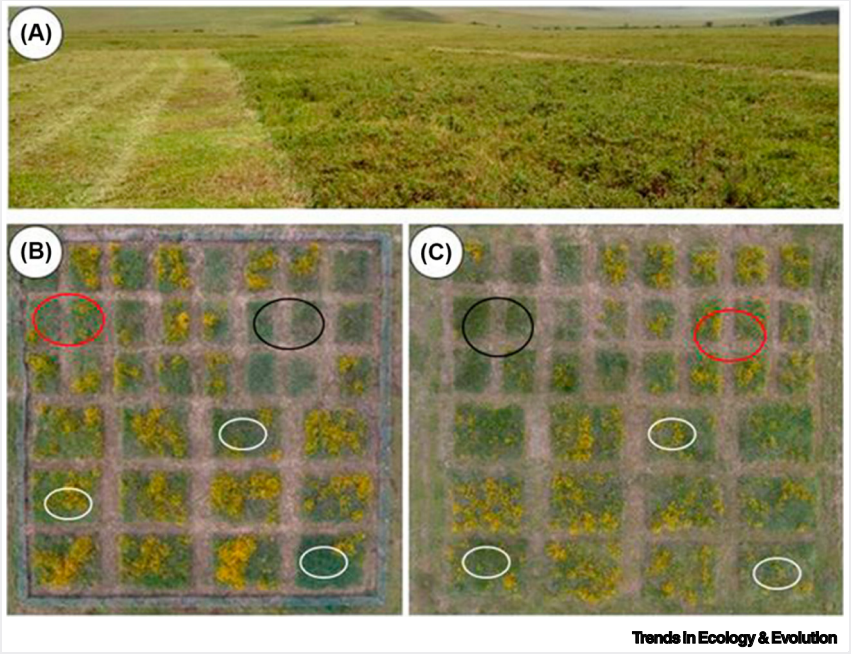

Figure II. A field experimental plot within Ngorongoro Crater in the Ngorongoro Conservation Area (NCA) demonstrating the effectiveness of the nature-based approach (NbA) (white circles = reseeding of 133 g/20 m^2 of *Cynodon dactylon* as the most competitive native fodder, red circles = reseeding of 50 g/6 m^2 of *Desmodium intortum*, and black circles = spraying of 100% *D. intortum* leaf extract from an allelopathic native plant). (A) Invasive plant biomass being cleared from the ground to maximize the effectiveness of the treatments, that is, before control experiment (yellowish vegetation = an invasive plant: *Bidens schimperi*); (B) and (C) are fenced and unfenced plots, respectively, where research on the control of *B. schimperi* was carried out for four (two wet and two dry) seasons for 2 years.

Invasive species are projected to increase in the near future [13], which implies that the number of invasive plants introduced per a complex landscape will also increase. Managing these invasives using conventional methods is likely to be challenging due to differences in traits, habitats, and restricted use of some control methods in protected landscapes. While the use of 'cover crops' and 'competitive plant varieties' in suppressing invasive plants has been recommended in farmlands [14], it is evident that some native species are likely to play such a role in complex landscapes while leaving the ecosystem uncompromised. Similarly, there is an emerging opportunity that nature provides for managing invasive plants which needs to be utilized – 'allelopathy' [15], that is, a biological phenomenon by which a plant produces one or more biochemicals that influence the germination, growth, survival, and reproduction of other plant(s). Identifying such native plants will add to effective management of invasive plants through intercropping [9] or by spraying invaded areas with their natural crude extracts [3]. When combined together, the use of (i) native allelopathic plants, (ii) native plants that provide greater soil cover, and (iii) highly competitive native plants while managing invasive plants' pathways and drivers, together with a good understanding of the species involved and practicing adaptive governance, provide an opportunity as an approach for managing invasive plants (Figure 1). The use of NbA in managing invasive plants is likely to be limited by social and ecological complexities surrounding the invasives and invaded landscapes; and its effectiveness may vary on a case-by-case basis depending on species, cost-effectiveness, stakeholder, and/or region.

With the continued increasing rate of invasion, we urge that NbA is the best fit approach for managing invasive plants in complex landscapes that continuously face pressures due to demand for land for various uses. Open concepts such as NbA can be useful because they encourage stakeholders to take part in the dialog and provide an opportunity to apply aspects such as indigenous knowledge in managing invasions. Perhaps one answer to NbA is to consider it as an umbrella term for all related applications of ecosystem services, natural capital, and 'lessons from nature' in managing invasions. If implemented properly, NbA can provide solutions to eradicate invasives, restore degraded biodiversity, and help ecosystems become more resistant to future invasions. With ecosystems such as grasslands and forests, we strongly recommend that authorities invest more in research to develop more NbAs that utilize available flora and fauna to generate solutions that can not only manage invasive plants but also other environmentally-related challenges.

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Declaration of interests

The authors declare no conflict of interest.

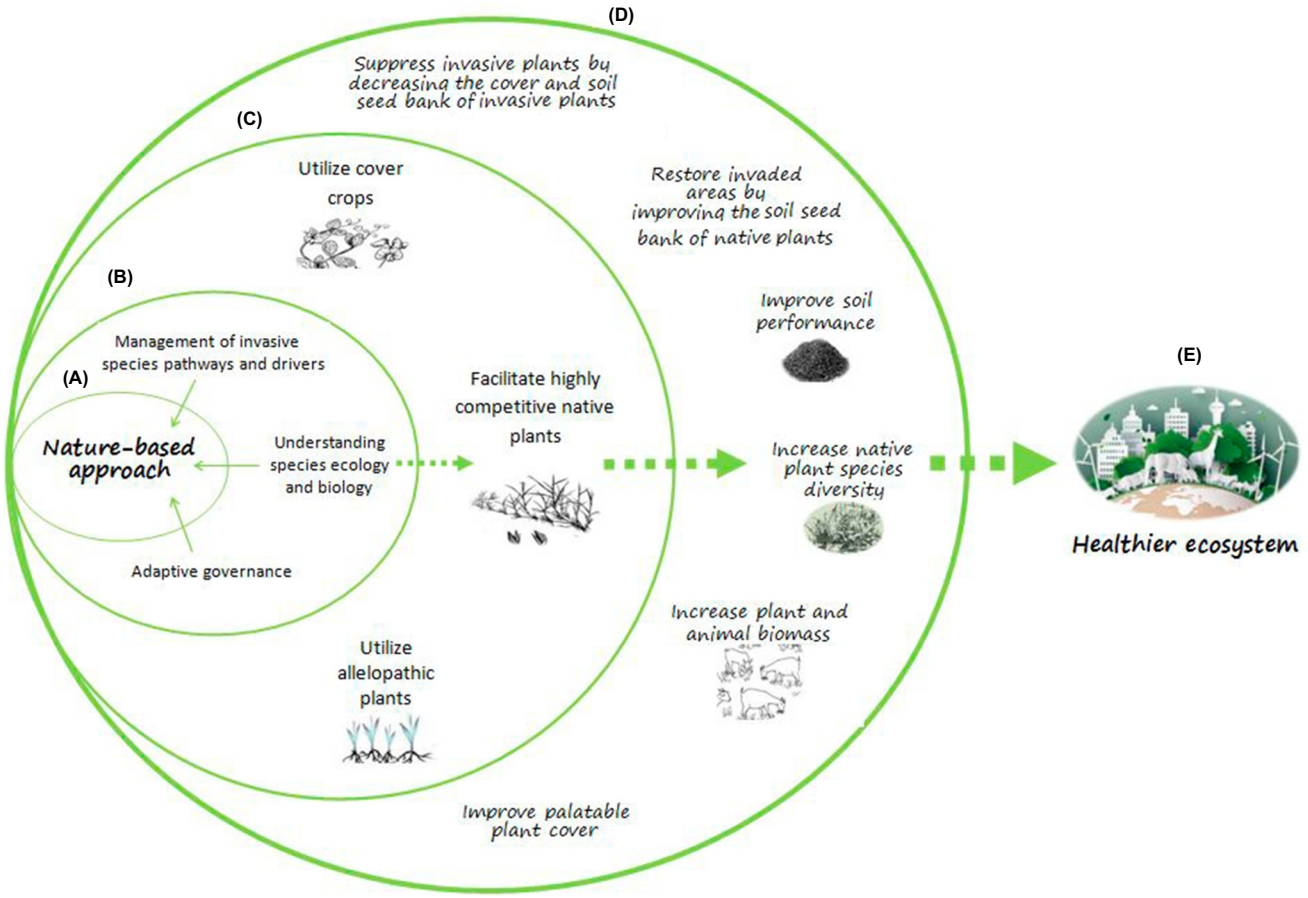

Figure 1. A nature-based approach for managing invasive plants (A). The approach anchors at three pillars: (i) adaptive governance, (ii) management of invasive plants pathways and drivers, and (iii) a good understanding of the ecology and biology of invasive and noninvasive plants (B). It involves facilitation and manifestation of the most competitive native plants that coexist with invasive plants and those native plants that either improve soil cover or have an allelopathic effect on targeted invasive plants (C). These natives when coexisting with invasives can suppress invasive plants by decreasing both the cover of invasive plants and their soil seed bank, restore invaded areas by improving the soil seed bank of native plants, soil fertility, native plant's species diversity, and palatable plants' cover and weight (biomass), which in turn ensure food availability to other biota, for example, herbivores and carnivores, along the food chain (D), leading to the formation of a healthier ecosystem (E).

Resources

[i]https://iucn.org/theme/protected-areas/about/protected-area-categories

[ii]https://population.un.org/wpp/Download/Standard/Population/

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