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Abstract

Scenarios are important tools to facilitate the communication among scientists, practitioners, and decision-makers, and, thus to support policy and management decisions. The use of scenarios has an enormous potential to reduce ecosystem restoration costs and to optimize benefits, but this potential remains poorly explored. Here, we recommend and illustrate six best practices to guide the use of scenarios for planning native ecosystem restoration. We argue, first, for a participatory process to consider aspirations of multiple stakeholders along the whole scenario building process, from planning to implementation and review phases. Second, targeted restoration outcomes should be defined by key-actors (those who have direct interests in restoration) and directly involved stakeholders, within a clear socio-environmental context and under a well-defined problem statement, considering a broad range of nature and human benefits that can be derived from ecosystem restoration. Third, methodological choices, such as scenario types, spatial and temporal scales, drivers, restoration-related variables, and indicators, should be defined according to the multiple desired outcomes. Fourth, we encourage the consideration of the interactions among variables, within a spatially explicit, and temporally dynamic multi-criteria approach. Fifth, analysis and dissemination of scenario results should highlight the trade-offs and synergies among different restoration outcomes, identifying the scenarios that maximize benefits and minimize costs and resistance (i.e. the cost-effective and most feasible scenario) for multiple targets. Finally, promoting capacity building, through a wider consultation process including interaction with a broader group of stakeholders, is critical for the successful implementation and review of restoration interventions. Scenarios that support ecosystem restoration should follow an adaptive and iterative process, aiming to continuously improve restoration interventions and outcomes.

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Suggested reviewers	James Aronson, Paul Leadley, Robin Chazdon, Michael Obersteiner

Submission Files Included in this PDF

File Name [File Type]

Metzger_etal_rev#1_coverletterf.docx [Cover Letter]

Metzger_etal_rev#1_highlightsf.docx [Highlights]

Metzger_etal_rev#1_GAf.pptx [Graphical Abstract]

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Metzger_etal_rev#1_glossaryf.docx [Figure]

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São Paulo, October 2, 2017

Dr. Owen Petchey,
Guest Editor
Current Opinion in Environmental Sustainability

Dear Dr. Petchey,

We greatly appreciate the careful review and constructive comments of the two reviewers, and your own evaluation of our manuscript "Best practice for the use of scenarios for restoration planning" (COSUST 2017_67), submitted to the Special Issue on "Global Change and Biodiversity". We now enclose a revised manuscript, in which we have incorporated or responded to all comments.

The most important change in the revised version is the inclusion of several case studies in the text and a new box to illustrate our best practices. We also deleted all reference to our unpublished systematic review about restoration scenarios (Acosta et al.), and tried to improve our figures. Overall, we have aimed to incorporate all reviewer suggestions, and provided a detailed response (in blue) to each comment in the following pages.

We would be happy to undertake any further revisions necessary.

Sincerely,

Jean Paul Metzger (corresponding author) on the behalf of all co-authors

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DETAIL RESPONSES to Editor and Reviewers

Editor (Owen Petchey)

I have received two valuable, reasonable, relatively positive, and very prompt reviews of your article. I believe that all the comments are important and valid, and could lead to a significantly improved manuscript. I believe positive changes to the article in response to all the comments will easily come to mind, but clarify one: Reliance on unpublished works presents reviewers and readers considerable problems. They have no access to that evidence, so cannot assess its support of the statements. It is also not possible to assess the relationship between the two works (e.g. amount of overlap). (Please note that I am not suggesting that the evidence is not supporting, or any problems with the relationship between the two works.) Hence, please very carefully consider how your article can be presented without referring to unpublished works. Or perhaps there is some alternative solution, such as to make cited unpublished work openly available, for example by publishing it on a preprint server.

Reply from authors: We understand and agree with this difficulty, and so we decided to omit all reference to the literature review developed by Acosta and colleagues. In the main text, we deleted half of a paragraph in the introduction, and we also excluded (former) box 1.

I left the deadline for revision as the system default (17.9.2017). Please let us know if and when we can expect the revision not then.
Best wishes
Owen

-Reviewer 1

The authors state that the goal of the paper is to "Here, we provide guidelines for the use of scenarios for ecosystem restoration planning that can facilitate and stimulate their implementation and optimize restoration actions in the context of the ambitious global restoration commitments planned for the coming decades." The authors clearly outline a set of principles for planning. I strongly concur with the authors about the need to have more systematic and inclusive planning process that include a diverse group of stakeholders who consider specific outcomes and trade-offs at large spatial scales. However, the paper seemed like a lot of jargon to me without introducing something new. For example, principle 1 is "the adoption of a participatory, transdisciplinary, and adaptive management approach". Calls for this type of a planning approach are abundant in the restoration literature. I just came from the Society for Ecological Restoration conference and there were many talks that called for or described planning processes that were participatory. Even the authors note toward the end of the paper that "Most of these suggestions are quite general and well-known in other management practices". So, I had a hard time identifying what was new in this paper. But perhaps that's acceptable since these are supposed to be review papers. The glossary was helpful in defining the various terms.

Reply from authors: From the systematic literature review developed by Acosta et al. (unpublished data) we identified a gap in the use of scenarios for restoration planning. We argue here that scenarios can be useful tools to improve restoration benefits and efficiency, and with this manuscript we aim to stimulate the use of restoration scenarios, suggesting six best practices. We recognize that individually most of those best practices are already well-known in other management activities, applied sciences or even for restoration without the use of scenarios. Some of these have already been used for restoration scenarios (see the new box 2 for examples), but as far as we know, no one has put them together in a systematic and organized framework for the use of scenarios for restoration. All authors considered this as an original contribution, as stated in the introduction. In addition, we changed the approach of the paper from a more theoretical set of best practices to an illustrative case of best practices in planning restoration scenarios, as suggested by the reviewer in the next comment.

I kept waiting for the authors to provide a single example to illustrate how this has been successfully used in a specific system and potential challenges. The challenge is always to operationalize complex ideas proposed by primarily academics in a real world setting. The process described is fairly vague and seems cumbersome. Of course, I agree that identifying all drivers of degradation and conducting spatially explicit planning are important, but getting many stakeholders to participate in that sort of process is challenging. This paper would be much more convincing and novel if the authors could illustrate the process and what was learned from the process through a case study. For example see- Lazos-Chavero et al. 2016. Stakeholders and tropical reforestation: challenges, trade-offs, and strategies in dynamic environments. Biotropica 48:900-914 where they describe principles of a participatory process and illustrate the process with a case study to make it more tractable to the reader.

Reply from authors: We fully agree with the reviewer that our first version of the manuscript was more theoretical and general, with few illustrations of how the suggested practices can be applied in real situations. In this new version, we cited several examples in the text, and developed a new box highlighting three case studies that applied some of our best practices. We restrict our examples to the ones that consider scenarios for restoration, and not for the ones that considered restoration activities without the use of scenarios. With these modifications, we consider that our manuscript is now more clear and easy to be understood and incorporated into future restoration scenarios. We thank the reviewer for this suggestion.

At multiple points in the paper, the authors refer to an in preparation paper "Acosta et al." that is never cited in the references. For example starting on line 65, the entire paragraph reviews this paper, and Box 1 is also focused on describing the methods for this paper. This is problematic since most journals don't allow citation of papers unless they are in press since the reader can't refer to the source to evaluate the more detailed information. It felt like the authors were leaving the concrete information in the current manuscript for the Acosta paper and that maybe the two need to be combined. At any rate, the authors need to rewrite the paper to exclude this reference if it isn't accessible to readers.

Reply from authors: We agree and excluded all reference to our systematic review (Acosta et al. in prep.).

I didn't find the figures that helpful. It seemed like the authors tried to put all the various terms on one of the figures to show how they were linked. Figures should clarify ideas (i.e. a good picture is worth 1000 words), but I spent more time trying to understand the figures so they didn't help much.

Reply from authors: We agree that the figures were not clear but believe the figures are important elements to synthesize our proposed framework. Thus, in this new version, we have tried to simplify and make them easier to be understood. Particularly, we simplified the framework figure in box 1 and improved the presentation of figure 1.

-Reviewer 2

This is a timely paper that calls attention to the importance of using modeling scenarios in decision making for restoration. The principles presented increase the effectiveness of scenarios and promote the participation of important stakeholders in the process of building and analyzing different restoration scenarios and identifying tradeoffs and potential conflicts. The manuscript focuses on ecological restoration as the approach used, but repeatedly mentions the importance of spatial issues and landscape planning. This left me a bit confused about whether landscape restoration would be a better choice for the approach used. For example, forest landscape restoration is the approach designated by the Bonn Challenge. To my mind, this is not a trivial issue and landscape restoration should be discussed in relation to scenario results and how these assist decision making with respect to the extent and location of planned interventions within landscapes.

Reply from authors: Indeed we think a spatial perspective, considering appropriate scales of analysis, is important and this is highlighted in principle #4 and in several examples (see text and box 2). On the other hand, some of the suggested principles are not directly related to a spatial or landscape approach (for example, principles # 1, 2 and 6), and a landscape restoration perspective is not really presented here (because this was not our aim). We understand that a landscape perspective is important, but our principles go beyond a landscape ecological restoration, and can be applied in other situations or perspectives, for example to plan local restoration actions. We thus prefer to maintain our text more general, including landscape restorations, but not being restricted to this situation.

The points are all very well made, but general statements have limited effectiveness in conveying them. More specific examples of scenarios would be useful to illustrate each principle. Examples of dialogue workshops (mentioned in lines 357-359) would also be useful. Where are these dialogues happening, and in what context?

Reply from authors: We agree and as mentioned previously, we included several examples along the text and in box 2. Specifically, dialogue workshops were illustrated by the work of Mitchell et al. (2015) (see box 2).

I suggest using a well developed example of a restoration scenario to illustrate specific points and principles.

Reply from authors: We agree and presented in more detail three case studies in box 2, illustrating all six best practices.

Also, some information on software tools for scenario building would be useful to include in an Appendix.

Reply from authors: Thank you for this comment. We decided to include the following supplementary material (which is quoted in the methodological principle #4):

After an extensive literature review (Acosta et al. unpublished data) on the use of scenarios in restoration, we did not find any comprehensive software tool for building scenarios. To build scenarios it is necessary to use *different types of data* (e.g. interviews, climate models, land use/land cover data), *multiple analyses* (e.g. algorithms, models), *obtained from diversified sources* (e.g. data gathered by

participatory approaches, or by satellites), and results can be *presented in many formats* (e.g. graphs, maps, raster). As a result, it seems natural that the process of generating scenarios for environmental restoration will need multiple and diversified methodological approaches, as well as analytical tools.

In the absence of a comprehensive restoration scenario building software, here we provide a few examples of software that can be used to create and model some of the necessary inputs for building restoration scenarios. For example, FRAGSTAT is frequently used to mathematically characterize landscape structure [1]. CONEFOR [2] and Circuitscape [3] are suitable tools to evaluate connectivity. DYNAMICA-EGO [4] can be used to simulate land use and land cover dynamics. Maxent [5] and DISMO [6] and Biomod2 [7] are good examples of tools to evaluate environmental suitability or to map potential species distributions. InVEST, ARIES, TESSA are tools to evaluate ecosystem service provision (see a more comprehensive list and references in [8]). To read, integrate, map, and plot all those analyses in a spatially explicit way, GIS platforms (e.g. ArcGIS, DivaGIS, MapINFO, QGIS) and programming languages such as Python, Mathematica, Matlab, S-PLUS, and R language are encouraged.

The development of restoration scenarios requires thus multiple data types and sources, analyses, and models, which is only possible by integrating different software tools.

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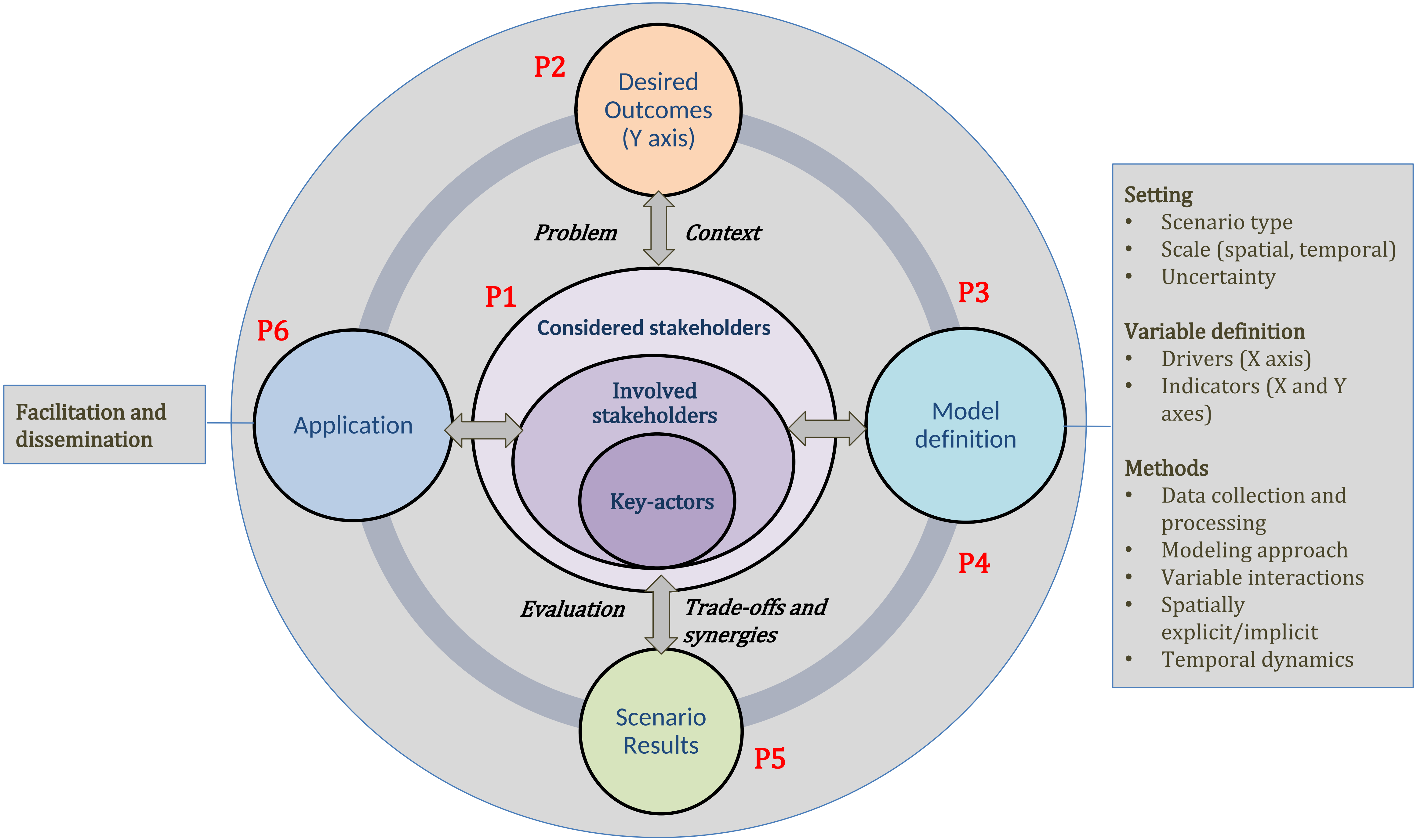
Thank you very much for this careful review and consideration. We appreciate all Editor's and Reviewer's suggestions which were very helpful to substantially improve the quality and clarity of the manuscript.

Highlights

- Scenarios are useful tools in improving ecosystem restoration cost-effectiveness and efficiency
- To be more effective, we propose a participatory, transdisciplinary, and adaptive management approach, where involvement of stakeholders is key throughout the whole process, from planning to implementation and review
- Scenarios supporting restoration need to follow an adaptive and iterative process, where synergies and trade-offs among different outcomes can be discussed within a spatially explicit and temporally dynamic multi-criteria approach.


Desired Outcomes (Y axis)
P2
Problem
Context
P1
Considered stakeholders
Involved stakeholders
Key-actors
P3
Model definition
P4
Scenario Results
P5
Evaluation
Trade-offs and synergies
P6
Application
Facilitation and dissemination
Setting
• Scenario type
• Scale (spatial, temporal)
• Uncertainty
Variable definition
• Drivers (X axis)
• Indicators (X and Y axes)
Methods
• Data collection and processing
• Modeling approach
• Variable interactions
• Spatially explicit/implicit
• Temporal dynamics

Best practice for the use of scenarios for restoration planning

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Abstract

Scenarios are important tools to facilitate the communication among scientists, practitioners, and decision-makers, and, thus to support policy and management decisions. The use of scenarios has an enormous potential to reduce ecosystem restoration costs and to optimize benefits, but this potential remains poorly explored. Here, we recommend and illustrate six best practices to guide the use of scenarios for planning native ecosystem restoration. We argue, *first*, for a participatory process to consider aspirations of multiple stakeholders along the whole scenario building process, from planning to implementation and review phases. *Second*, targeted restoration outcomes should be defined by key-actors (those who have direct interests in restoration) and directly involved stakeholders, within a clear socio-environmental context and under a well-defined problem statement, considering a broad range of nature and human benefits that can be derived from ecosystem restoration. *Third*, methodological choices, such as scenario types, spatial and temporal scales, drivers, restoration-related variables, and indicators, should be defined according to the multiple desired outcomes. *Fourth*, we encourage the consideration of the interactions among variables, within a spatially explicit, and temporally dynamic multi-criteria approach. *Fifth*, analysis and dissemination of scenario results should highlight the trade-offs and synergies among different restoration outcomes, identifying the scenarios that maximize benefits and minimize costs and resistance (i.e. the cost-effective and most feasible scenario) for multiple targets. *Finally*, promoting capacity building, through a wider consultation process including interaction with a broader group of stakeholders, is critical for the successful implementation and review of restoration interventions. Scenarios that support ecosystem restoration should follow an adaptive and iterative process, aiming to continuously improve restoration interventions and outcomes.

Highlights

- Scenarios are useful tools in improving ecosystem restoration cost-effectiveness and efficiency
- To be more effective, we propose a participatory, transdisciplinary, and adaptive management approach, where involvement of stakeholders is key throughout the whole process, from planning to implementation and review
- Scenarios supporting restoration need to follow an adaptive and iterative process, where synergies and trade-offs among different outcomes can be discussed within a spatially explicit and temporally dynamic multi-criteria approach.

Graphical Abstract: Figure in Box 2

Introduction

One of the main environmental challenges of this century is to reverse current anthropogenic landscape degradation trends, acting decisively to restore degraded ecosystems, as recognized by different international commitments, such as the Bonn challenge, the CBD Aichi targets 14 and 15, or the Initiative 20x20 in Latin America [1]. However, restoring ecosystems at the spatial and temporal scales proposed by these commitments represents a considerable challenge, which can only be achieved by establishing clear targets, considering the diversity of stakeholders involved and the political, economic, socio-cultural, environmental, legal, and technological contexts of ecosystem restoration. As the resources for restoration are limited and this is a costly activity [2,3], strategic planning is an obligation. The cost-effectiveness, however, will depend on the uncertainties related to the costs of necessary interventions and the potential benefits that can be obtained from restoration actions. Here, scenario comparison can be a key tool for restoration prioritization.

Scenarios were recently defined as representations or storylines of possible futures, including alternative policy or management options [4*]. Scenarios are a way to simulate, explore, and compare the possible outcomes of a decision, which makes them an essential decision-making tool. They need to be combined with robust models in order to translate the initial conditions defined by each scenario into realistic outcomes [4*].

While scenarios are already used to confront and avoid future degradation processes [5], they are less common in restoration planning, where they can be useful to assess potential impact on biodiversity or ecosystem services [e.g. 6], and to evaluate the restoration costs [e.g. 7,8]. Here, we recommend six best practices to guide the use of scenarios for planning native ecosystem restoration. These practices can facilitate, stimulate and optimize restoration actions in the context of the ambitious global restoration commitments planned for the coming decades. An international group of scientists and practitioners, with a wide range of ecosystem restoration experience from around the world, identified these six best practices or principles for the development of more robust restoration scenarios to reduce restoration costs and associated conflicts while optimizing its benefits. The ideal framework to use restoration scenarios should consider a transdisciplinary, participatory, and adaptive management approach, from which our main recommendations of best practices can be derived (Box 1). We also provide a *glossary*, which should assist scientists and practitioners to more precisely access the set of decision-making tools that scenarios offer to support restoration actions.

Principle #1 – Adoption of a participatory, transdisciplinary, and adaptive management approach

Ecosystem and landscape restoration aims to conserve biodiversity, safeguard essential ecosystem services for human well-being, and achieve social and economic benefits [1,9]. Therefore, restoration scenarios should capture the aspirations of multiple stakeholders, including those who have power to influence restoration initiatives (e.g. government, NGOs, scientists, private companies, community leaders), and also those who are likely to be influenced by the restoration projects (e.g. local communities, landowners).

Stakeholders can have different degrees of involvement in the scenario development process. *Key-actors* initiate the process and are those individuals or institutions that have a direct interest in the restoration process (e.g. government agency implementing a restoration policy). These key-actors are responsible for identifying the problem statement and socio-environmental context on which to base the scenarios, as well as supporting financially and technically the scenario building process. They also ensure the participation of other parties. *Involved stakeholders* are individuals and/or institutions recruited by the key-actors because of their potential influence over the scenarios, either directly through their actions on restoration sites or because the scenarios, or the potential outputs of them, directly involve these stakeholders in other ways. Throughout the scenario development process, *key-actors* and *involved stakeholders* have to contemplate another group of *considered stakeholders.* This group may be directly or indirectly affected by the restoration outcomes but do not necessarily have an interest or a need to participate in the restoration scenario development (Figure 1).

Each individual or stakeholder group can have different expectations on restoration outcomes, hence a *transdisciplinary* [*sensu* 10] and *participatory approach* [11] is necessary to have these perspectives correctly represented (see examples in Box 2). The group developing the scenarios, particularly *key-actors* and *involved stakeholders*, should ensure that the whole range of potential perspectives and interests are represented, aggregating academic and non-academic knowledge. Similarly, they should interactively act on all steps of scenario development, including scenario design, methodological definition, analysis of results, dissemination, and reanalysis, within an *adaptive management approach* [12].

Taking such a participatory, transdisciplinary, and adaptive management approach is important for two main reasons: it allows the consideration of aspirations and knowledge of multiple stakeholders, while also anticipating constraints for undertaking restoration programs and scenarios. Indeed, the most successful and creative projects involving social-environmental complexity are those where project leaders pursue co-production and co-ownership of knowledge throughout the process [13*]. For example, Palacios-Agundez et al. [14] and Convertino et al. [15] showed that developing participatory restoration scenarios that include stakeholder's feedback and preferences generates more realistic scenarios and increases community engagement.

The participatory process, although essential, is not straightforward. Deciding who should be involved in the process is complex (Box 2), as individuals or institutions can have diverse interests. Similar to landscape governance, informal networks, multi-stakeholder coalitions, and/or public-private partnerships are needed to achieve collective, place-bound outcomes [16]. Competencies in decision-making and communication are critical to the process of developing mutual understanding, openness to diverse ideas and progress towards end goals [17]. This complexity requires purposeful and active management and can be time-consuming and expensive [13*]. The core leaders of the group need to pay careful attention to transparency to encourage participation of those on the periphery of the process and to nurture their involvement through regular meetings [18]. In particular, such leaders have to consider power relationships, as imbalances can derail the entire process [19*,20]. Being informed about the complexities of group dynamics and organization behavior can help to guide the team-based process [21,22].

A participatory process involving co-production of knowledge is thus needed to generate relevant and reliable restoration scenarios that account for multiple perspectives and sources of information. This is a well-known procedure applied in different management contexts [23,24], but it is still poorly incorporated into restoration planning and even less adopted when scenarios are developed for restoration (but see [25,26]).

Principle #2 – Multiple desired outcomes should be clearly identified

A restoration initiative usually involves multiple actors with diverse perspectives, requirements, and desires. Through a participatory process, those aspirations should be clearly translated or represented in the "*expected outcomes*" or "*goals*" of the restoration scenarios, which can also be considered as the targets to be achieved (see glossary).

Desired outcomes should be simply and clearly illustrated, for example, if quantifiable, as the Y-axis or the response variable of the scenario graphs (i.e. conservation outcomes and/or nature's contributions to people), which can be projected into the future by each scenario through models [4*]. Such *outcomes* can be diverse, including matters such as habitat structure (e.g. biomass, vegetation stratification), provision of ecosystem services (e.g. water supply, soil stabilization), presence or abundance of a particular species (e.g. threatened species, or species providing relevant ecosystem services), richness or diversity of a taxonomic group, or control of invasive species. However, it is important to realize that these desired outcomes may not fully occur even if the projected restoration scenario is implemented, as there will always be uncertainties associated with the modeling process as well as with the trajectory that a habitat under restoration might take.

To appropriately define potential outcomes, *key-actors* and *involved stakeholders* need first to identify a common "*problem statement*" and define the *socio-environmental context*. For example, in South Africa's Cape Floristic Region, invasive alien trees threatened not only indigenous biodiversity but also water provision, livestock production, and livelihoods [27]. The socio-environmental context related to budget limitations, management capacity, and landowner attitudes constrained decisive actions for invasive species control, and needed to be considered in the scenario development [28*,29]. In a South American example, the conservation of two mammal species was considered in a context of limited funds. Alternative scenarios were thus considered by maximizing habitat availability and biogeographical representation, while minimizing land acquisition costs to restore 12 million ha of Atlantic Forest [7]. Through this process of problem statement and social-environmental context definition, conservation and economic interests of different stakeholders should be taken into account (see examples in Box 2).

Following the social process outlined above will ensure credibility (technical evidence or premises are adequate), saliency (findings are relevant to decision-makers), and legitimacy (all views and beliefs are considered and impartially tackled), key ingredients for an effective scenario development process [30].

Principle #3 – Definition of methodological choices according to expected outcomes

The development of scenarios involves multiple methodological choices regarding the type of scenarios, the selection of direct and indirect drivers influencing restoration, as well as other restoration-related variables and indicators. Those choices are not always obvious, and for this reason they need to be based, first of all, on the desired outcomes provided by the involved and considered stakeholders and on the type of restoration required.

First, it is critical to determine the appropriate type of scenario. There are four types of scenarios according to the typology proposed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services - [4*]): i) *Exploratory scenarios* examine different plausible futures based on past trends and in possible (e.g. positive/negative, optimistic/pessimistic) storylines or future trends of some variables, usually indirect drivers such as socio-political, economic, or technological factors; ii) *Target-seeking scenarios* define targets of Y-axis outcomes (e.g. nature or nature's benefits to people) to be achieved in the future, and then consider different initial conditions and scenarios to attain those targets; iii) *Policy-screening scenarios* compare different ways to apply a particular policy (such as restoration) based on their impact on required outcomes (Y-axis); and iv) *Retrospective policy evaluations* compare the projected outcomes obtained from scenarios applied in the past with actual achievements, analyzing the reasons for differences between expected and realized outcomes. All these scenarios can be applied to restoration, depending on the restoration phase: exploratory scenarios are useful for agenda setting, target-seeking and policy-screening ones are adequate for an intervention phase, while retrospective policy evaluations are suitable for a review phase [4*].

Second, involved and considered stakeholders must identify key direct and indirect drivers (see glossary) that may influence the restoration process, taking into account the desired outcomes (Figure 2). For example, rural-urban migration is a main indirect driver for large-scale forest recovery in some Latin American countries, and thus should be considered in large-scale restoration planning, both at the exploratory (exploratory scenarios) and intervention stages (target-seeking or policy-screening scenarios). Similarly, sustainable agricultural intensification (direct driver) is a mechanism that can avoid agricultural expansion and consequently spare land for restoration [31*]; hence it is an important factor to consider in scenario development. For instance, Bohnet et al. [32] developed a landscape toolkit with which stakeholders create and evaluate spatially-explicit land use and management change scenarios. This process offers more transparency and highlights possible conflicts of interest among different stakeholders.

Third, there are specific restoration-related variables that should be considered when scenarios are modeled [33], such as biotic (e.g. persistence of soil seed banks, dispersing fauna) and abiotic variables (e.g. soil quality, slope, precipitation, rainfall seasonality, landscape structure parameters). These variables can affect the local and landscape resilience of the study system, modulating the system's capacity to intrinsically recover [34*], and defining when a passive restoration strategy is possible, or inversely, when an active restoration is required [35]. The spatial and temporal scales of restoration initiatives as well as data uncertainty and availability are likely to drive the choice of restoration-related variables (Figure 2). Additionally, variables should be chosen in a participatory manner, considering the perspectives of key-actors and other stakeholders (as shown in the general framework figure in Box 2), who possess the technical expertise and on-the-ground knowledge regarding restoration drivers and their future trajectories [36].

Fourth, as multiple drivers and restoration-related variables may be involved in planning restoration, a multi-criteria approach that compares scenarios with different targets is critical. Egoh et al. [37], for example, explore scenarios to achieve a European Union 15% restoration target (target-seeking scenario), considering both endangered species conservation and ecosystem service provision. To develop the models, they compared sets of scenarios with a different combination of targets to better explore the most suitable combination of outcomes. Restoration scenarios also need to be based on the identification of specific, observable, and measureable indicators that will be used to assess the suitability of scenarios in terms of whether they reach the desired outcomes or targets, as well as the cost-effectiveness of the restoration initiative [7].

Principle #4 - Scenarios should be spatially explicit, temporally dynamic and should consider outcome interactions

Once the scenario type, drivers, and restoration-related variables are identified, the restoration project can move forward to the modeling stage. At this stage, the participants of the restoration project have to make a series of decisions that will form the basis of the models that will be used to compare the different scenarios.

First, they have to decide whether the model will be spatially explicit (e.g. does the spatial arrangement of the landscape matters to the restoration process being modeled?), implicit (e.g. does the spatial location of each habitat patch need to be specified in the model?), or non-spatial (e.g. do theoretical models reveal the interaction among variables, without any reference to space?). Since restoration outcomes are clearly affected by the surrounding landscape and the functioning of the latter is affected by restoration areas [34*,38], we strongly advocate for a spatially explicit approach (see Box 2 and Figure 2). This approach optimizes results and enables planning a restoration scenario that simultaneously minimizes costs (for example, properly allocating areas for passive restoration) and identifies priority areas for active restoration (e.g. with an increase in biodiversity status and ecosystem services provision). In this context, for example, Perry and Enright [39] compared outcomes from spatially explicit and implicit models applied to the same system (using the same initial parameters), supporting the notion that spatially explicit models are better for restoration applications (see also [40] and Box 2 for more information).

Second, a wide range of methods can be used for modeling scenarios, including mental maps, conceptual models, systematic conservation planning, and mathematical models. For example, both Tambosi et al. [41] and Crouzeilles et al. [7] approached the effects of habitat availability on the identification of priority areas for restoration in the Atlantic Forest. However, while the former ranked landscapes based on their contribution to increase connectivity, the latter used a systematic conservation planning approach to solve a mathematical problem statement. Solutions to restoration prioritization modeling regarding mathematical problem statements tend to be more complex, but are more informative to decision makers as they deal with specific targets and costs [42].

Third, it is important to identify and set parameters for the interactions and feedbacks among the chosen drivers and restoration-related variables, focusing on temporal dynamics. For example, the potential for natural forest regeneration depends on the amount of forest in the surrounding landscape (among other restoration-related variables), which can change over the time that the restoration takes place [L. Tambosi, PhD thesis, University of São Paulo, 2014; [43]]. The interactions between variables through time will determine scenario trajectories, which in turn can significantly affect the duration and outcome of restoration initiatives, as well as their costs, demanding adaptive management. We argue here that a dynamic approach is necessary to correctly plan and evaluate restoration outcomes.

Finally, the parameters that define variable interactions and their temporal dynamics must be identified through rigorous data collection, experimentation, modeling, and/or expert knowledge. Data can be collected from multiple sources, such as literature reviews of past restoration studies or other reports on the trends or behavior of variables. Parameterization of variables for the model(s) will also benefit significantly from the inclusion of expert knowledge, which can come from the key-actors, involved and/or considered stakeholders, or from other restoration experts (Box 2).

We note that the development of restoration scenarios requires multiple data types and sources, analyses, and models, which is only possible by integrating different software tools (see supplementary material).

Principle #5 - Analysis and dissemination should highlight outcome trade-offs and synergies, promoting an iterative process of scenario construction

As soon as scenario results are available, an adequate strategy for analysis and dissemination among stakeholders should be initiated. Such strategy should clearly outline the steps that will be taken to verify the adequacy of the results, followed by a detailed analysis and discussion of the synergies and trade-offs that were identified by the scenarios. For example, by comparing land use scenarios, Butler et al. [44] assessed trade-offs between food and fibre production and water quality regulation, affecting differently farmers and fishermen in The Great Barrier Reef, Australia. A broad stakeholder consultation of scenarios' results may help to identify and solve such kind of potential conflicts.

The sub-set of stakeholders who participated in the model definition should also engage in the analysis of the scenario and model outputs (see Box 2 for examples). These parties should compare the outcomes for each scenario and assess whether the scenario outcomes adequately represent how the indirect and direct drivers interact with each other and with other restoration-related variables. In a multi-criteria approach, scenarios can be compared, through cost-effective or cost-benefit analysis, i.e. identifying the scenario that results in the highest targeted benefits per unit of costs. It is also important to compare trade-offs between scenarios, since the most cost-effective situation may not reach the minimum desired outcomes. The choice of spatial and temporal scales, as well as the level of uncertainty given data availability, should also be explicit in the results. Additionally, these stakeholders should evaluate whether the resulting outcomes are compatible with the initial targets of the restoration project, and verify whether the restoration drivers and variables that were chosen in the model definition reflected those objectives properly. If there are discrepancies, those inputs need to be modified, or alternative inputs should be added. These decisions should be done in consultation with the parties involved, in an iterative or adaptive management approach, as previously mentioned.

When analyzing the final results, a close examination of the trade-offs and synergies among the resulting scenarios is necessary, especially when a great number of variables and criteria are adopted in the scenario construction. This can be done by plotting the different scenario results against each other, using, for example, spider diagrams or portfolio maps to identify trade-offs and win-win solutions [45,46], or by applying a spatially explicit analysis to map trade-offs and win-win situations [46,47]. The examination of these trade-offs and synergies allows identifying the scenarios that maximize synergies and minimize trade-offs for all targets and all stakeholder expectations. It might well be the case that no single scenario reaches all objectives, or inversely, there could be certain scenarios that impact negatively on the interests of a particular stakeholder group. In these cases, new scenarios that reflect different sets of viewpoints might be needed, following an adaptive management approach.

To resolve potential conflict among stakeholders, scenario selection requires repeated stakeholder consultation, in particular when intervention scenarios are considered (see Bohnet et al. [32] for an example of stakeholders building and selecting scenarios). If conflicts exist, it might be necessary to perform this step with the different key-actors and stakeholder groups separately, before moving on to joint consultations that include all stakeholders. In these consultations, the results of the scenario analysis should be presented in a way that is tailored to each stakeholder group(s), i.e. "translated" appropriately [48]. The feedback provided from the stakeholder groups, and the additional knowledge received, is then incorporated into a set of new or modified scenarios. This iterative process allows for the selection of scenarios that are acceptable for the different actors involved in the exercise and leads to a set of feasible scenarios that reflect the actors' perceptions, practical experience, and viewpoints [25].

Principle #6 – Interactive, face-to-face meetings coupled with field days can optimize communication, capacity building, and application of scenarios' insights

The first step towards successful application of the scenarios developed is their appropriate dissemination to key-actors and stakeholders, including a description of their indirect and direct drivers, and how they impact on the selected restoration-related variables of interest. Communicating the process and key outcomes to a wider audience can facilitate buy-in from a broader stakeholder community. Communication can take on a multitude of forms, depending on the audience to be reached, and the desired level of interaction and stakeholder engagement. Workshops allow time for interventions and face-to-face discussions among experts and key-actors, and facilitate reflection on the potential impacts of the scenario outcomes, which can, ultimately, lead to improved decision-making [49]. Coupling workshops with excursions or field days makes the results even more tangible. Exhibitions, "road shows", and lecture series are designed to address a broad audience, while scientific publications and policy briefs target a very specific audience. Social media can serve as an excellent outreach tool, with webinars and Massive Open Online Courses allowing for direct interaction with the audience. More interactive formats can also be used to promote capacity building and to provide the targeted audience with the necessary skills to understand the results and apply the outcomes of the different scenarios (see Box 2 for examples).

Promoting capacity building also facilitates the incorporation of the results and outcomes of the scenarios into policy. Dialogue workshops between decision-makers, policy-makers, and experts maximize the knowledge transfer and uptake of results, while workshops with practitioners and managers facilitate the conversion of the scenario results into practical restoration applications [50]. These workshops and dialogues enable the formulation of implementation plans and, using the variables of interest, the development of monitoring plans. Regular monitoring and reporting of results can then be used to verify the scenario outputs and results [51], and to adapt the parameterization of the models and re-adjustment of scenarios. The iterative interaction between practitioners, key-actors, and experts enables true adaptive management and formulation of adequate legislation and incentive mechanisms. Hence, direct interactions with the group of people that have the power of influencing restoration and those mostly affected by its outcomes are key to achieving a successful community of practice and successful restoration programs.

Final remarks

The use of scenario modeling to improve restoration planning is not yet fully explored, but is critical to guide cost-effective restoration interventions at the unprecedented scales promoted by emerging global restoration commitments. Restoration programs now have to progress beyond the simplistic definition of a given number of hectares to restore, and start considering the inherent challenges to address the expected trade-offs arising from the combination of multiple restoration goals in areas already disputed by other land uses and interests [52*]. To fully realize the potential of scenario modeling for restoration, we advocate for the use of the guidelines presented here. We reinforce the need to incorporate a transdisciplinary, participatory, and adaptive management approach to restoration scenario building. During this scenario building process it is essential that key-actors and other stakeholders negotiate their interests and select desired outcomes, participate actively in methodological choices, discuss the synergies and trade-offs among different outcomes, communicate results with a broader audience, and engage in an adaptive cycle that leads to improved restoration scenarios, and from this allow for more successful restoration projects. We also encourage the application of a spatially explicit and dynamic multi-criteria modeling approach, at adequate scales, with a well-developed problem statement, and the use of multiple iterative and face-to-face communication and capacity building activities to successfully achieve restoration outcomes. Most of these suggestions are quite general and well-known in other management practices, but they can facilitate the use of scenarios in the context of ecosystem restoration. The use of scenario tools has to go beyond their more common usage to avoid degradation processes. A more widespread application of scenarios to guide restoration planning, implementation, and monitoring in large-scale programs is possible.

Conflicts of interest

There is no conflict of interest.

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Glossary

General definitions

Scenarios – We adopted the definition of IPBES [4*], which considers scenarios as "representations of possible futures for one or more components of the system, particularly for drivers of change in nature and nature's benefits, including alternative policy and management options."

Models are simplified representations of real systems. Models can be qualitative or quantitative, and represent some components of the systems and their relationships [4*]. For ecological restoration, models are particularly important to relate restoration-driven changes in ecosystems structure, with their consequent implications for the functioning of ecosystems, particularly with the provision of ecosystem services.

Ecological restoration consists of human interventions to assist the recovery of an ecosystem that has been degraded, damaged, or destroyed (sensu SER, [53]). Those actions include the reduction of ongoing degradation processes and an active action to reverse degradation (*active restoration action*), but can also include actions of halting or avoiding degradation processes, without any other intervention (*passive restoration action*). Active restoration is a more expensive and labor-intensive action than passive restoration, however passive restoration is only possible if the system is still resilient, and thus can recover by itself (e.g. by natural regeneration processes).

Stakeholders

Key-actors are those individuals or institutions that have a direct interest in the restoration process, e.g. government agency concerned with enabling policy (signatory to CBD, Aichi targets), landowners. They initiate the process.

Involved stakeholders are those individuals or institutions who may affect restoration scenarios through their direct actions on restoration sites or through the impacts that scenarios can have on them.

Considered stakeholders are those individuals and institutions who do not necessarily have an interest or need to participate in the restoration scenarios development, do not have potential to influence the scenarios, but may be directly or indirectly affected by the restoration.

Scenario approach

Transdisciplinarity is an interdisciplinary or integrative approach, which crosses disciplinary/academic boundaries, and allows integration of knowledge from academic and non-academic (e.g. practitioners empirical experience or local knowledge) participants to deal with a common research goal [10].

Participatory approach is an approach in which a range of stakeholders are directly involved in the whole process, from the design to the assessment of scenarios. The approach takes into account different perspectives and issues and adds value to the assessment of synergies and trade-offs.

Adaptive management approach is an iterative and learning-based management approach, where actions are constantly tested and evaluated, in order to be improved over time. This approach helps to deal with uncertainty and incomplete knowledge in decision-making process, reducing the gap between science and practice [12].

Scenario and model setup

Outcomes (Y-axes) are results, goals or targets to be achieved that address the problem statement according to the perspectives of key-actors and stakeholders. There may be conflicting *desired outcomes*, but those will provide input into the scenario development process.

Input variables are all variables that can affect expected outcomes, which can include a wide array of direct and indirect human drivers, such as abiotic (e.g. parameter related with relief, climate) and biotic conditions (e.g. regional species pool, local seed banks, seed rain, and germination), landscape structure (e.g. isolation or connectivity to potential source patches, anthropogenic matrix type, fragment size, surrounding habitat amount), time elapsed since restoration, and history of degradation [33].

Problem statement is the identification of the situation that needs to be solved through ecological restoration, taking into consideration the socio-environmental context.

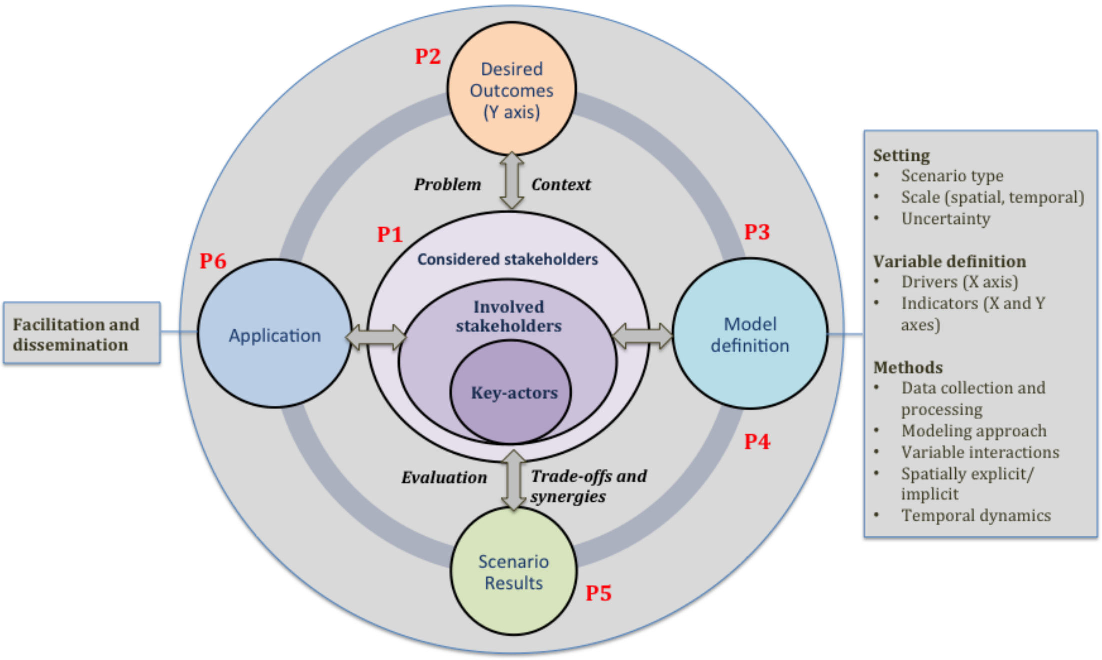
Socio-environmental context includes both the biophysical context (i.e. the ecosystem and its bio-physical drivers) as well as the associated societal / social and political actors and institutions.

Anthropogenic drivers are factors or processes associated with human actions or activities that lead to changes in the study systems. Drivers of anthropogenic degradation and restoration will particularly affect biodiversity and the related ecological processes and ecosystem services. Drivers can be either natural (e.g. tornados, landslides, flooding regime) or anthropogenic, but here we focused on anthropogenic direct and indirect drivers.

Anthropogenic direct drivers are those anthropogenic processes that directly affect ecosystems, and thus depend on a human decision, both related to a degradation process (e.g. native habitat destruction or degradation, introduction of invasive species, construction of infrastructure) or to a restoration action (e.g. reforestation, dam withdrawal). Direct drivers can include: i) land use change (which relates to the contraction and/or expansion of the areas available for restoration); ii) land use and land cover degradation (that results from anthropogenic loss of native cover and from other anthropogenic disturbances such as contamination); iii) disturbance regimes (natural factors that affect the landscape, such as fire, pests, flooding); iv) invasive species; and, v) climate change.

Anthropogenic indirect drivers are factors controlled by humans that operate by altering the level or rate of change of one or more direct drivers [4*]. They are usually underlying causes of biodiversity and nature's benefit changes, which include institutional and governance structures, as well as socio-political, economic, technological, legal and cultural factors that can affect both degradation processes and restoration actions. Some major indirect drivers of change are: i) demographic (e.g. human population growth, density, and migration); ii) economic (e.g. markets, income distribution and demand, incentives, tax benefits, land-use opportunity costs and restoration costs); iii) science, knowledge (technical or scientific knowledge, including indigenous and local knowledge systems), and technology (physical objects and procedures); iv) institutions and governance (corporate, governmental, judicial); and v) cultural (e.g. willingness to restore); vi) legal (laws affecting restoration commitment).

Box 1. Proposed framework for building restoration scenarios that should support restoration planning.



Schematic representation of the six principles (P1 to P6) of the proposed framework to guide the use of scenarios and models for restoring native ecosystems.

Principle 1 - The restoration framework begins in the nucleus of the figure with the **key-actors**. These individuals or institutions have a direct interest in developing a restoration project (e.g. government agency implementing restoration policy). They initiate the restoration scenario building process by identifying the ***problem statement*** and the ***socio-environmental context*** on which the scenarios will be based. They are also responsible for gathering the financial and technical resources that will be needed for the scenario building process, while also ensuring the participation of other parties. **Involved stakeholders** have a direct influence on the scenarios, either through their actions or through the impacts that the scenarios can have on them. Therefore, they are recruited by the key-actors to actively participate in the scenario building process. These actors consider the interests of a broader group of **considered stakeholders** who may be directly or indirectly affected by the restoration process.

Principle 2 - By means of a participatory process, key-actors and involved stakeholders work together to determine the **desired outcomes** of the scenarios, which represent the range of nature and human benefits of restoration (e.g. enhancing biodiversity or carbon sequestration).

Principles 3 and 4 -The nature of the selected desired outcomes informs the ***setting***, ***variable definition***, and ***methods*** that form the basis of the model definition. The setting includes the scenario type (exploratory, target-seeking, retrospective policy evaluation, or policy-screening), scale and level of uncertainty. The variables that will be included into the model comprise the indirect and direct drivers of restoration, as well as the indicators that will be used to measure the effectiveness of the model and of the restoration initiative. Scenario building methods include the modeling approach, data collection and processing, variable interactions, and spatial and temporal specifications.

Principle 5 -The scenario results undergo an ***evaluation*** based on the indicators that were specified in the model definition. Through a participatory consultation process, a sub-set of stakeholders assess the ***trade-offs and synergies*** of the scenario results in terms of how they work to achieve the desired outcomes. If necessary, they can redefine the desired outcomes and revise the model definition accordingly.

Principle 6 - Once a set of scenario outcomes are agreed upon, the process continues on to the **application** of the recommendations provided by the scenarios. This last step may include ***facilitating*** the incorporation of the results into policy and ***disseminating*** the results to a larger audience. As the application of the results from the scenarios takes place (through restoration actions), key-actors may choose to address a new problem statement, restarting the cycle.

Box 2. Case studies to illustrate the suggested principles for building restoration scenarios

Stakeholder involvement and scenario outcome identification (Principles #1, 2, 3 and 5)

Reed et al. [54] and Mitchell et al. [50] provide good examples of how to integrate multiple stakeholders in the restoration scenario building process **(Principle #1).** By contrasting two scenarios based on extensifying or intensifying land management in the UK uplands, *Reed et al.* identified stakeholders by conducting a series of interviews and workshops with interested parties. They then used stakeholder analysis and social network analysis to select a representative and interconnected group of stakeholders. This smaller group was involved in exploring the current and future perceived challenges of the upland system, developing a conceptual model of the main themes and desired outcomes **(Principle #2)**, constructing scenarios by focusing on the drivers of change within the system and interactions among potential outcomes **(Principle #3),** and refining and prioritizing those scenarios based on their trade-offs and synergies **(Principle #5**). Similarly, for their case study of the Tasmanian Midlands, an agricultural landscape and grassland biodiversity hotspot, *Mitchell et al.* engaged government officials, conservationists, rural organizations, land-holders and scientists by conducting participatory workshops **(Principle #1)**. Through these workshops, participants reviewed the historical transformation of the landscape, discussed their desired outcomes, and the likely effects of climate change, other dynamic drivers of change, and governance influencers on the future of the region **(Principles #2 and #3)**. This process built upon a prior social-ecological-system analysis of the dynamics affecting native grasslands, and was illustrated through a conceptual model **(Principle #3)**. On both cases, the workshops ensured that stakeholder's comments were incorporated into the conceptual model and scenario design **(Principle #1)**.

Methodologies for scenario design (Principle #3), and benefits of using a spatially explicit approach (Principles #4 and 5)

Reed et al. [54] and Birch et al. [6] created their restoration and ecosystem service scenarios through a spatially explicit approach, which provides the unique opportunity to exactly locate areas with restoration potential across large landscapes **(Principle #4)**. After receiving inputs from involved stakeholders, *Reed et al.* used spatially explicit computer models to identify the externalities and explore the ecosystem service trade-offs and synergies of two contrasting policy scenarios **(Principle #5)**. The policy scenarios were on one hand the extensification of land use management in the UK uplands, which refers to restoring land to sequester carbon and to provide habitat for some species, and on the other hand, the intensification of agriculture and livestock production to achieve food security. Their models included variables related to land manager behavior, vegetation dynamics, population dynamics of wildlife species of interest, carbon dynamics, and water quality **(Principle #3)**. Similarly, in their case study of four different degraded drylands in Latin America, *Birch et al.* applied a spatially explicit approach to assess the potential impact of restoration on the net value of ecosystem services such as carbon sequestration, timber and non-timber forest products, tourism and livestock production **(Principle #4)**. The scenarios included business-as-usual state, passive restoration, passive restoration with protection, and active restoration, constructed with a forest dynamics model **(Principle #3)**. Each of these ecosystem services and their estimated net present values (the difference in value between the business-as-usual scenario and the restoration scenarios) were mapped under each scenario **(Principle #4)**. A cost-benefit analysis of restoration was conducted by estimating the "net social benefit of restoration", or the net value of the ecosystem services minus the costs of reforestation, considering the different discount rates involved in land use change **(Principle #3)**. In addition to showing that restoration leads to increased ecosystem service provision in almost all cases, and that there are marked differences in the cost-effectiveness of the different kinds of restoration scenarios, their results indicate that using a spatially explicit approach can allow areas with the greatest potential benefit per unit cost to be prioritized for conservation planning **(Principle #4)**. Both studies conclude that using a spatially explicit approach allows identification of the exact location of trade-offs and complementarities among desired outputs in order to minimize externalities and create a win-win situation for the environment, climate change, and for the livelihood of local landowners **(Principle #5)**.

Analyzing outcome trade-offs and synergies (Principle #5) and communicating results effectively (Principle #6)

Mitchell et al. [50] and Reed et al. [54] make use of story lines and narratives to construct and communicate their restoration scenarios effectively **(Principle #6)**. After their workshops and stakeholder consultations, *Mitchell et al.* applied a systems-based strategy to consider critical uncertainties within the drivers of change on the Tasmanian Midlands system dynamics. They created a quadrant matrix of scenarios comprising the possible combinations of these uncertainties. A smaller group of researchers (here considered as key-actors and involved stakeholders) was then able to refine scenario narratives based on scientific expert consultation. The scenarios varied on the basis of farmer profitability and social and human capital, ranging from agricultural loss and rural decline to sustainable and profitable agriculture. These narratives were then brought back to the community so that stakeholders could understand how their decisions would affect their environment **(Principle #6)**. In a similar fashion, *Reed et al.* used story lines and narratives to define their extensification or intensification policy scenarios in the UK uplands **(Principle #6)**. The narratives were communicated to stakeholders by film, which facilitated the integration of information from a wide range of sources, including local and scientific knowledge, and gave public relevance to the issue while also providing rigorous evidence **(Principle #6)**. The films illustrated and communicated those narratives in a way that was easy for people from different backgrounds and education to understand and endorse. For both studies, the narratives allowed stakeholders to identify opportunities for biodiversity conservation and potential sources of financial support to incentivize local stakeholders to pursue win-win opportunities whenever possible **(Principle #5)**.

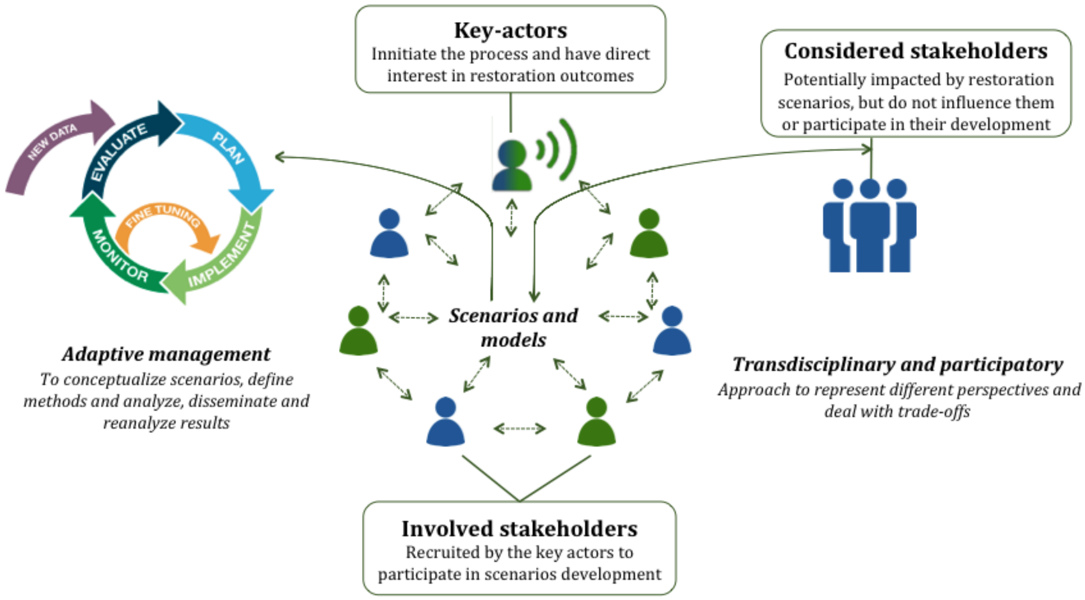


Figure 1. The development of scenarios involves potential stakeholders influencing (green), or being influenced by (blue) restoration, with different roles in the process. A transdisciplinary and participatory approach is employed to harmonize different and sometimes conflicting perspectives on restoration, while adaptive management safeguards scenario functionality in a changing socio-environmental context.

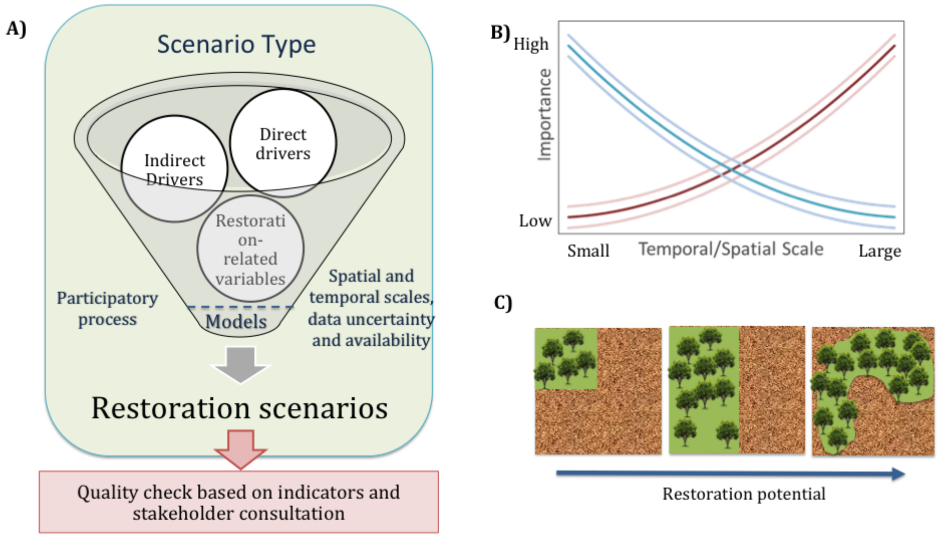


Figure 2. A) The type of scenario (from IPBES, [4*]) will inform the selection of direct and indirect drivers and restoration-related variables, by means of a participatory process, and considering spatial and temporal scales as well as data uncertainty and availability. These variables will then interact with each other based on their given parameters. The chosen model filters those interactions to generate different restoration scenarios. Once the scenarios are built, the results should be evaluated based on pre-established indicators and in consultation with multiple stakeholders. **B)** Drivers and restoration-related variables can be more or less important depending on their temporal and spatial scale. For example, climate change can be very important at a large temporal and spatial scale, but not necessarily for a short-term plot level restoration project (red line). Similarly, an abiotic restoration-related variable such as soil quality can be crucial when planning restoration at a small scale, but less relevant for a large landscape with multiple soil types and varying soil fertility (blue-line). Such changing relevance must be considered when choosing drivers and restoration-related variables. **C)** Adopting a spatially explicit approach is important to model restoration scenarios. In particular, the spatial configuration of existing forest patches and new restoration areas can strongly influence the speed, type, and cost of restoration, while also determining functional connectivity.

Glossary

General definitions

Scenarios – We adopted the definition of IPBES [4*], which considers scenarios as "representations of possible futures for one or more components of the system, particularly for drivers of change in nature and nature's benefits, including alternative policy and management options."

Models are simplified representations of real systems. Models can be qualitative or quantitative, and represent some components of the systems and their relationships [4*]. For ecological restoration, models are particularly important to relate restoration-driven changes in ecosystems structure, with their consequent implications for the functioning of ecosystems, particularly with the provision of ecosystem services.

Ecological restoration consists of human interventions to assist the recovery of an ecosystem that has been degraded, damaged, or destroyed (sensu SER, [53]). Those actions include the reduction of ongoing degradation processes and an active action to reverse degradation (*active restoration action*), but can also include actions of halting or avoiding degradation processes, without any other intervention (*passive restoration action*). Active restoration is a more expensive and labor-intensive action than passive restoration, however passive restoration is only possible if the system is still resilient, and thus can recover by itself (e.g. by natural regeneration processes).

Stakeholders

Key-actors are those individuals or institutions that have a direct interest in the restoration process, e.g. government agency concerned with enabling policy (signatory to CBD, Aichi targets), landowners. They initiate the process.

Involved stakeholders are those individuals or institutions who may affect restoration scenarios through their direct actions on restoration sites or through the impacts that scenarios can have on them.

Considered stakeholders are those individuals and institutions who do not necessarily have an interest or need to participate in the restoration scenarios development, do not have potential to influence the scenarios, but may be directly or indirectly affected by the restoration.

Scenario approach

Transdisciplinarity is an interdisciplinary or integrative approach, which crosses disciplinary/academic boundaries, and allows integration of knowledge from academic and non-academic (e.g. practitioners empirical experience or local knowledge) participants to deal with a common research goal [10].

Participatory approach is an approach in which a range of stakeholders are directly involved in the whole process, from the design to the assessment of scenarios. The approach takes into account different perspectives and issues and adds value to the assessment of synergies and trade-offs.

Adaptive management approach is an iterative and learning-based management approach, where actions are constantly tested and evaluated, in order to be improved over time. This approach helps to deal with uncertainty and incomplete knowledge in decision-making process, reducing the gap between science and practice [12].

Scenario and model setup

Outcomes (Y-axes) are results, goals or targets to be achieved that address the problem statement according to the perspectives of key-actors and stakeholders. There may be conflicting *desired outcomes*, but those will provide input into the scenario development process.

Input variables are all variables that can affect expected outcomes, which can include a wide array of direct and indirect human drivers, such as abiotic (e.g. parameter related with relief, climate) and biotic conditions (e.g. regional species pool, local seed banks, seed rain, and germination), landscape structure (e.g. isolation or connectivity to potential source patches, anthropogenic matrix type, fragment size, surrounding habitat amount), time elapsed since restoration, and history of degradation [33].

Problem statement is the identification of the situation that needs to be solved through ecological restoration, taking into consideration the socio-environmental context.

Socio-environmental context includes both the biophysical context (i.e. the ecosystem and its bio-physical drivers) as well as the associated societal / social and political actors and institutions.

Anthropogenic drivers are factors or processes associated with human actions or activities that lead to changes in the study systems. Drivers of anthropogenic degradation and restoration will particularly affect biodiversity and the related ecological processes and ecosystem services. Drivers can be either natural (e.g. tornados, landslides, flooding regime) or anthropogenic, but here we focused on anthropogenic direct and indirect drivers.

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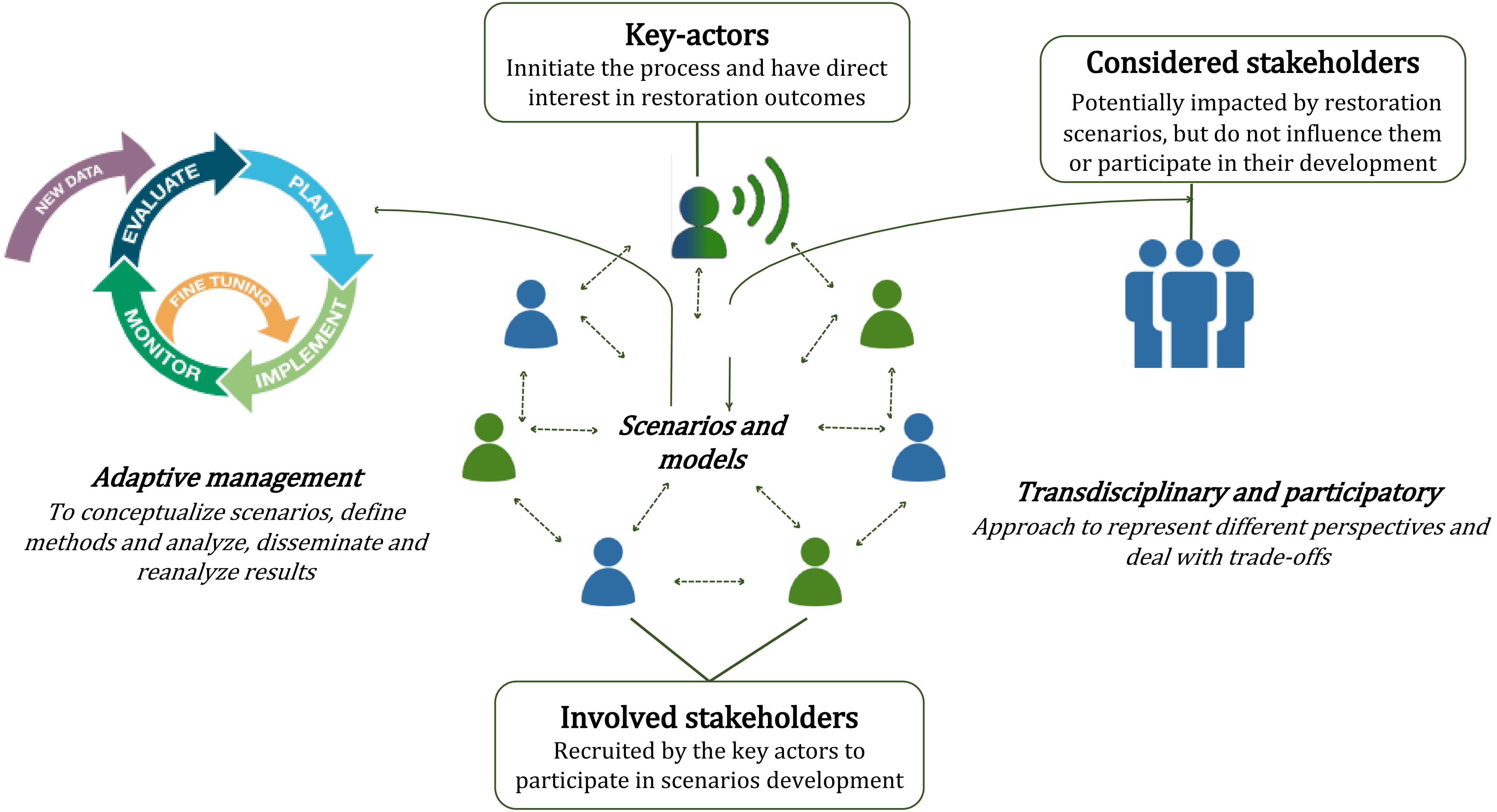
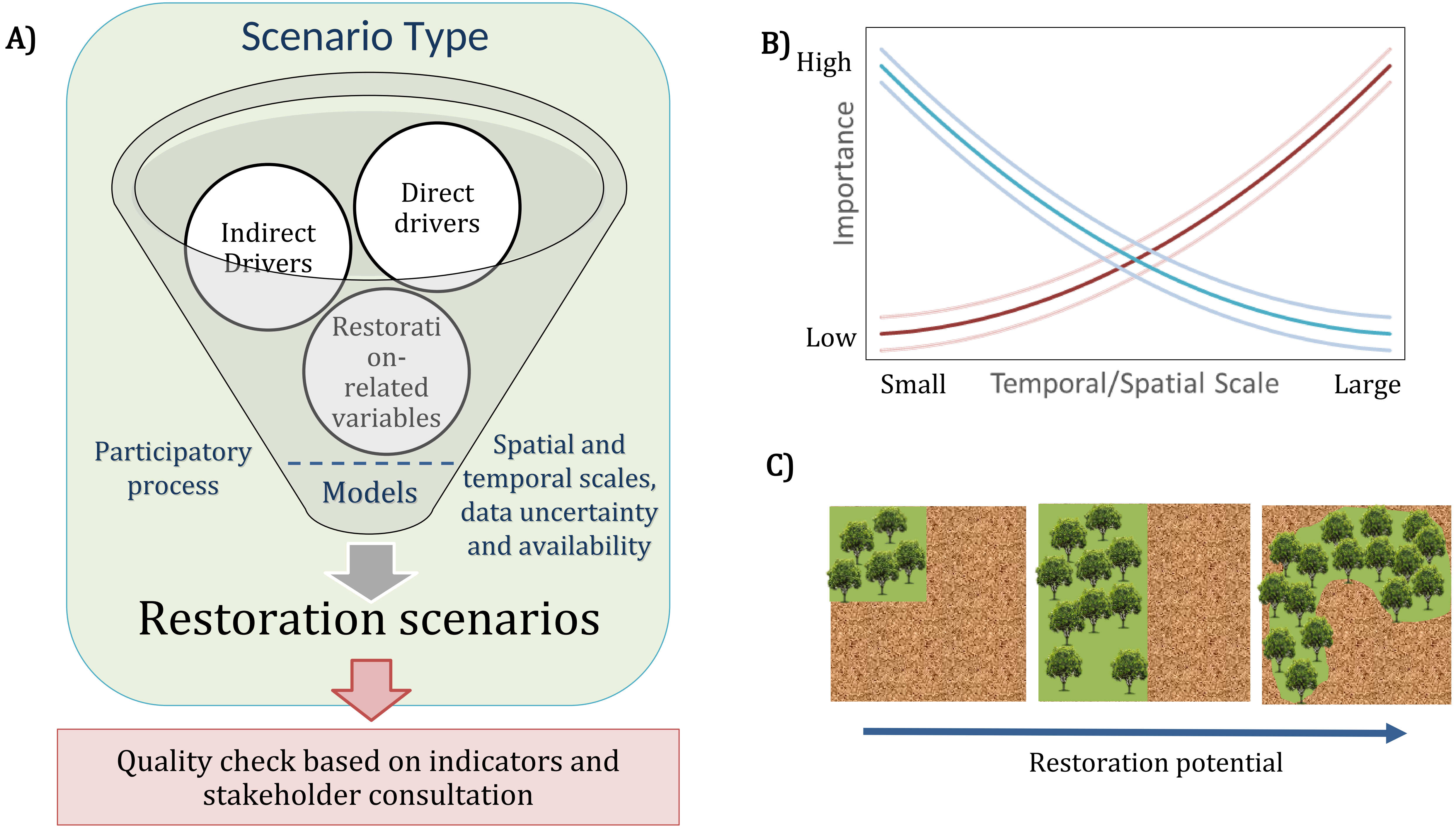
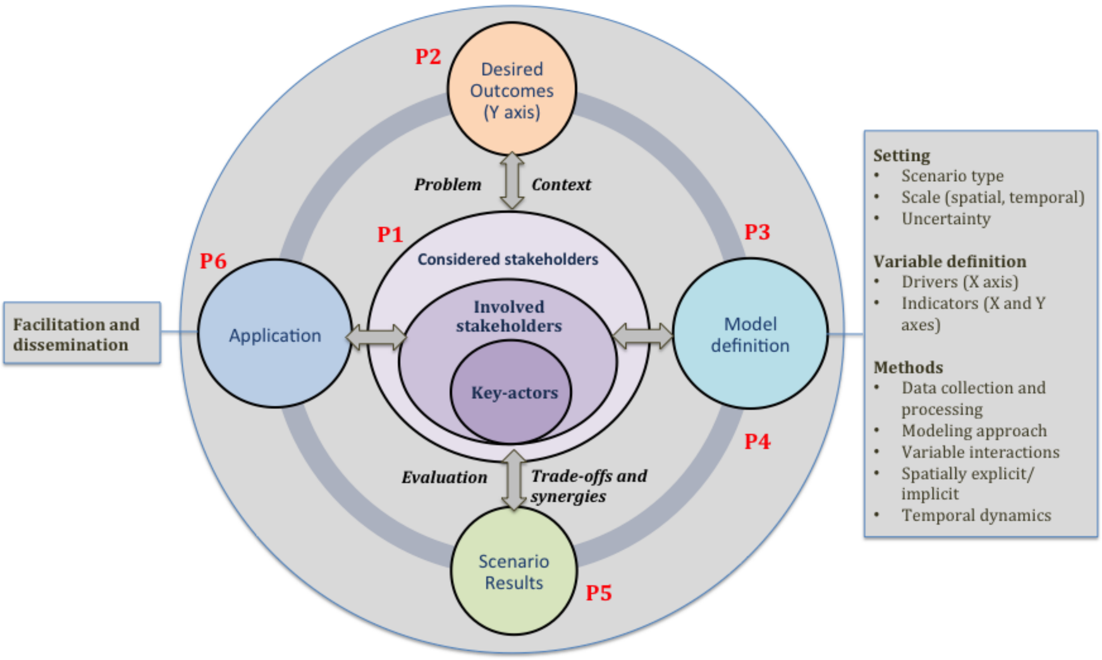

Key-actors
Innitiate the process and have direct interest in restoration outcomes
Considered stakeholders
Potentially impacted by restoration scenarios, but do not influence them or participate in their development
NEW DATA
EVALUATE
PLAN
FINE TUNING
MONITOR
IMPLEMENT
Scenarios and models
Adaptive management
To conceptualize scenarios, define methods and analyze, disseminate and reanalyze results
Transdisciplinary and participatory
Approach to represent different perspectives and deal with trade-offs
Involved stakeholders
Recruited by the key actors to participate in scenarios development


A)
Scenario Type
Indirect Drivers
Direct drivers
Restoration-related variables
Participatory process
Models
Spatial and temporal scales, data uncertainty and availability
Restoration scenarios
Quality check based on indicators and stakeholder consultation
B)
High
Importance
Low
Small
Temporal/Spatial Scale
Large
C)
Restoration potential

Box 1. Proposed framework for building restoration scenarios that should support restoration planning.



Schematic representation of the six principles (P1 to P6) of the proposed framework to guide the use of scenarios and models for restoring native ecosystems.

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Box 2. Case studies to illustrate the suggested principles for building restoration scenarios

Stakeholder involvement and scenario outcome identification (Principles #1, 2, 3 and 5)

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Analyzing outcome trade-offs and synergies (Principle #5) and communicating results effectively (Principle #6)

Mitchell et al. [50] and Reed et al. [54] make use of story lines and narratives to construct and communicate their restoration scenarios effectively **(Principle #6)**. After their workshops and stakeholder consultations, *Mitchell et al.* applied a systems-based strategy to consider critical uncertainties within the drivers of change on the Tasmanian Midlands system dynamics. They created a quadrant matrix of scenarios comprising the possible combinations of these uncertainties. A smaller group of researchers (here considered as key-actors and involved stakeholders) was then able to refine scenario narratives based on scientific expert consultation. The scenarios varied on the basis of farmer profitability and social and human capital, ranging from agricultural loss and rural decline to sustainable and profitable agriculture. These narratives were then brought back to the community so that stakeholders could understand how their decisions would affect their environment **(Principle #6)**. In a similar fashion, *Reed et al.* used story lines and narratives to define their extensification or intensification policy scenarios in the UK uplands **(Principle #6)**. The narratives were communicated to stakeholders by film, which facilitated the integration of information from a wide range of sources, including local and scientific knowledge, and gave public relevance to the issue while also providing rigorous evidence **(Principle #6)**. The films illustrated and communicated those narratives in a way that was easy for people from different backgrounds and education to understand and endorse. For both studies, the narratives allowed stakeholders to identify opportunities for biodiversity conservation and potential sources of financial support to incentivize local stakeholders to pursue win-win opportunities whenever possible **(Principle #5)**.

Conflicts of interest

There is no conflict of interest.

SUPPLEMENTARY MATERIAL

After an extensive literature review (Acosta et al. unpublished data) on the use of scenarios in restoration, we did not find any comprehensive software tool for building scenarios. To build scenarios it is necessary to use *different types of data* (e.g. interviews, climate models, land use/land cover data), *multiple analyses* (e.g. algorithms, models), *obtained from diversified sources* (e.g. data gathered by participatory approaches, or by satellites), and results can be *presented in many formats* (e.g. graphs, maps, raster). As a result, it seems natural that the process of generating scenarios for environmental restoration will need multiple and diversified methodological approaches, as well as analytical tools.

In the absence of a comprehensive restoration scenario building software, here we provide a few examples of software that can be used to create and model some of the necessary inputs for building restoration scenarios. For example, FRAGSTAT is frequently used to mathematically characterize landscape structure [1]. CONEFOR [2] and Circuitscape [3] are suitable tools to evaluate connectivity. DYNAMICA-EGO [4] can be used to simulate land use and land cover dynamics. Maxent [5] and DISMO [6] and Biomod2 [7] are good examples of tools to evaluate environmental suitability or to map potential species distributions. InVEST, ARIES, TESSA are tools to evaluate ecosystem service provision (see a more comprehensive list and references in [8]). To read, integrate, map, and plot all those analyses in a spatially explicit way, GIS platforms (e.g. ArcGIS, DivaGIS, MapINFO, QGIS) and programming languages such as Python, Mathematica, Matlab, S-PLUS, and R language are encouraged.

The development of restoration scenarios requires thus multiple data types and sources, analyses, and models, which is only possible by integrating different software tools.

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