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Measuring rewilding progress

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Summary

Rewilding is emerging as a promising restoration strategy to enhance the conservation status of biodiversity and promote self-regulating ecosystems whilst re-engaging people with nature. Overcoming the challenges in monitoring and reporting rewilding projects would improve its practical implementation and maximise its conservation and restoration outcomes. Here, we present a novel approach for measuring and monitoring progress in rewilding that respond to a pressing need for developing monitoring guidelines informed by the best available science. We devised a bi-dimensional framework for assessing the recovery of processes and their natural dynamics through a) decreasing human forcing on ecological processes and b) increasing natural complexity of ecosystems. The framework incorporates the reduction of material inputs and outputs associated with human management, as well as the restoration of natural stochasticity and disturbance regimes, landscape connectivity and trophic complexity. Furthermore, we provide a list of potential activities for increasing ecosystem complexity after reviewing the evidence for the effectiveness of common restoration actions. For illustration purposes, we apply the framework to three flagship restoration projects in the Netherlands, Switzerland and Argentina. This approach has the potential to broaden the scope of ecological restoration, facilitate sound decision-making and connect the science and practice of rewilding.

Introduction

Increasing global consumption of natural resources, population growth and rapid environmental changes have led to widespread loss and degradation of ecosystems [1–3], with potentially serious consequences for biodiversity and human well-being. These global changes involve different degrees of simplification and homogenization of natural systems, from defaunation that cascades through trophic networks reducing

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ecosystem function [4] to extreme depletions of biodiversity in intensively transformed ecosystems as land use changes proceed [5].

Rewilding is emerging as a promising restoration strategy in a human-dominated world to promote self-sustaining ecosystems and enhance the conservation status of biodiversity [6–9]. The idea of rewilding is gaining momentum and becoming increasingly influential in restoration ecology and conservation science. Paul Jepson recently posited that rewilding initiatives are leading to the emergence of an empowering environmental narrative that he labels 'Recoverable Earth' [10] and places the restoration of ecological systems at the centre of societal change. In addition, rewilding is viewed as a possible pathway societies can take towards sustainability [11], since it has the potential to generate co-benefits that extend beyond natural heritage conservation [e.g., 12–14].

Recent studies describe rewilding as a nature restoration action that emphasizes the dynamic character of ecosystems and that explicitly acknowledges the role of reducing human forcing of the system [14,15]. Furthermore, rewilding initiatives aim to give response to public demand for a sense of 'wildness'[16], strongly supporting the emotional value of exposure to perceived untamed nature. With the number of rewilding initiatives growing [10,17,18], it is imperative that monitoring and assessment plans are developed and adopted. Overcoming the challenges in monitoring and reporting in rewilding projects would improve the practical implication of rewilding and maximise its conservation and restoration outcomes. In this study, we adopt the definition of rewilding as the process of restoring the structural and functional complexity of degraded ecosystems while gradually reducing the human influence [15]. Underpinned by this idea, we aim to provide a framework for measuring and monitoring the natural complexity of ecosystems and reducing the human forcing on these (thereafter referred to as 'measuring rewilding progress'). As a starting point, we focus on rewilding as a nature restoration action, whereas the broad socio-economic consequences and requirements of rewilding, though important, are out of the scope of this paper.

Approaches to monitor restoration progress and success rely on the quantification of indices of recovery progress [19,20], recovery completeness [21] or both [22], which compare degraded, restored, and intact reference ecosystems. In all these cases, a key step in assessing restoration progress is finding and agreeing on a reference ecosystem, though increasingly considering environmental change. Furthermore, organizations such as IUCN and the Society for Ecological Restoration (SER) provide guidelines to audit restoration projects [23,24]. One of the key principles underpinning these guidance documents is restoring the natural integrity of ecosystems. To that end, natural integrity is mainly assessed by monitoring the structure, function and composition of an ecosystem in the IUCN guidance (https://www.iucn.org/content/ecological-restoration-protected-areas-principles-guidelines-and-best-practices)[23], whereas the SER guidelines propose monitoring the absence of threats, physical conditions, species composition, structural diversity, ecosystem functionality, and external exchanges (https://www.ser.org/page/SERStandards)[24]. However, there is no restoration monitoring framework at present that balances the human forcing on natural processes and the changes in ecosystem complexity.

Within this restoration context, rewilding is aligned with newer visions of restoration [e.g., 'Restoration v2.0' 25, or 'open-ended restoration' 26,27] that are process-oriented and recognize the dynamism of landscapes and of ecological processes (Hiers et al., 2016; Higgs et al., 2014; Rohr et al., 2018). These approaches use historical knowledge as a guide and not as a template for determining restoration goals, highlight the continuing dynamic nature of the ecosystem as an embedded restoration goal, accept multiple potential trajectories for ecosystems, emphasize process over structure and composition, embrace pragmatic approaches to address human livelihoods and cultural needs, and are particularly useful from landscape to larger scales (Higgs et al., 2014; Hughes et al., 2012, 2016; Palmer et al., 2005; Stanford et al., 1996). Our framework for measuring rewilding progress does not conceptually departs from these guiding principles but it rather emphasizes some specific aspects mentioned above and further developed in the next section.

Here, we present a novel approach on how to measure and monitor rewilding progress. We devised a bi-dimensional framework to measure and monitor the recovery of processes and their natural dynamics through a) decreasing direct human inputs and outputs of materials into the system and b) restoring the natural complexity of ecosystems [15,32]. This framework also allows the comparison of rewilding trends between areas. For this, we propose the use of state variables and associated indicators describing the human control over the system and the ecosystem's natural complexity to measure its position along a natural condition gradient. This approach has the potential to broaden the scope of ecological restoration, facilitate sound decision-making and connect the science and practice of rewilding.

A bi-dimensional monitoring framework

Conceptual framework

Building on recent ecological research developments, we assume that the condition of ecosystems is a function of the intensity of human forcing over natural processes and the system's natural complexity [15]. We defined a bi-dimensional space to capture these two dimensions (figure 1), and identified a set of state variables contributing to each of the two axes (table 1). The position of the system in that space can change as a result of restoration actions, thus allowing the measurement and monitoring of rewilding through time.

In this framework, both axes capture changes in the natural condition of the system at different temporal scales. The axis of human inputs and outputs (*H*), captures the impacts of direct human forcing on the ecosystem at the time of measurement; thus, changes in management regimes will immediately be captured by changes in the rewilding score on this axis. This metric of human control can be considered an application of the 'cultural energy' framework in Anderson, 1991, whereby the 'unnaturalness' of a system can be quantified by the degree of human-associated energy inputs required to maintain the ecological system in its current state; however, instead of measuring the actual energy inputs, we propose measuring indicators of human inputs and outputs that can be readily assessed by practitioners without specialized knowledge or data. On the other hand, the natural complexity axis (*N*) is affected by human legacy effects on ecological composition, structure and functions. Hence, there will be temporal lags – from days to even centuries – between the implementation of restoration actions and the resulting increase in the complexity of system [21,34]. In other words, these human legacies (e.g., caused by roads or dams) and the natural dynamics of ecosystems including species colonization and extinction rates constitute the ecological inheritance of the ecosystem and will determine its trajectory into the future [26]. Uncovering these human legacies contributes to explaining the distinctive characteristics of a rewilding area, identify constraints or challenges in shaping the ecosystem in the future and plan active restoration actions (e.g., road or dam removal).

The human forcing on natural processes and ecosystem dynamics is defined here as a function of the direct human inputs and outputs of material into the systems that are linked to today's management:

$$H = f(i, o)\#(2.1)$$

where *i* corresponds to material inputs into the system (e.g., baiting of wildlife) and *o* to material outputs (e.g., timber production, hunting, mining). While some indicators combine both inputs and outputs (e.g., agricultural production), we do not quantify inputs and outputs separately. Importantly, this axis also captures impacts from management activities (e.g., removing deadwood for pest control or wildlife population control) and, in some cases, conservation management activities with a direct influence on the system dynamics, such as population reinforcements that are expected to have a limited duration. That said, certain rewilding projects might require an initial level of active restoration to overcome constraints that prevent full restoration of natural processes that eventually will translate into an increase of natural complexity.

Whilst most approaches to monitor restoration progress focus on the composition, structure and function of ecosystem [24,35], we consider that the natural complexity of ecosystems is defined according to three core principles critical for self-sustaining ecosystems, namely to 1) allow for natural stochasticity and disturbances influencing ecological processes [36]; 2) enhance completeness of degraded trophic networks [8]; and 3) increase landscape connectivity of terrestrial and aquatic systems [37]. For instance, it has been shown that natural disturbances contribute to ecosystem-level processes (e.g. primary production, sedimentation, ecological succession), species interactions (e.g. trophic relationships), structural effects (e.g. development of mosaics of habitats), and allowing intraspecific processes (e.g. migration in rivers) (table 1). Likewise, recovering diverse species communities requires maintaining viable populations and enabling the recovery of declining and depleted populations, though rare species could also allow dynamism to the system.

We adopt these three guiding principles as normative standards for measuring the natural complexity of the system in the *N* axis:

$$N = g(d, c, t) \#(2.2)$$

where *d* represents the naturalness of disturbances and stochastic events, *c* the connectivity of terrestrial and aquatic systems, and *t* the composition and complexity of the trophic network. The value of these three components should be increased to initiate a rewilding process. By considering the interaction among these ecosystem components, this approach allows us to gauge the ability of an ecosystem to support and maintain ecological processes and biodiversity as well as for adapting to ongoing and future changes [38]. Human legacy effects on ecosystem dynamics, for example harmful invasive species competing with ecologically important native species or altering ecological processes, are accounted for in this axis.

Within this framework, people can exist and thrive in the rewilding system without the target area being substantially penalised as long as their activities do not compromise the progress towards decreasing the human forcing of ecological processes and increasing the natural complexity of the system (e.g., non-extractive industries, controlled eco-tourism). In other words, there is space for human activities that penalise for a minimal amount.

Operationalising the framework

The framework presented here was developed combining expert knowledge, analysis of data and feedback from stakeholders including conservation and rewilding practitioners in an attempt to balance between the reliably recording ecological changes (i.e., how accurately the score reflects the natural condition of the system) while ensuring real-world applicability (i.e., the degree to which the approach could be routinely operationalized with the best available knowledge or data). Our focus was on expert practitioners who gained expertise in rewilding initiatives by applying their practical, technical or scientific knowledge to solve questions of ecosystems restoration. To select experts from each case study, we first identified the type of expertise required to monitor rewilding progress including understanding of the complexity of different ecosystem components and familiarity with spatial information. Then we considered the spatial and temporal scope of the study. Finally, we selected experts with demonstrated background on the study system in the field, and the professional connection to conservation or restoration agencies [39].

Our set of state variables and indicators allows measuring the rewilding progress on a particular unit, namely the rewilding project. This focal unit may be defined at any spatial and temporal extent. Nevertheless, we recognize that human infrastructure and activities beyond the spatial boundaries of the rewilding area might interfere with the recovery of its natural completeness, in particular through their impact on connectivity and dispersal. In addition, because of the slow speed of expected ecosystem recovery and the long-term nature of rewilding projects, 5-year or longer monitoring cycles are recommended (Hughes et al. 2016).

To select state variables and indicators, we drew up a list of the major human inputs and outputs into ecosystems, and of potential indicators that could be used to describe the naturalness of disturbance regimes, landscape connectivity and composition, and trophic processes. We then revised the indicators to ensure that they were conceptually independent and that they were implementable by practitioners without specialist knowledge (for instance, the deviation of the existing vegetation community from the pre-human baseline vegetation community was dropped as assessing this baseline with any degree of certainty would require intensive paleo-ecological analysis). In addition, following best practices, indicators should ideally be: 1) feasible to monitor; 2) useful at multiple spatial and temporal scales; 3) practical to implement, without prohibitive technical or financial requirements; 4) respond predictably to human impact; and 5) represent a causal impact on the desired outcome [40–42]. It was also essential that practitioners can quantify these indicators in a standardised and replicable manner across a range of scenarios and contexts. We assembled a suite of 18 indicators tied to particular restoration actions, from passive or non-intervention to active management (table 1 and table S1). These include a combination of quantitative and qualitative indicators, with the emphasis given to indicators that best navigate the trade-off between simplicity and accuracy. We adopted quantitative indicators where we felt the technical capabilities required were realistic for practitioners. For the qualitative indicators, we adopted an approach that used a combination of multiple qualitative indicators to reduce biases affecting any individual indicator.

In the bi-dimensional space (figure 1), it is possible to compare systems described under the same set of components and to monitor changes in time. The framework informs on the system's state at a certain time relative to the maximum plausible long-term improvement that could be achieved for each state variable in terms of maximizing natural complexity. To do so, we give a score (S) to each state variable. The scores are described on a continuous 0-1 scale, in which 1 represents the maximum intensity of human forcing (H_{max}; for variables in the *H* axis) or the maximum natural complexity (N_{max}; for state variables in the *N* axis, e.g. hydrological regime is not regulated), and 0 represents an area without human inputs or outputs into the system (H_{min}) or with minimum influence of human legacy effects on ecosystem composition, structure and functions (N_{min}), respectively. Reference values for each indicator are proposed in tables 1 and S1, which also provide guidance for expert assessments.

The score for each of the four components of the framework is calculated as the average standardized scores of the state variables within such component. Thus, a normalized score on a continuous 0-1 scale is obtained for the human inputs and outputs into the system ($\overline{S\iota o}$), the naturalness of disturbance regimes ($\overline{Sd}$), the landscape connectivity ($\overline{Sc}$), and the trophic complexity ($\overline{St}$). Next, the position of a given system in the *N* axis is calculated as the geometric mean of the scores for the naturalness of disturbance regimes, the landscape connectivity, and the trophic complexity. This integration emphasizes the critical role of the interactions among the three ecosystem components in rewilding. In addition, the use of a geometric mean indicates the central tendency the set of components defining the natural complexity of ecosystems by using the product of their scores.

Finally, the values for the *H* and *N* axes describe the position of a given system at a snapshot in time. The combination of both values yields a total cumulative rewilding score (*R*):

$$N \cdot (1 - H) = \left(\sqrt{\overline{Sd} \cdot \overline{Sc} \cdot \overline{St}}\right) \cdot (1 - \overline{S\iota o})\#(2.3)$$

where *R* values range from 0 to 1. For a particular site, a higher positive change in *R* means a higher success of rewilding, i.e. a reduction in human forcing over natural processes and/or increase in natural complexity. Given that they are based on a standardised set of indicators, *H*, *N* and *R* can be compared across diverse rewilding projects. However, a complementary set of additional indicators could be tailored specifically for any given rewilding project to capture the local nuances. In this case, however, the general equation including distinction of the components – namely, direct human inputs-outputs, naturalness of disturbance regimes, landscape connectivity and complexity of trophic networks – may no longer be comparable between systems.

Evidence-based restoration actions for rewilding projects

Rewilding initiatives need to move beyond anecdote, personal experience, expert criteria, and conventional wisdom, towards a more systematic appraisal of evidence collected by practitioners tackling a given restoration action. Here, together with the list of state variables and indicators, we provide a list of management activities for increasing ecosystems complexity based upon the review of evidence related to the effectiveness of commonly used restoration actions inspired by the Conservation Evidence approach (www.conservationevidence.com)[43]. Thus, for each state variable and indicator in the framework, we identified the key restoration action that could be implemented in order to increase the score for that state variable (e.g., state variable 'deadwood removal', restoration action 'do not remove deadwood in ecosystems').

We gathered evidence on the effectiveness of 16 restoration actions by reviewing 137 primary studies from key scientific journals for each action. We used Web of Science and Google Scholar to identify and reviewed primary studies evaluating the evidence for each action where available. When no reviews were identified, we searched for studies on each topic published since 2014, and used these publications to identify further relevant studies for evaluating each action. Next, we reviewed the collated evidence and added further key studies when required. Then, we summarized the evidence for each restoration action in table S2 and scored these activities from 0 to 4 according to the effectiveness of the intervention (e.g., 2 - 'trade-off between benefit and harm', 4 - 'Beneficial'). We conceive these evidence syntheses as a key first step towards systematic revision of evidence for the effectiveness of each restoration action in the context of rewilding projects.

Case studies

To illustrate and test the framework, we applied the assessment to three flagship restoration projects with very different characteristics: the rewilding area of Millingerwaard in a highly urbanized landscape 10 km outside Nijmegen (the Netherlands); the Iberá Project (Argentina), which is one of the largest naturalised inland wetland systems in South America [44]; and the Swiss National Park (southeast Switzerland), which has been managed to minimize the human control of ecological processes for over a century (table 2, figure 2). As the knowledge required was highly context-specific (and thus, the number of experts was very limited), we contacted one practitioner per study area. They were invited to fill in a questionnaire that compiled the indicators previously mentioned. The expert provided a score for each indicator at the beginning of the rewilding project and at present. The encoding schemes were documented by a guidance document that included an extended description of the indicators, reference values, and examples (table S1). This makes it possible to scrutinize the methods and to reproduce and validate the assessments. Finally, reception of the questionnaire was followed up by an interview to ensure a consistent assignment of scores.

Results and Discussion

The monitoring framework proposed here has been shown to be applicable to measure rewilding progress across three different restoration contexts. Our results indicate some clear trends resulting from the set of restoration strategies in the case studies (figure 2), although caution should be used when inferring general conclusions. Firstly, the overall rewilding score increased across all sites as a result of the rewilding initiatives. Secondly, the species richness and viability of populations of large animals increased universally since the beginning of the projects, which is consistent with the successful active reintroduction efforts and spontaneous recolonisation of species across sites. Thirdly, human outputs from ecosystems either decreased or remained stable across all sites, including notable reductions in hunting and agricultural production in both Millingerwaard and Iberá since the projects started. Finally, in areas where fire occurs either naturally or because of ecological management, fire regimes have become more natural over the course of the rewilding initiatives.

Whilst the rewilding scores increased over time in the different areas, the magnitude of changes in natural complexity and human forcing differed across areas. Although the Millingerwaard project started from a considerably less wild baseline than the other projects, it experienced substantial increases in the natural system’s condition along both dimensions. This improvement was in part associated with the transition from farmland to natural grazing areas and the restoration of the natural hydrological regime via dam and dyke removal. The Swiss National Park has undergone a complete reduction in direct human inputs and outputs since 1914, driven by the end of the Alpine ibex (*Capra ibex*) reintroduction programme occurring in the reserve's early years and accompanied by artificial feeding initiatives. Over the course of the project, the ecological succession has significantly progressed in the area. Had it not been for the reservoirs that were built during this period within the park’s boundaries, the natural complexity would have increased even more. This infrastructure fragmented the aquatic habitats and affected the natural hydrological regime, which is now artificially regulated to improve the ecology of the river [45]. Finally, the Iberá project experienced an increase in natural complexity over the past decades mainly driven by increases in the number of large mammal species and the viability of populations associated with the project's ambitious reintroduction programme [46] and woody expansion. On the other hand, the associated intensive management effort to facilitate the recovery of wildlife species that were hunted to extinction during the twentieth century has increased the human inputs in the systems. Nevertheless, it is expected that this score improves in future years if the reintroductions are successful and these management activities can be reduced.

This is the first attempt at establishing and implementing a generalised practical monitoring framework for rewilding initiatives, meeting a clear need highlighted in restoration [47]. Our study fills an important gap in applied rewilding science, namely the identification of a set of restoration actions and their associated results that define ecological restoration following the rewilding principles. Measuring changes in rewilding facilitates the achievement of several goals, including i) assessing progress in increasing the natural complexity of ecosystems and the reduction of human forcing over them, and ii) incentivizing rewilding ambitions beyond a single component of the framework such as increasing trophic complexity. Further, our definition of rewilding progress combining human inputs and outputs with measures of the natural stochastic and disturbance regimes, landscape connectivity and trophic completeness contributes to a scientifically robust rationale for the guidance and operationalization of rewilding.

One strength of this framework is that it recognizes that exclusive reliance on reducing direct human inputs and outputs into the system might not immediately translate into an increase of the system's natural complexity. Specifically, this may occur because of long lag times of recovery or land-use legacies in systems that have undergone intense landscape transformation resulting from intensive management or infrastructure development. An obvious example - which many rewilding projects address - is the large-scale extirpation of ecologically important species, where recovery may lie hundreds or thousands of years into the future without assistance [48]. Therefore, whilst the framework incentivises initial interventions through immediate changes in the human inputs and outputs, it also intrinsically lays out long-term ecological targets for the system (i.e. the recovery of more complex ecosystems), providing guiding goals for rewilding in the medium- and long-term. Moreover, the fact that the framework monitors not only the condition of the ecosystem at a given time, but also how human activities might be expected to influence its future condition, makes the framework an almost uniquely forward-looking approach for monitoring restoration outcomes.

The framework provides readily applicable indicators to assess rewilding in projects involving very different spatial and temporal scales and under contrasting settings from urban areas to extensive natural land. However, the framework also allows for the refinement and inclusion of new indicators as needed. Future iterations might incorporate the community composition of aquatic systems in a manner similar to the one we have implemented for terrestrial communities, and potentially include indicators representing the degree to which large-bodied terrestrial and aquatic species are able to fulfil their ecological function. The framework could even be taken forward to marine ecosystems [47]. The addition of biodiversity indicators of small-bodied species such as insect community composition and diversity would assist with capturing rapid ecological changes resulting from restoration actions (van Klink et al., this special issue). Information from the surrounding landscape could help identify off-site influences, which in some cases may need to be reduced or eliminated before restoration can be successful. For instance, expanding the connectivity indicators to capture regional-scale connectivity would facilitate understanding the role of the area in landscape-scale processes such as metapopulation dynamics, dispersal, and migration [49]. Finally, indicators that are currently qualitative because of lack of data availability, or the requirement of prohibitive technical skills, might be transformed into quantitative indicators when high-quality data is readily available.

While we contend that our approach reasonably captures rewilding progress, we acknowledge a set of limitations to be addressed in future work. Firstly, caution should be taken when comparing the progress of initiatives occurring over considerably different spatial or temporal scales. For example, the Millingerwaard project scored more positively on the fragmentation indicators than the Swiss National Park project, despite the latter contains a far greater extent of continuous habitats owing to the project being over 20 times the area of the former. Furthermore, the changes in natural complexity in the Swiss National Park have occurred over the last century, in contrast with 28 and 19 years associated with the Millingerwaard and the Iberá projects, respectively. Comparisons of the absolute magnitude of the changes in *R* scores between different sites should appreciate the alternative spatial and temporal contexts, and in any case this framework is designed to monitor progress in the mid to long term.

Secondly, some of the indicators are more sensitive to changes than others, meaning that differential amounts of effort are required to induce changes in the various indicators. For instance, reducing agricultural production or removing a large dam requires more effort than ceasing deadwood removal. Future iterations of the framework might weight the different indicator contribution to the overall score relative to the sensitivity of those indicators [50]; this would prevent rewilding initiatives from 'gaming' their scores by selecting management actions that are easier to pursue without confronting some of the more critical constraints [51,52]. In relation to potential constraints, some authors have argued in favour of substitutions for restoring missing ecosystem functions [8,53]. Recognizing the uncertainties and controversies associated to these taxon substitutions [54], these could be eventually integrated into the framework for those cases where evidence-based guidelines for implementing taxon substitution become available.

As for other type of restoration [23,24], the goals of rewilding projects go beyond improving natural complexity of ecosystems and its success will be dependent on the local context and the way it benefits and engages with people [55]. Rewilding is not yet at the stage where a unified framework has been developed for

integrating economic, social and cultural considerations into projects, but the concept is moving in that direction and it is an obvious next step for further work. Our method focuses on human management and ecological complexity, which may in some cases induce trade-offs between rewilding progress and alternative socio-economic objectives [56]. However, activities are penalized only if they affect ecosystem processes, so sustainable uses with minimal impacts on ecological processes will be penalized proportionally little. Therefore, we argue that all but the uppermost extreme system's scores can be achieved whilst balancing a multitude of socio-economic benefits [57]. Nevertheless, in order to capture the impacts of non-extractive human forcing of ecological processes, future developments might define an acceptable upper bound to indirect human interventions and integrate this within our framework. We stress that achieving the highest score should not be considered as the default objective or ambition, but that gradual increases in the natural condition of ecosystems at lower and intermediate scores can constitute a sensitive restoration target in many situations where it is critical to balance the socio-economic consequences. In these cases, our monitoring framework should be used in conjunction with other socio-economic management objectives to optimise the trade-off between maximizing ecosystem complexity and delivering sustainable socio-economic value to communities and users [58]. For instance, involving people through multiple avenues – from participation to sustainable consumption of ecosystem goods and services to cultural renewal – can promote public engagement and stewardship of local ecosystems and improve restoration success [59].
, and non-extractive uses such as wildlife watching are not penalized in its present form.

The approach presented here responds to calls to better integrate the science and practice of rewilding [60,61]. Although there are challenges remaining, we believe that the implementation and further development of our monitoring framework will help catalyse a positive and ambitious vision for rewilding. Furthermore, the application of this framework provides guidance for practitioners, funders and decision makers to incorporate or demand a multifaceted perspective for rewilding initiatives and, simultaneously, incentivize conservation initiatives to go beyond the recovery of species and habitats and include ecosystem function and processes.

Additional Information

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Data Accessibility
The datasets supporting this article have been uploaded as part of the electronic supplementary material.

Authors' Contributions
WH, DS, NF, AT, FS and HMP conceived the study. All authors defined the conceptual framework in the context of a workshop. AT, NF, SzE and AP wrote the draft of the paper. All authors contributed to revisions of the manuscript and approved the final version to be published.

Competing Interests
WH, DS and FS works at Rewilding Europe. They have endeavoured to be as honest and balanced as possible and to write in the spirit of academic discussion rather than organisational promotion.

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Tables

Table 1.

State variables	Indicator	Score	Restoration action	EF
DIRECT HUMAN INPUTS AND OUTPUTS				
Artificial feeding of wildlife	Is artificial feeding of animals allowed, and how influential is it on ecological processes?	0 - No artificial feeding; 0.5 - Some type of artificial feeding is provided at levels unlikely to significantly affect animal movements, species diet, seed dispersal and other ecological processes; 1 - High levels of artificial feeding and/or evidence for feeding affecting ecological processes (e.g. artificial food is an important component in the diet of a species).	Reduce to a minimum or eliminate any type of artificial feeding that may potentially influence animal behaviour and ecology	2
Population reinforcement	Have any animals been (re-)introduced into the area within the last years?	0 - No population reinforcement at least during the last year; 0.5 - Species populations of conservation concern sporadically reinforced to improve their conservation status; 1 - Regular to intensive population reinforcement for the conservation of populations that would otherwise decline, or reinforcement of non-declining populations or populations of no conservation concern.	Establish self-sustaining populations so that further population reinforcement is unnecessary	0
Agricultural outputs	Cropland area and farming intensity	$\sum H_{crop} \times \%_{crop}$ Where: $\%_{crop}$ = proportion of the total rewilding area devoted to cropland, H_{crop} = 0 - No harvested or fallow for at least 5 years (i.e. land abandonment); 0.5 - Cropped and harvested under traditional, extensive farming practices; 1 - Intensive harvesting, every year	Reducing farming intensity and extent (land abandonment)	2
Forestry outputs	Forest area dedicated to forestry production (e.g. wood, timber, pulp) and forest management intensity	$\sum H_{logg} \times \%_{logg}$ Where: $\%_{logg}$ = proportion of the total rewilding area devoted to production forestry, H_{logg} = 0 - No logging for at least 5 years; 0.5 - Selective logging; 1- Clear-cut logging	Cessation and/or reduced harvesting. This should prioritise old-growth forest	4
Grasslands outputs	Grassland area dedicated to hay and livestock production and intensity of production. Free-roaming wild ungulates	$\sum H_{grass} \times \%_{grass}$ Where: $\%_{grass}$ = proportion of total rewilding area devoted to managed grasslands,	Reducing mowing and ploughing in grasslands, reducing complementation and	2

	do not count towards this indicator	H_{grass} = 0 - No harvesting for at least 5 years (land abandonment); 0.5 - Mowed under traditional, extensive farming practices; 1 - Intensive harvesting or very high livestock stocking densities	reducing livestock intensity	
Mining outputs	Area devoted to mining and intensity of the impacts of mining on the ecosystem	$\sum H_{mine} \times \%_{mine}$ Where: $\%_{mine}$ = proportion of total rewilding area devoted to open mining, H_{mine} = 0 - No mining for at least 5 years; 0.5 - Mining with non-destructive production practices (e.g., artisanal mining) and strict regulation and mitigation of pollution; 1 - Intensive mining with destructive mining practices and clear evidence of degradation	Reduce mining and mining impacts	3
Harvesting of terrestrial wildlife	Is hunting allowed? To what extent is the ecosystem affected by hunting?	0 - No hunting; 0.5 - low levels of hunting unlikely to significantly affect the growth rates of wildlife populations, animal movements, or other species with which hunted species interact; 1 - High levels of hunting and/or probable or demonstrated effects on the growth rates and/or the population structure of harvested populations or species interactions	Restriction of hunting	4
Harvesting of aquatic wildlife	Is extractive fishing allowed? To what extent is the ecosystem affected by extractive fishing?	0 - No extractive fishing; 0.5 – fishing only in artificial ponds or low levels of extractive fishing unlikely to significantly affect the growth rates of wildlife populations, animal movements, or species with which fished species interact; 1 - High levels of extractive fishing and/or probable or demonstrated effects on the growth rates and/or the population structure of harvested populations or species interactions	Restriction of extractive fishing	4
Carrion removal	Does regulation permit leaving medium and large carcasses in the field?	0 - Carcasses from wild animals and extensive livestock are left in the field; 0.5 - Carcasses of wildlife are left in the field, those from extensive livestock are removed; 1 - All carcasses are removed from the field	Legislative change to permit leaving carcasses in the field	2
Deadwood removal	Is deadwood (dead trees and woody debris) removed?	0 - No deadwood removal; 0.5 - Low levels of deadwood removal (e.g., on roads and footpaths) unlikely to affect disturbance regime, animal movements and other ecological processes significantly; 1 - High levels of deadwood removal	Allowing deadwood to remain in the forest	3
NATURAL COMPLEXITY				
Disturbance regimes				
Natural avalanche and/or rock slide	Are avalanche and/or rock slide regimes regulated?	0 - Regulation of avalanches and/or rock slides across the whole rewilding area; 0.5 - avalanches and/or rock slides only in certain places with risk for human life; 1 - No regulation of the avalanche and/or rock	Restoring the natural regime of avalanches and	3

regimes		slide regime.	rock slides	
Natural fire regimes	Are there deviations of the natural fire regime due to human pressures (this might be in either direction, i.e. fire suppression, or prescribed burning)?	0 - Fire regime heavily modified by human intervention including both artificial burning and/or fire suppression; 0.5 - Artificial burning and/or fire suppression is very localized and only cause minor ecological impacts; 1 - There are no deviations of the natural fire regime	Restoring the natural regime of fires, including restoration and/or natural regeneration of native fire-dependent vegetation	3
Natural hydrological regimes	Are hydrological regimes (including flood regimes) heavily modified?	0 - High regulation of the natural hydrological regime; 0.5 - Dams in place, but cause only minor impacts on the overall hydrological regime; 1 - No regulation of the hydrological regime	Restoring the natural hydrological regime (e.g., removing dykes, channels, dams)	3
Natural pest regimes and mortality events	Are natural pest regimes and mortality events regulated? Are management actions implemented after mortality events (e.g., storms, pests)?	0 - Management actions implemented to avoid pests (e.g., pesticide or vaccination use) or after mortality events (e.g., salvage logging, removal of burnt wood); 0.5 - Low levels of management to avoid pests or after mortality events, unlikely to affect disturbance regime, animal movements and other ecological processes significantly; 1 - No management to avoid pests or after mortality events	Passive restoration after mortality events (e.g., avoiding pesticide use) and avoid acting against natural pests	2
Landscape connectivity and composition				
Terrestrial landscapes fragmentation	To what extent is the landscape fragmented by human infrastructure? What is the effective mesh size of the rewilding area?	0 - Landscape highly fragmented (fully covered with heavily used infrastructure); 0.5 - Landscape crossed by low-traffic roads and infrastructure1- Landscape not fragmented	Restoring connectivity. Removing, bundling or reducing the extent of human structures (linear transport infrastructure and built-up areas excluding abandoned buildings).	4
Aquatic landscapes fragmentation	To what extent are migratory processes in river systems allowed?	0 - Fish migration fully impeded; 0.5 - Dams in place but alternative migration routes or fish cannons provided; 1 - No regulation of fish migration.	Restoring aquatic habitat connectivity	4
Spontaneous vegetation dynamics	What is the state of natural regeneration?	$\sum H_{time\ since\ abandonment} \times \%_{svd}$ Where: $\%_{svd}$ = proportion of area where spontaneous vegetation dynamics are allowed, $H_{time\ since\ abandonment}$ = 0.1 – early successional stages (< 50 years); 0.5 - (50 – 200 years); 1 - last successional stages adapted to each ecological region or biome (e.g., >200 years old growth forest). For	Allowing natural succession	4

		time since abandonment, allocate discrete scores (ie. not on continuous scale)		
Harmful invasive species	What is the impact of harmful invasive species on the rewilding area?	0 - Very severe impacts of invasive species on ecological communities in rewilding area; 0.5 Impacts of invasive species within small, localised communities within rewilding area; 1 - No major invasive species present	Removal of harmful invasive species	3
Trophic processes				
Terrestrial large-bodied fauna (>5 kg)	Species composition of large-bodied (>5kg) species	$\frac{\sum S_{curr} * T_{curr} * V_{curr}}{\sum S_{max} * T_{max} * V_{max}}$ Where: *S* is the space occupied by the species in the area, estimated from 0-1; *T* is the percentage of the time in a year that species are present in the area they occupy (estimated 0-1, except for migratory species that if present should score 1); *V* is the viability of the population to which the individuals of the species belong, can be larger than the focal area (estimated 0-1); *curr* denotes the values for each species at a given time; and *max* denotes the maximum possible value for each variable for that species (always equals 1)	Functional recovery of large herbivores, large carnivores, and large scavengers due to their important ecosystem effects via top-down trophic and coupled bottom-up and non-trophic effects.	3

Table 2.

Project	Ecological description	Initial sources of degradation	Main restoration actions developed	Ecological responses
Millingerwaard (The Netherlands) Project start: 1990 Size: 700 ha	Naturalised floodplain, matrix of grasslands, cropland and wetlands.	Use of land for agriculture. Dykes to reduce the flooding risk.	Dyke removal, restoration of natural hydrological regime, release of Konik horses (*Equus ferus*) and Galloway cattle (*Bos taurus*) to promote natural grazing, reversion of agricultural land to unmanaged. Reintroduction of beaver (*Castor fiber*) and Atlantic sturgeon (*Acipenser oxyrinchus*).	Recovery of riverine vegetation and ecological communities. Surplus of horses and bovines relocated away annually. Recovery of ecosystem engineers such as wild boar (*Sus scrofa*) and other native predator species including otter (*Lutra lutra*) and white tailed eagle (*Haliaeetus albicilla*).
Swiss National Park (Switzerland) Project start: 1914 Size: 17,000 ha	Large extent of alpine and sub-alpine habitats, including ca. 30% coniferous forest and ca. 20% grasslands. The area captures full successional gradient from short-grass pastures to Swiss stone pine stands (*Pinus cembra*).	Before 1914 the area was widely used for timber production and alpine farming.	IUCN category 1A nature reserve, affording strict protection to all natural ecological processes in the park (except fire, which is suppressed in most of the park). Reintroductions of the ibex (*Capra ibex*) in 1920s-30s and the bearded vulture (*Gypaetus barbatus*) in 1990s-2000s.	Uninhibited succession across the park, but subalpine grasslands are kept open at least partly through browsing pressure [62]. Viable populations of numerous large herbivores, including red (*Cervus elaphus*) and roe deer (*Capreolus capreolus*) and chamois (*Rupicapra rupicapra*), and of smaller predators such as the golden eagle (*Aquila chrysaetos*). Sporadic presence of lynx (*Lynx lynx*) and brown bear (*Ursus arctos*).
Iberá (Argentina) Project start: 1999 Size: 150,000 ha	Rain-fed wetland, with ca. 60% permanently flooded. Matrix of grasslands and forests [63].	Hunting of large terrestrial animals to extinction, grazing by livestock, burning of rangelands and logging of trees for timber	Multiple reintroductions including giant anteaters (*Myrmecophaga tridactyla*), pampas deer (*Ozotoceros bezoarticus*), collared peccary (*Pecari tajacu),* tapirs (*Tapirus terrestris*) and green-winged macaws (*Ara chloropterus*). A jaguar (*Panthera onca*) breeding programme has also begun [46]. Restrictions on agricultural activities.	Successful reintroductions of large animal species have led to recovery of viable populations, and restrictions on agriculture have promoted recovery within remnant forest fragments. Recovery of resident populations of marsh deer (*Blastocerus dichotomus*), capybara (*Hydrochoerus hydrochaeris*) and other species.

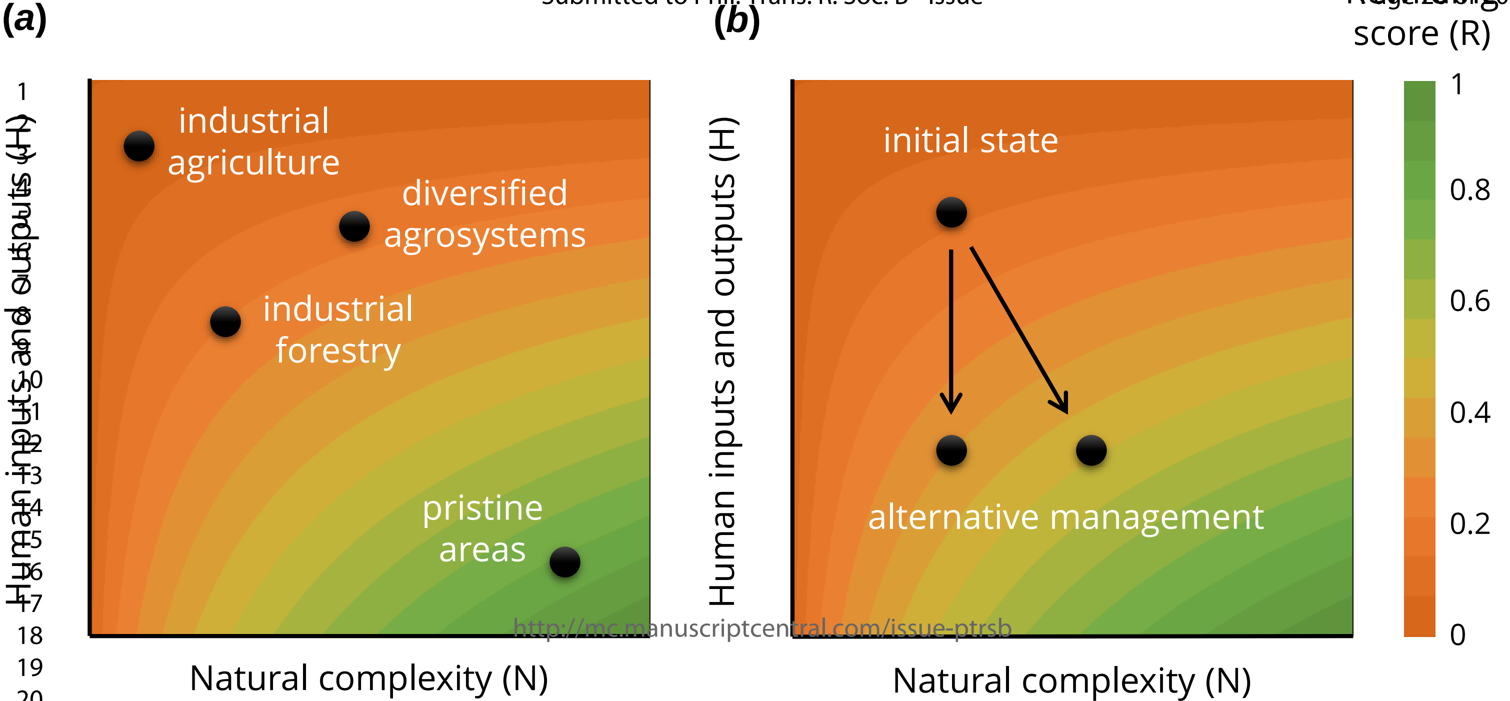
Figure and table captions

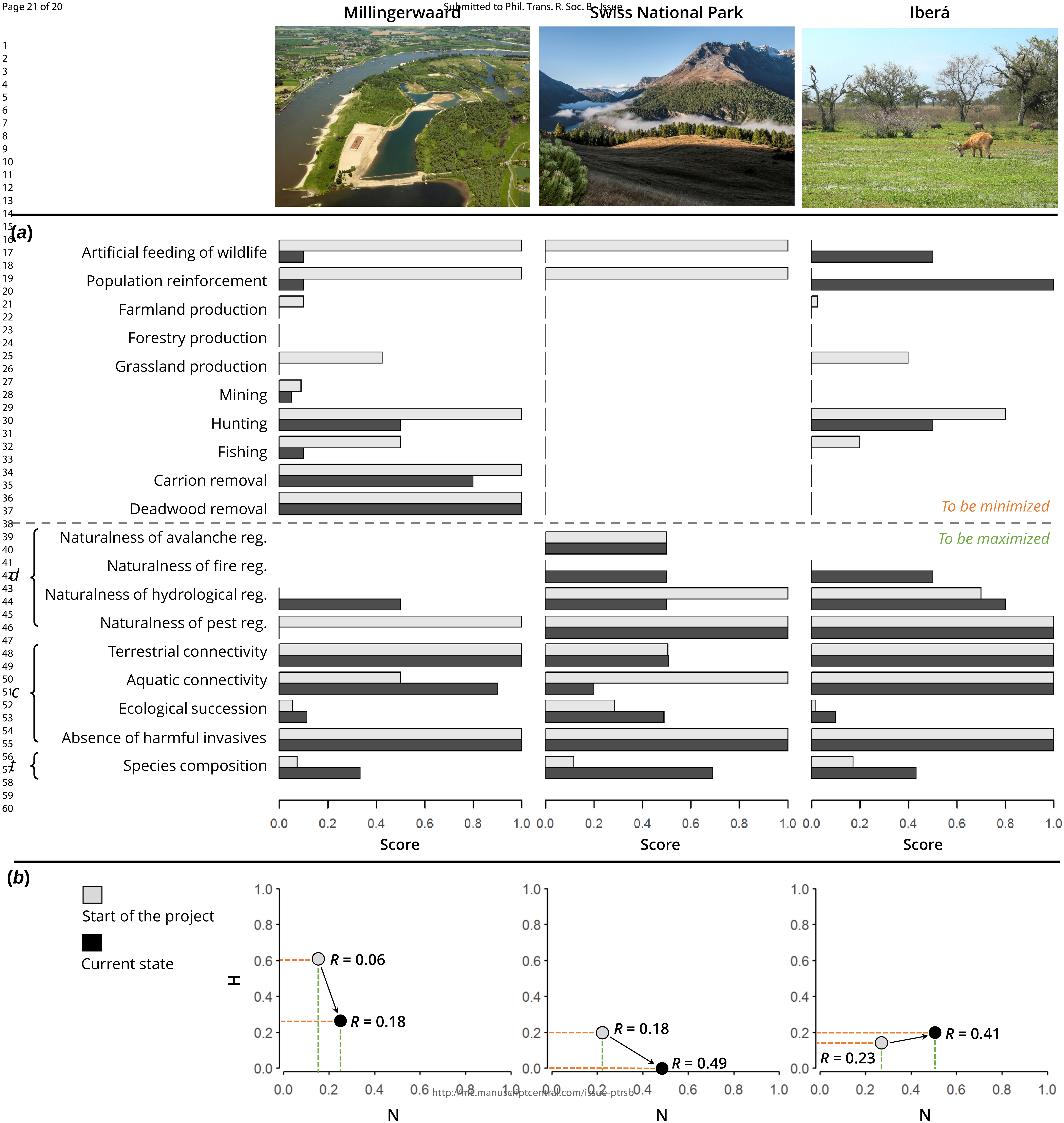
Table 1. List of state variables and indicators proposed for measuring rewilding progress, and associated restoration actions. The scores are assigned in a continuous scale from 0 to 1. Reference values provide guidance for expert assessments (further details in table S1). Effectiveness of restoration actions (EF) for achieving rewilding objectives – namely, to restore trophic processes, landscape connectivity, natural disturbance regimes and/or biodiversity – was based upon the review of evidence (table S2) inspired by the Conservation Evidence approach (www.conservationevidence.com) [43], where EF = 0: No evidence or unknown effectiveness of restoration action, EF = 1: Likely to be ineffective, EF = 2:Trade-off between benefit and harm, EF = 3: Likely to be beneficial, EF = 4: Beneficial.

Table 2. Overview of the three rewilding projects used as case studies sorted by increasing size.

Figure 1. Bi-dimensional space representing the condition of the system along axes of direct human inputs and outputs (*H*) and natural complexity of ecosystems (*N*). Background colours represent the values of the rewilding score quantified through the Equation 2.3. (a) Conceptual illustration showing areas associated with common land uses classified within our framework; (b) Scheme of how changes in either dimension can lead to changes in overall system condition.

Figure 2. Panel showing the results of applying the monitoring framework to three projects, namely the Millingerwaard project (the Netherlands); the Swiss National Park (Switzerland); and the Iberá project (Argentina). (*a*) Scores obtained for the state variables at the beginning of the project and at present. A description of the variables and indicators is available in tables 1 and S1. (*b*) Representation of the estimated scores of direct human inputs and outputs (*H*) and natural complexity of ecosystems (*N*) in the bi-dimensional framework for each case study. The arrows indicate the trajectory of change from the beginning of the projects to present. The rewilding score (*R*) is placed next to each point in time and has been calculated based on the scores shown in (*a*). Photographs courtesy of Rijkswaterstaat, SNP/H. Lozza and N. Fernández.


(a)
industrial agriculture
diversified agrosystems
industrial forestry
pristine areas
Human inputs and outputs (H)
Natural complexity (N)
(b)
initial state
alternative management
Human inputs and outputs (H)
Natural complexity (N)
Rewilding score (R)
1
0.8
0.6
0.4
0.2
0


Millingerwaard
Swiss National Park
Iberá
(a)
Artificial feeding of wildlife
Population reinforcement
Farmland production
Forestry production
Grassland production
Mining
Hunting
Fishing
Carrion removal
Deadwood removal
To be minimized
To be maximized
d
Naturalness of avalanche reg.
Naturalness of fire reg.
Naturalness of hydrological reg.
Naturalness of pest reg.
c
Terrestrial connectivity
Aquatic connectivity
Ecological succession
Absence of harmful invasives
t
Species composition
0.0 0.2 0.4 0.6 0.8 1.0
Score
(b)
Start of the project
Current state
H
N
R = 0.06
R = 0.18
R = 0.18
R = 0.49
R = 0.23
R = 0.41