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Perspective

Integrating public engagement to intensify pollination services through ecological restoration

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SUMMARY

Globally, human activities impose threats to nature and the provision of ecosystem services, such as pollination. In this context, ecological restoration provides opportunities to create managed landscapes that maximize biodiversity conservation and sustainable agriculture, e.g., via provision of pollination services. Managing pollination services and restoration opportunities requires the engagement of distinct stakeholders embedded in diverse social institutions. Nevertheless, frameworks toward sustainable agriculture often overlook how stakeholders interact and access power in social arenas. We present a perspective integrating pollination services, ecological restoration, and public engagement for biodiversity conservation and agricultural production. We highlight the importance of a comprehensive assessment of pollination services, restoration opportunities identification, and a public engagement strategy anchored in institutional analysis of the social arenas involved in restoration efforts. Our perspective can therefore guide the implementation of practices from local to country scales to enhance biodiversity conservation and sustainable agriculture.

INTRODUCTION

The concepts of ecosystem services and of Nature's Contributions to People (NCP) have highlighted how human societies depend on biodiversity.[1] Biotic pollination, for example, has important ecological and economic impacts supporting biodiversity maintenance, ecosystem stability, food production and security, socio-environmental sustainability, and human welfare.[2] Alarmingly, pollinators have been declining globally, mainly because of land use change, habitat loss and fragmentation, pesticide use, resource diversity decrease, climate change, and invasive species.[3] Such drivers are common threats to biodiversity and NCP in general, making clear that conservation efforts are paramount to sustain human socioeconomic activities.[4] Although never as important or effective as conservation of native vegetation, restoration initiatives help reestablish functions and services in modified landscapes if implemented through adequate actions.[5] There is now potential for restoration of almost 1biha globally,[6] opening up the opportunity to plan biodiversity recovery and NCP simultaneously.

Incorporating pollination services as a key justification for future restoration efforts is based on how native pollinators directly enhance crop productivity, which can motivate changes in agricultural practices.[4] Farms close to natural or semi-natural areas show higher and more stable flower visitation across space and time, greater pollinator richness, and higher crop yields.[7,8] Flower visitation rates and pollinator richness can be reduced by as much as half in farms 1 km distant from natural areas compared to farms closer to natural areas.[9] Additionally, landscapes with higher proportions of natural areas and greater heterogeneity (distinct land use and cover) show higher pollination services (i.e., increment in crop yield due to pollinator activity[10]). Furthermore, management and composition of landscapes affect bee communities, with organic farms (vs. conventional) and locally diversified systems, i.e., mixed crops (vs. monocultures) supporting the highest bee abundance.[9,11] Ecological restoration contributes to the recovery of pollinator

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and flowering plant communities in managed landscapes, with benefits to agriculture via pollination services.[10,12] Moreover, pollinator-friendly landscape management also results in NCP synergies, such as higher biological pest control.[13] Therefore, ecological restoration emerges as an additional option to promote landscapes that maximize NCP benefits while reducing cropland expansion.

Multiple synergies and potential trade-offs between pollination service and crop production have been postulated.[13] However, socioeconomic and institutional factors that affect practices for ecological restoration and provision of pollination services are often overlooked.[14] There is a need for an integrated pollination assessment to achieve optimal agricultural landscapes that maximize pollination services and take advantage of current restoration opportunities to foster the implementation of ecological intensification of agriculture. Such integration and intensification are important because restoration has the potential to change how we design landscapes with profound effects from small to large farmlands, while other initiatives such as floral plantings have been more restricted in scale and impact.[15]

Restoration opportunities arise from existing capacity (public sector, NGOs, or private companies), legal requirements, government incentives, and voluntary initiatives by farmers.[16] Motivations may be diverse and potentially divergent between distinct sectors involved in restoration projects. For instance, mandatory restoration is likely to be effectively implemented through its appeal to stakeholders,[17] but is usually not designed to target pollinator conservation and pollination services. Thus, there is still a gap between studies that evaluate NCP (including pollination services) and evidence-based actions.[18] An effective approach to implementing ecological intensification through restoration should rely on public engagement among consumers, government bodies, private sector, producers, and researchers. Here, we follow the definition of public engagement as 'any activity or benefit of research that can be shared with the public'.[19] A successful public engagement strategy will result in useful and usable evidence-based practices. Thus, it is necessary to develop strategies in which researchers and practitioners together create usable knowledge, with further consideration of socioeconomic and governance dimensions.[20] Such strategies should be tailored to a local context to enhance biodiversity conservation and provision of pollination services, while considering an interactive and pluralistic process among researchers and practitioners.[21] The design of local strategies depends on understanding local interactions between distinct stakeholders that determine access to common goods such as NCP,[22] although an assessment of social structures has not been applied in the context of pollination services.

Here, we present a perspective focused on the implementation of evidence-based actions in transdisciplinary projects to achieve biodiversity conservation via pollination services and restoration. We describe important concepts and tools, highlighting the analysis of social and cultural structures often neglected when mapping pollination services and restoration opportunities. To this end, we point to three interactive processes (Figures 1 and 2): (1) assessment of pollination services and (2) mapping of restoration opportunities that will result in (3) biodiversity-friendly practices. Importantly, public engagement is fundamental to ensure that all three processes operate iteratively, understanding that any one process can change the desired outcomes envisioned by all involved partners. To guide our analysis, we apply a version of the Institutional Analysis and Development (IAD) adapted from Ostrom.[22] To illustrate general guidelines for application, we present working examples containing elements of the proposed tools.

Public engagement and IAD (Institutional Analysis and Development)

The gap between scientific information and its implementation in evidence-based solutions has long been acknowledged in medicine and in environmental sciences.[23] This gap is attributed in part to cultural barriers between stakeholders, resulting from a mismatch between academics' values and potential users' values.[24] Moreover, conservation projects often face interaction problems regarding lack of communication and epistemological barriers (differences in the types of knowledge or mode of producing knowledge considered valid).[25] Such barriers highlight the need for strategies to enhance the usability of scientific knowledge. In this context, scientific information regarding pollination services has been characterized as mostly produced and communicated via unidirectional approaches, in which academia produces relevant information and transmits it to interested sectors.[26] A unidirectional approach can magnify cultural and epistemological barriers because potential users are not engaged in the process of producing scientific evidence, making it harder for them to value such information.[27] Thus, it is necessary to engage stakeholders to foster the use of evidence-based solutions regarding pollination services and restoration.

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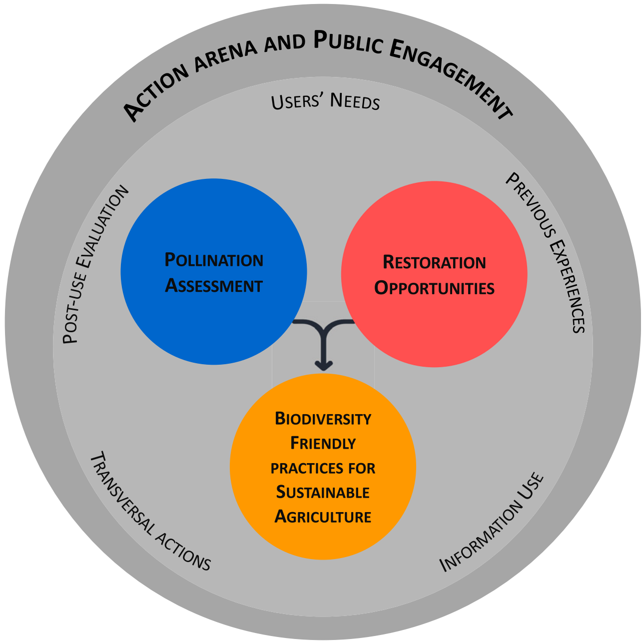


Figure 1. Conceptual synthesis

Two processes interact to achieve restoration aimed at enhancing pollination services: assessment of pollination services (blue circle) and identification of restoration opportunities (red circle). Pollination assessment would ideally include distinct environmental and socioeconomic aspects of pollination services. Accordingly, it is desirable to identify environmental and socioeconomic opportunities for restoration. This approach is based on the combination of public engagement[19] with Institutional Analysis and Development (IAD[22]) frameworks (outer gray circle). The combination of these frameworks results in a robust analysis of the social action arena in which pollination assessment and identification of restoration opportunities are undertaken in two-way collaborative restoration projects between the generators of information (producers, academia, tertiary sector, etc.) and the users of information (producers, government, consumers, etc.). The public engagement strategy includes, but is not limited to, an assessment of previous experiences of the actors, identification of users' needs (e.g., demands for increased pollination services) and how information is sourced and used (where users seek and obtain information and how they apply it). Additionally, the application of IAD results in the identification of the rules-in-use (institutional rules, laws, informal rules), interactions and potential outcomes between the actors. Ultimately, this iterative process would result in restoration as a part of a broader context of biodiversity-friendly practices for sustainable agriculture (yellow circle).

Public engagement is key for fostering the adoption of biodiversity friendly evidence-based agricultural practices.[20] Public engagement should be anchored in two-way approaches, in which academia and other interested sectors jointly produce and/or assess relevant information (i.e., knowledge co-production[27]). Two-way approaches have the advantage of reaching potential solutions which are viewed as usable by stakeholders. To facilitate the implementation of a public engagement strategy, it is necessary to understand the social and institutional context in which evidence-based practices will be adopted. Thus, there is a need to broaden the focus and consider evidence-based projects as socio-ecological systems, in which understanding socioeconomic and cultural factors is vital to assess pollination services and restoration opportunities. The IAD[22] can be used to evaluate the social context in which natural pollination intensification will occur (Figure 3). It has the potential to assess relevant information on how stakeholders collectively act and make decisions, thus enabling effective public engagement strategies aimed at reaching common goals.

The IAD approach has been widely used in the social sciences to analyze how distinct human institutions influence socio-environmental issues.[28] Furthermore, the socio-ecological systems framework, an extension of the IAD, was designed to facilitate analysis focused on situations involving environmental and common-pool resources shared by the stakeholders.[29] Common-pool resources are natural or man-made resource systems in which excluding users is 'non-trivial (but not necessarily impossible) and the yield of the resource system is subtractable'.[30] In our case, the common resources are native vegetation and its provision of pollination services, which are both affected by how stakeholders manage their land. The

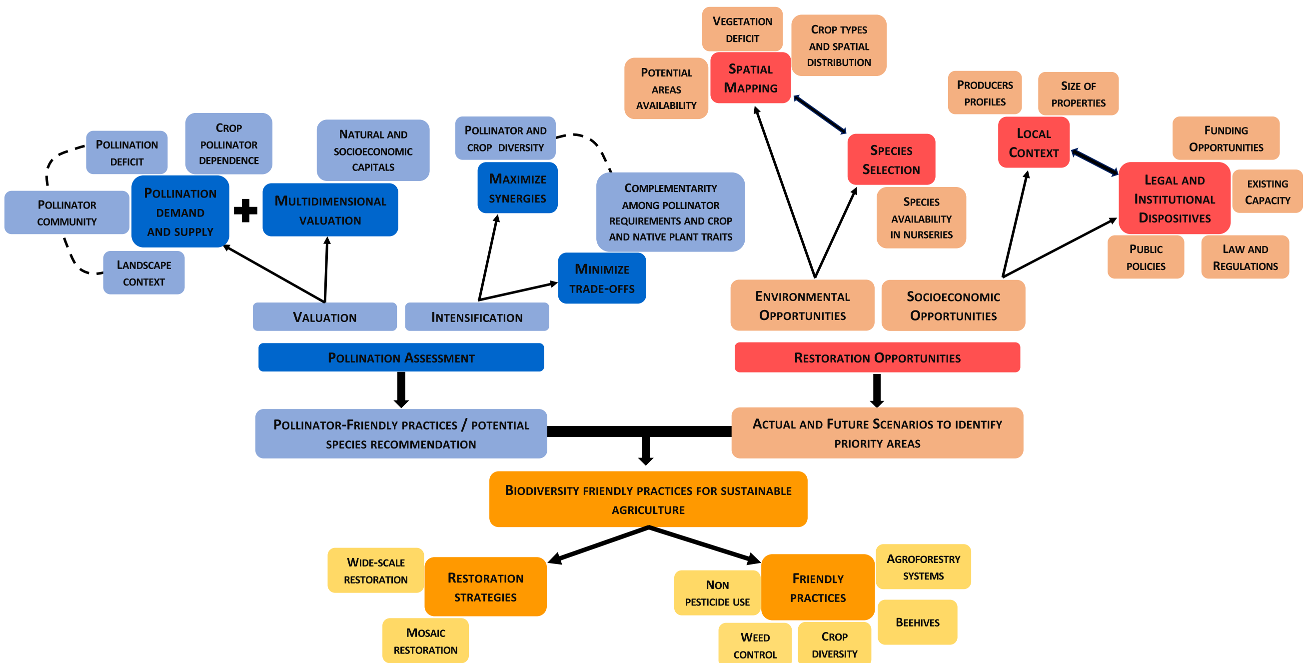
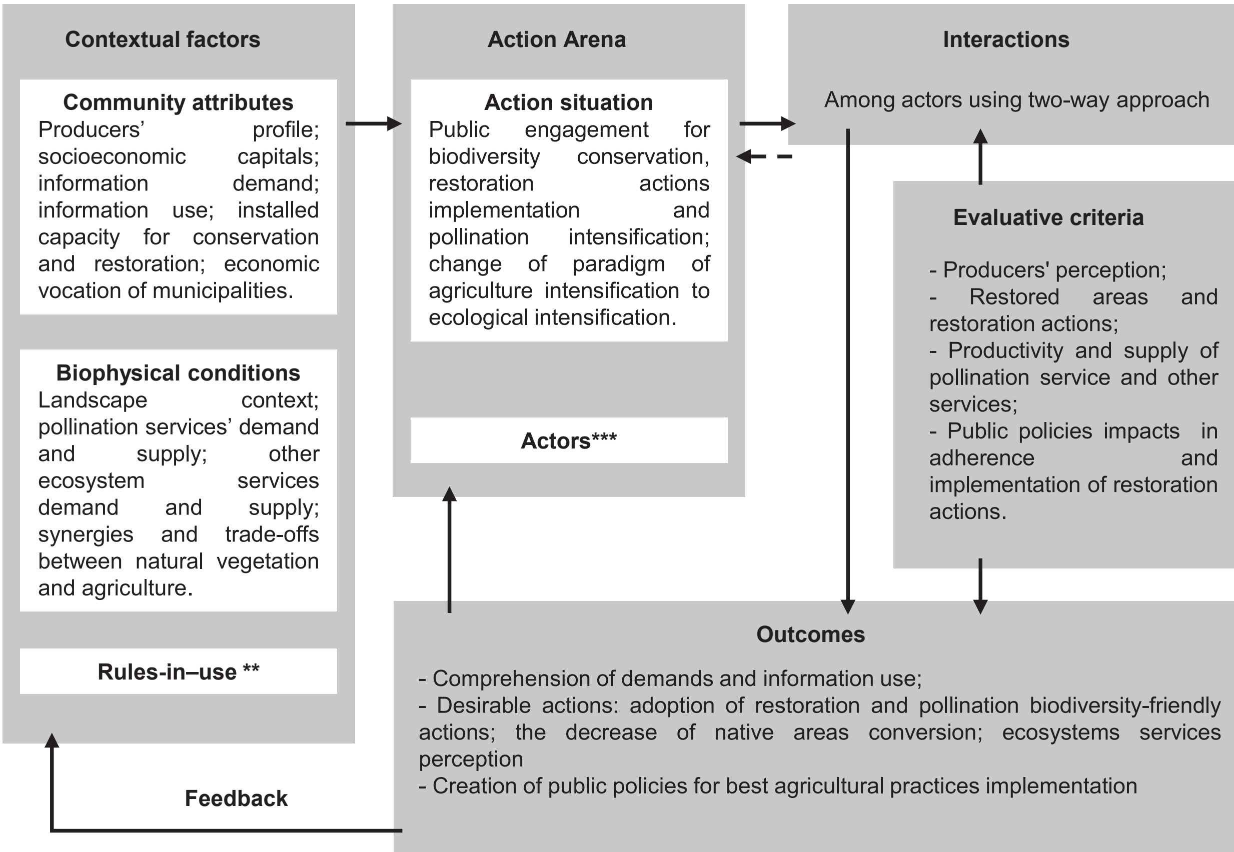


Figure 2. Disentangling pollination assessment (blue) and restoration opportunities (red) processes toward biodiversity-friendly practices for sustainable agriculture (yellow)

We present a summary of the main aspects to be evaluated to achieve natural pollination intensification as a contribution to practices for sustainable agriculture. Solid lines refer to direct interactions among factors. Dashed lines refer to indirect interaction among factors. The "+" symbol refers to an integrated assessment of pollination services.

analysis element of IAD is centered in identifying and describing an action situation in which stakeholders act and collectively make decisions. In this case, the action situation is management of pollination services. Generally, this action situation will involve stakeholders directly related to agriculture (e.g., farmers, government sectors related to agriculture) and/or biodiversity conservation (e.g., government sectors related to conservation, NGOs) or that act as knowledge brokers (e.g., technical assistance bodies, NGOs, academia) (Figure 3). Ultimately, the IAD approach allows understanding how human institutions lead to certain outcomes (e.g., current land use management) and, consequently, which governance model could then lead to novel outcomes (e.g., ecological intensification of agriculture through pollination services and restoration opportunities).

The action situation has two main inputs: exogenous and endogenous factors.[22] Exogenous factors are related to the biophysical and socioeconomic context. For instance, mapping pollination services and restoration opportunities provide a guide to identify crucial exogenous factors, such as landscape features and existing capacity to conduct restoration and conservation efforts. Moreover, it is also important to map socioeconomic capitals such as social relationships, cultural values, farmer profile and economic structures mediating the provision of pollination services and restoration opportunities. The last exogenous factor is to identify rules-in-use, that is, formal and informal rules that support the relationships between stakeholders. Such rules-in-use are closely related to identifying shared demands and information use in public engagement strategies. Formal rules concerning pollination services appear in the form of legislation and public policies (e.g., Hipólito et al.[31]), but will also include the monitoring and regulation actions of government bodies and local associations. The management of natural resources by the commons;[22] in other words, how informal rules such as collective decision-making, verbal agreements, cooperation, and local territory rules can also shape both pollination services and restoration. This repertoire of strategies defines how stakeholders interact in the social situation greatly influencing the outcomes. Given their importance, it is worth distinguishing which are the relevant rules defining the governance system.[29] Tools from the social sciences, from field observation to discourse analysis, will be important to identify community attributes and rules-in-use, which can be elicited and explored through structured polls. Once all exogenous and contextual factors are determined, they will inform the design of the



Simplified table relating three actors, their rules-in-use (IAD) and role in the dialogue of shared demands (Public Engagement). The complete table can be found in Appendix B.

Actors***	Rules-in-use**	Direct contribution to the dialogue of shared demands
Small farmers	Internal community rules of space and resource use; Local dynamics defined by subsistence; Acquired knowledge about resources management and use; Local custom and uses; Higher-level organization (associations); Access to subsidies and funding; Power dynamics with local government and big farmers; Legal restrictions on land use.	Guide products (based on farmers' experience/demands) to delimit issues and problems; knowledge of internal rules of land use management
Scientists	Scientific demands; internal academic rules; knowledge hierarchies with small and big farmers	Evidence-based problems and solutions; multisectoral communication
Public Policymakers	National and international market demand and supply; National and international agreements on biodiversity conservation and restoration; Power dynamics with associations and cooperatives; Power dynamics with small and big farmers;	Public policy decisions; financial support; implementation of governance models

Figure 3. Essential components of Institutional Analysis Development

The framework above identifies and describes the action situation in which restoration projects aimed at providing pollination services will take place. The action situation is performed by all stakeholders involved in the productive sector and in restoration projects and is influenced by community attributes (socioeconomic context) and biophysical conditions (environmental context), as well as by rules-in-use, i.e. formal and informal rules that define the

Figure 3. ***Continued***
interactions among stakeholders and the governance system. The action situation is dynamic and changes according to the actors' interactions. Consequently, the actors' change results in rules-in-use changes within contextual factors. Here, we identified and detailed actors' groups and rules-in-use and recognized direct contributions to the dialogue of shared demands in public engagement strategies considering the stakeholders that may be involved in the Bragança Paulista region (Figures 4 and 5).

most effective public engagement strategies to bring together all stakeholders and implement collective actions.

The action situation will be the result of endogenous factors such as the interaction between stakeholders, i.e., the relationships among each individual governed by formal and informal rules.[28] Specifically, interactions mediated by rules encompass access to power; forms of punishment; assigning and controlling responsibilities; and roles in the action situation.[29] For instance, territorial rules can define access to goods that foster pollination services, such as access to restoration opportunities. Moreover, mapping restoration opportunities will also require identifying producers' profile and existing restoration implementation capacity, information that is likely to come from knowledge brokers such as rural producer organizations. In this case, endogenous factors are directly related to important processes in public engagement initiatives: shared demands, knowledge gaps and transversal actions.[19] Inter-sectoral dialogues, including all parties involved in a project, should first identify shared demands,[32] defined as transversal problems related to natural pollination intensification and restoration that connect biodiversity conservation and agricultural productivity (e.g., pollination deficits, reduced crop productivity, barriers to implement restoration actions and so on). Distinct sectors may present different but complementary demands, and the dialogue through common goals achieves alignment of values.

Once shared demands are identified, it will be possible to understand which knowledge gaps are related to such demands. Examples may include general gaps, such as which type of restoration to conduct, or how to mitigate pollination deficit in a given crop. General solutions may be viewed with skepticism if local specificities are not being considered, hindering confidence in evidence-based practices.[25] Therefore, what would be apparently minor and specific gaps in a purely academic perspective, may be key to achieve solutions applicable to multiple real-world situations. The knowledge needed to fill these gaps will often pertain to farmers, who have a direct relationship with land and local biodiversity.[33] A useful example in this sense is the use of local knowledge on bee nesting sites to guide floral plantings and restoration.[34]

Shared demands and knowledge gaps will result in transversal actions, defined here as practices that require distinct parties to work together. Such practices can happen in all steps of pollination services and restoration projects, from producing information to implementing actions. For instance, farmers, rural associations, and researchers may develop a pollination assessment tailored to cover local specificities (Figure 3). Moreover, it may be necessary to involve knowledge brokers as intermediaries for communication between sectors. One successful example of identification of shared demands, knowledge gaps, and transversal actions is the implementation of large-scale restoration through the Atlantic Forest Pact in Brazil.[35]

Even when demands, gaps and actions are jointly delimited by distinct stakeholders, there may remain barriers to translation and use of evidence.[36] This may be due to a lack of understanding how evidence is used to guide practices.[37] Such analysis should then reveal the need for, the motivation for, and the way of using information. In other words, the need for information is how the identification of shared demands should be translated into specific needs. For instance, farmers may want to know how soon restoration efforts will produce benefits through pollination service. Another important aspect is to identify the motivations for use, or what is expected from evidence. This is important because scientists often value scientific information while farmers tend to value government and agricultural-sector sources, which may lead to conflicts on which information to use or what to prioritize.[38] Finally, it is also important to identify ways of using information, which include media and reliable resources of information. This can be done via surveys involving farmers, associations, and technicians in order to identify potentially useful and usable products. Thus, we recommend the identification of the following aspects to circumvent common problems in two-way approaches: shared demands, knowledge gaps, transversal actions, and how information is assessed.

The public engagement strategies outlined here are intended to be as iterative as possible, so that identification and provision of important information can interact with each other. For instance, identifying the accumulated experience and knowledge of each sector involved will directly determine their motivation for using information. Once experiences start to build and return benefits, it will be important to report these experiences and benefits to society and disseminate the accumulated knowledge. Sharing this broader communication goal will be important to create a network of successful and beneficial experiences and to gain scale in restoration aimed at promoting ecological intensification through pollination services.

Assessment of pollination benefits in agriculture

Ecological restoration aspires to the partial recovery of native floral and pollinator communities and the reestablishment of as much pollination function as possible.[39] Landscape patterns affect demand (amount of service required), supply (potential delivery of service), and provision (realized service) of pollination services.[40] Restoration has vast potential to promote ecological intensification of agriculture via landscape modification and recovery of plant-pollinator interactions. Realization of this potential calls for an integrated assessment of pollination service (Figure 2).

Pollination evaluation helps to quantify the demand for pollinator services in an area (Figure 4). We here adopt a broad demand concept, which refers to how much pollination services are required in an area, also considering crop yield dependence on pollinators.[41] Crop dependence on pollinators varies from low (decrease of less than 10% in crop production without pollinators, e.g., lemon) to total (no production without pollinators, e.g., passionfruit).[41] One feasible way to evaluate the contribution of pollinators is to map crops spatially and collate their dependence levels from published sources (e.g., IPBES[3]). Using methods such as the dependence ratio,[42] pollination demand is estimated from crop production in an area weighted by each crop's dependence level. Thus, pollination service is easily translated into the economic value of crop production in the short term.[43] This approach can be used to identify areas with a high pollination demand as potential targets for implementing restoration efforts to provide NCP, for example, at a whole country scale.[44] In this context, pollination demand can be used as a rationale and motivation for restoration, promoting restoration opportunities.

In small-scale projects, pollination demand may be finely quantified as the acreage of pollinator-dependent crops.[47] Moreover, the actual pollination deficit (i.e., how much demand exceeds available pollination services, also known as "pollination shortage"[47]) depends on the interactions with pollinators taking place in the area. In other words, the dependence level for a given crop in a scenario of total absence of pollinators represents the maximum deficit of pollination services, while the actual deficit can be reduced depending on pollinator availability.[48] Pollination deficit is measured by comparing the production with maximum pollination (achieved by supplying flowers with pollen) and the current production achieved by local pollination levels. For instance, high pollinator density in small farms and high pollinator richness in large farms can reduce pollination shortage.[48] Thus, measuring pollination shortage offers a farm-based perspective to foster restoration opportunities and plan small-scale restoration actions.

It is also important to estimate pollination supply, i.e., the potential capacity of an area to provide pollination services (*sensu* Metzger et al.[40]; Figure 4). At local scales, pollination supply is measured by monitoring pollinator communities (composition and functional traits) and gathering data on abundances, phenology, nesting sites, and use of floral resources. To estimate pollination supply at large scales, land use maps are used and each patch in a landscape is scored depending on its potential resource provision to pollinators as a proxy of abundance, with natural areas being predicted to provide more numerous and more stable floral resources and nesting sites.[49] Then, available pollinator data from the literature can be used to refine the mapping of pollination supply in a landscape. Importantly, such supply models reflect pollinator richness and abundance measured in natural areas and croplands,[9] which supports their use as a basis for restoration efforts. Pollination supply models can also inform potential pollination flows, i.e., processes that connect the supply and demand of pollination services.[40] This is done by incorporating distances between cropland (demand areas) and native vegetation (supply areas), as well as pollinator flight ranges (i.e., if pollinators can reach crop areas from natural ones[49]). In this context, restoration can be used to enhance pollination supply and flow, especially where there is a high pollination demand and/or deficit. Besides potential delivery of pollination services, it is also interesting to consider actual pollination provision, i.e., realized pollination services in an area. At small scales, pollination provision can be accurately quantified *in situ*, by measuring pollinator activity in cropland (i.e., quantifying pollinator abundance, richness, and crop flower visitation) as well as its relationship with crop yield, as reported for soybean farms in

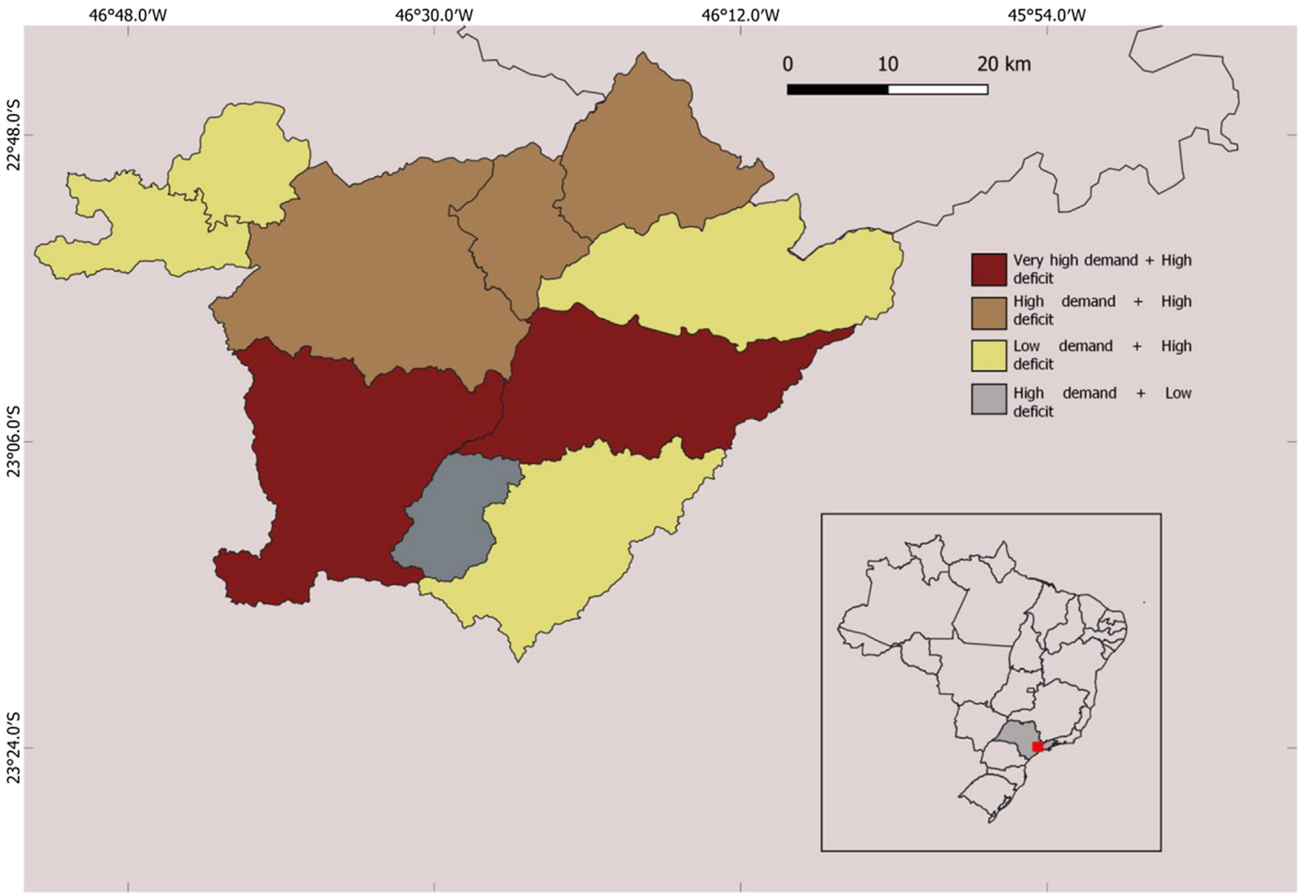


Figure 4. Actual scenarios to identify priority areas for restoration and pollination intensification

We valued pollination services at the municipality level through pollination demand (level of crop dependence on pollinators from BPBES-REBIPP,[45] based on crop production data available in sidra.ibge.gov.br/pam, following Bergamo et al.[44]). We then associated demand with the pollination supply using legal vegetation deficit (vis-à-vis Brazilian legislation, available in Guidotti et al.[46]), which sets current requirements for restoration (following Bergamo et al.[44]). The association between pollination demand with vegetation deficit can be used to detect general patterns: where reducing vegetation deficit via restoration will result in enhanced pollination supply to meet pollination demands. This assessment at the municipality level can be of special interest to decision-makers, aligning environmental policies with agricultural productivity to foster restoration opportunities. Then, local assessments will be important to design restoration efforts in the municipalities with highest pollination demand and supply.For this proof of concept, we select the municipalities of the Bragança Paulista region (hereafter, BP) in Brazil due to the range of crops and types of properties in this area (from large monocultures to small fruit-producing properties), distinct scenarios of land use (from urbanized areas to large native vegetation areas) and current opportunities for ecological restoration (initiatives led by TNC - The Nature Conservancy Brazil, tnc.org.br). In BP municipalities, high vegetation deficit were associated with very high (red) or high (brown) pollination demand; a second scenario of high deficit associated with low pollination demand (yellow); and a third one of low deficit with high pollination demand (grey). There is a high pollination demand but current high vegetation deficit. Once the social arena and shared demands of local stakeholders are mapped (Figure 3), such areas represent opportunities for ecological restoration to comply with legal requirements that can also maximize pollination services. Therefore, these results complement the IAD analysis in assessing the biophysical context for implementing restoration efforts. Scale bars indicate that 1 cm corresponds to 10 km.

Argentina.[50] Pollination shortage can also be viewed as the gap between demand and provision, in other words, how much the demand is actually met, as measured in blueberry farms in the USA.[51] However, these approaches are prohibitively resource-intensive at large scales. For this reason, pollination supply or flow are often used as surrogates of pollination provision (see Jordan et al.,[52] for an example in the USA). The integration of pollination demand, supply and flow to estimate provision may achieve a more realistic surrogate of realized services in a landscape.[40] Importantly, translating these estimates into economic and social gains can help engage other stakeholders.

Pollination provision may provide other social benefits besides economic gains. For instance, continuous provision of pollination services enhances crop production stability,[53] which guarantees food supply for

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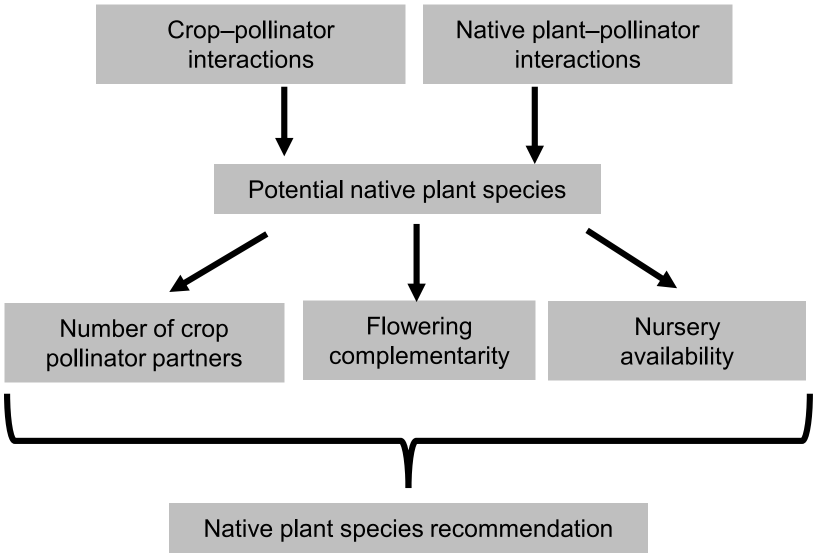
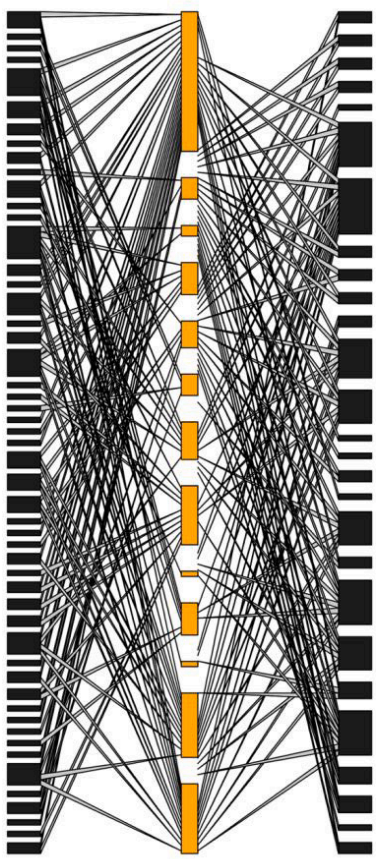


Plant species recommendation workflow



Tripartite network showing the interactions between crops (left), pollinators (center) and native plants (right).

Figure 5. Species recommendation for restoration and pollination intensification

We here present a workflow to reach specific recommendations of plant species for restoration that maximize pollination services. Importantly, this should be viewed as a method to complement existing lists since pollination is one of many other desired functions while restoring native vegetation. Several plant species should be used to reach a multi-functional restoration. We here used the same municipalities of the Bragança Paulista region in Brazil (BP, Figure 3). First, we build a tripartite network between crops, pollinators and native plants. The tripartite network was based on crop production data (sidra.ibge.gov.br/pam) and native floras.[64] Then, we used databases on crop-pollinator[45] and native plant-pollinator (abelhaseplantas.cria.org) interactions to infer the links in the tripartite network. For this example, we selected four pollinator-dependent crops which are among the most produced in BP: chayote, coffee, eggplant and zucchini. We then identified 26 native plant species that share pollinators with these crops (Appendix A).

The list containing 26 species can then be ranked according to criteria enhancing pollination intensification. Maximizing the number of distinct pollinator species is important because pollinator richness and functional diversity are often associated with higher crop yield.[57] Therefore, we recommend the number of pollinator species a plant species shares with crops as a criterion. To minimize potential trade-offs, we recommend native species that do not co-flower with crops. We gathered phenology data from virtual collections to estimate flowering peaks of native plants in the region (splink.org.br). Finally, we also gathered data on native plant availability in nurseries[65] to reach plant species recommendations for immediate restoration efforts. Thirteen species are already available in nurseries (Appendix A). Another implication of our approach is a special attention to the species not available in nurseries, as producing them will enhance the capacity of restoration actions aligned with pollination intensification. This can also alleviate the need to remove only some species from native areas to keep nursery production.

subsistence in small farms and food security at a country-level.[54] Economic and social variables (e.g., income, work, education, health) can be associated with environmental variables (e.g., pollination demand, landscape configuration) to understand the socioeconomic arena for pollination services. Such multidimensional valuation may lead to broader recommendations that also include human and social development goals. One clear example is the reduction and regulation of pesticide use that benefits both pollinators and human health.[55] Moreover, socioeconomic aspects also define restoration opportunities, which highlights the potential of multidimensional valuation as an integrative method to connect pollination services and restoration. This multidimensional valuation approach has been applied in other contexts; for instance, deforestation (and thus, decrease of NCP provision) was not correlated with human development indices in the Amazon, prompting calls for a change in the current deforestation trends.[56]

To implement natural pollination intensification, it is necessary to maximize synergies between restoration, biodiversity and provision of NCP but also minimize potential trade-offs. In this context, native pollinators provide equally or more effective services to the majority of crops compared to managed honeybees and managed bumblebees.[57] Instead of using managed introduced pollinators that may cause the loss of native fauna, efforts to conserve native pollinator populations are needed to provide equally or more effective pollination services. For instance, indiscriminate use of honeybee colonies may cause honeybee spillover to adjacent natural areas, increasing competition and risk of infectious diseases for native pollinators.[58] High pollinator diversity also enhances crop productivity by ensuring continuous provision of pollinator service even if one pollinator species declines.[13] Because managed landscapes present lower levels of pollinator diversity compared to native vegetation, restoration often recovers part of the native pollinator diversity.[14]

A potential trade-off when promoting natural pollination intensification is the competition for pollination service between crops and native plants.[59] One way to minimize competition is promoting functional complementarity between crops and native plants in their use of pollinators.[60] To achieve complementarity, it is necessary to select appropriate native plant species for restoration[61] (Figure 5). Species selection can also be conducted at distinct scales, resulting in lists of species chosen for properties in a locality but that can also scale-up to regions. Such planting recommendations should be based on three distinct datasets: (1) Crop pollinators' requirements: list of native pollinators that interact with crops and their use of floral resources (pollen, nectar, oil, etc.); (2) Crop traits: floral resources offered to pollinators and flowering phenology; and (3) Native plants and traits: list of native plants occurring in the area, especially a subset of native plants that interact with crop pollinators; floral resources offered and flowering phenology. From such lists, it is possible to select native plant species that are important to crop pollinators and, thus, will contribute to sustaining their populations; especially those that offer complementary floral resources and that flower at distinct times of the year in relation to crops.[62] This will help to produce flowering schedules to sustain resident pollinators in the area, in order to provide resources in periods between harvests and when crops are not blooming. The opposite scenario of functional redundancy can also be important in specific contexts to enhance the pollination service provision to a particular crop that shares pollinators with native plants.[63]

Restoration opportunities for mapping scenarios and implementing practices

The evaluation of restoration opportunities should consider some fundamental aspects such as the availability of potential and priority areas for restoration[66] (Figure 2). The analysis of landscape context is critical when aiming at natural pollination intensification, because extinctions of pollinators and plants in modified landscapes result from changes in landscape configuration (e.g., size, distribution and abundance of patches) and composition (e.g., amount, diversity and heterogeneity of land use and cover).[67] These landscape changes affect pollinators directly and indirectly, through habitat loss and isolation and the loss of interaction partners, especially those with specialized reproductive traits.[68–70] In terms of landscape composition, changes in types and amount of habitat lead to direct loss of pollinator diversity and indirect effects through changes in the availability of flower resources[71] and nesting sites.[72] In terms of landscape configuration, lack of connectivity among resource patches limits the foraging range depending on taxa mobility, limiting pollen flow among populations, which can cause further reduction in plant reproductive success.[73] Similarly, increased landscape complexity leads to a decrease in the overall number of pollinator visits[53] and also to changes in pollinator traits related to pollination efficiency.[54] Moreover, several crops are directly affected by changes in landscape structure, resulting in endangered biodiversity and productivity loss associated with lower stability of food production worldwide.[51,74]

Understanding opportunities for natural pollination intensification in socio-agricultural and degraded landscapes should also include in the first instance a comprehensive mapping of vegetation deficit, crops distribution, and potential areas (including abandoned and degraded lands). The stand and strategy choices for restoration must consider the reduction of distance among vegetation patches, to guarantee a higher offer of floral resources and consequently the efficiency of pollen transfer.[75] Targeted restoration planting to sustain and attract specific pollinators informed by target groups' requirements can be a successful restoration strategy in degraded ecosystems. The integration of mapping tools with data assessment of species traits (pollinators and plants), considering their role in the pollination networks,[76] can support species selection for restoration. Analysis of the local context facilitates the study of spatial processes and appropriate species selection promotes complementary flowering between crops and native plants. Finally, the availability of plant species for restoration should be considered for its impact on the feasibility of implementation under current and future scenarios. However, species selection as an alternative to promote restoration practices represents a complex sum of variables that should be considered in implementation context. Species lists should be extended to include multiple functions and serve as general guides to avoid imposing pressures on some plant species.[77] Restoration is a long-term endeavor and the ideal outcome is to maximize plant and pollinator diversity in order to achieve complementarity in changing crop scenarios.

As the outcomes of restoration interventions emerge from land use interactions and are largely shaped by landscape-level factors, a landscape restoration perspective seems a better option than a local restoration perspective. In this respect, as an alternative to wide-scale restoration (e.g., recovery of a large extension of natural areas), mosaic restoration approaches create a diverse land-use landscape, recovering abandoned degraded lands and maintaining a greater variety of agricultural areas, agroforestry systems, biological corridors, natural areas, and protected areas, which is more feasible in socio-agroecosystems.[78] Thus, restoration is an alternative to balance ecological and socio-economic needs in creating landscapes dominated by food production activities that can also offer multiple ecosystem services.[79] Restoration actions take time to reestablish ecosystem function and services,[80] and such long-term investment may be unattractive for farmers. Moreover, farmers may not feel the need to implement restoration because they can benefit from nearby restoration actions and consequent spillover of NCP provision from neighboring properties. Hence, developing policies that share the external benefits of restoration actions that provide pollination services is desirable.[81] We recommend policies that provide economic incentives to farmers who adopt practices that enhance pollination services provision (e.g., payment for environmental services – PES in Brazil). Equally, it is important to consider restoration practices and decisions as nonlinear processes subject to changes in time and space in response to changes in social values, environmental conditions, and scientific knowledge.[78]

Knowledge about how farmers collectively perceive cost-benefits in restoration practices is variable. Understanding why some practices are more widely adopted than others also can help to apply successful restoration. Despite the knowledge gap regarding how groups of farmers perceive cost-benefits of restoration, it is clear that in some cases, they are positive about evidence-based solutions but do not always have enough resources to implement them.[82] Thus, in general, they tend to accept and engage in practices with low interference in farming operations.[83] Moreover, such decisions are often collective, being shared by the farmers occupying the same area. Thus, we recommend, as an alternative, developing targeted strategies considering the group of farmers and their collective decisions concerning natural pollination intensification. Such collective approaches could be significant to achieving best outcomes and trade-offs between financial costs and benefits in the short-term and to convincing farmers and decision-makers. Once the results, revenues, and improved yield stability can be perceived, these may provide powerful arguments to continue actions and implement new restoration practices.

Legal and institutional judgements play an important role in the efforts of the implementation of restoration practices. International agendas, like the Bonn Challenge by World Resources Institute (WRI) and World Conservation Union (IUCN), and the Aichi target 15, ratified by the Conference of the Parties to the Convention on Biological Diversity, generate international demands and commitments to respond (e.g., United Nation Decade on Ecosystem Restoration 2021–2030). Nonetheless, international initiatives can only succeed through adequate integration in national and subnational programs[84] and the involvement of engaged governments with clear and supportive biodiversity and social agendas. Although regulation has a fundamental role in the implementation of restoration practices, generalization and standardization of solutions will compromise the efficiency of those practices if previous science-based evidence, people knowledge, and regional and local contexts are neglected.[77] The alignment of restoration actions with global, national, regional, and sectoral commitments and plans is important to evaluate results and to assure their relevance and attractiveness for decision-makers and stakeholders. Legal frameworks, reliability of institutions, and social perceptions (including cost and potential economic benefits) are the main opportunities to define approaches for restoration practices.[84] In this sense, knowledge as to how institutions operate can be crucial to develop public engagement strategies and to scale up restoration actions to attain national-level goals and deliver international commitments.

Economic gains of restoration may largely exceed both direct costs (costs of implementing restoration) and opportunity costs (i.e., economic loss due to the conversion of productive land to native vegetation).[85] The choice of passive or active restoration strategies depends on the local socioeconomic context and environmental conditions because there are trade-offs between costs and effectiveness.[86] Despite the higher costs involved, active restoration can be more appropriate in high degradation scenarios where propagule sources, dispersal and establishment are highly limited.[87] Nevertheless, natural regeneration plays a key role in degraded lands near propagule sources and is affordable if farmers have no financial resources for active restoration. Thus, natural regeneration can be an important strategy given that degraded land covers more area than intensively altered landscapes.[88] Robust economic estimates of restoration costs and financial opportunities through various channels (public, private, donor-funded) play an essential role in the decision to restore and in the choice of restoration strategy. Cross-country (e.g., REDD+ and GEF strategies) and local and regional initiatives (e.g., PES, technical training, economic incentives for commercial nurseries) for restoration investment may also help determine how stakeholders take action for restoration. Ultimately, such instruments should be used in agreement with all stakeholders and within governance models built around the specificities of each restoration project.

Restoration initiatives are essential for sustainable agriculture not only for recovery of diversity and species interactions and pollination services but also for their benefits to soil fertility, erosion control, diversification of livelihoods (as a source, for example, of timber and non-timber products), water provision and carbon sequestration.[89] We propose that choosing appropriate restoration strategies aligned with people's land-use rights, territory management, producers' profile, and properties' size can help landowners see short and long-term benefits. Thus, successful implementation of practices depends on the community's willingness to voluntarily participate in a restoration project and to engage in dialogue about shared demands. Moreover, understanding how stakeholders collectively deliberate and make decisions is crucial. Because of this, restoration strategies should adjust to the local economic, social, and ecological background which, in turn, directly relate to legal and institutional opportunities and funding.

Final remarks

Our primary purpose was to highlight the importance of integrated assessments in which social analysis and public engagement are fundamental to achieve sustainable agriculture. To this end, we linked concepts and tools that the iterative process of each restoration project will modify rather than proposing a universal formula. In synthesis, restoration efforts are supported by a multidimensional valuation of ecosystems services and are based on engagement of multiple actors for science-based action. Thus, multiple actors (i.e., producers, consumers, researchers, NGOs, government bodies, and the private sector) are crucial to achieve effective and successful action and for the continuity and scaling up of restoration plans. An integrated initiative helps not only to achieve institutional commitments on restoration but also to ensure the success and continuity of these actions.

The most frequent current practice of those producing scientific information for evidence-based projects is to map pollination services and restoration opportunities based mostly on the biophysical context (e.g., Bergamo et al.[44]). Instead, we suggest a broadening of focus to encompass mapping the social arena and institutional context using social sciences tools, such as IAD analysis.[22] This has potential to lead to relevant outputs such as a network of potential stakeholders and understanding of their social relationships. Such networks and understanding can facilitate formation of groups based on shared demands and engaged through common goals. The continuity of this engagement depends on actions tailored to improve within-group cohesion such as understanding and addressing barriers to communication and implementation of transversal actions, which are provided by tools from the public engagement frameworks.[19] Ideally, the choice and design of the tools to undertake the pollination assessment and the choice of restoration efforts can be co-produced by the group. For instance, there could be an active stakeholder network already in place, making it interesting to focus on understanding their social relationships to gain insight about the opportunities for restoration. In cases where pollination and restoration data are already available, the IAD and public engagement could be used to understand how stakeholders could use such data to implement actions. In all cases, integrating IAD and public engagement with current tools to map pollination services and restoration opportunities will help uncover the necessary socio-ecological information for evidence-based projects.

Restoration is both a scientific and a practical endeavor that can foster the creation of functioning networks for further evidence-based conservation efforts, effectively changing practices (e.g., Atlantic forest pact[35]). Restoration may also be the only option to recover biodiversity in intensively managed landscapes such as monocultures, which comprise a large portion of the agricultural land globally.[88] There is great potential to use restoration of pollination services to connect farmers and stakeholders in the agricultural sector to academia within the social arena of biodiversity conservation. In this sense, restoration should be considered a strategic pollinator-friendly practice that can play an essential role, because increased and more stable crop production can prevent the conversion and degradation of new areas (Figure 2). Friendly practices such as corridors, agroforestry systems, hedges, crop rotation, and wildflower strips complement restoration efforts and contribute to a mosaic restoration approach, a topic that merits further investigation (Figure 2). Importantly, these practices need to be well-founded to avoid some risks to biodiversity such as introduction of invasive species[90] or biotic homogenisation.[91]

Finally, through this integrative approach, we advocate pollination services as a compelling point of convergence for developing public policies and practices to recover and maintain many NCP. Therefore, pollination services are also a means to change paradigms of production with significant impacts on natural resource use and biodiversity conservation.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.107276.

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AUTHOR CONTRIBUTIONS

P.J.B. and K.F.R.: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review and editing, Visualization. L.F. and M.W.: Project administration, Conceptualization, Investigation, Writing – review and editing, Visualization, Supervision. B.F.V., E.G., E.N.L., M.M.M., A.R.R., F.D.S.S., I.G.V., K.A., M.C M.M., P.K.M., and N.R.: Conceptualization, Investigation, Writing – review and editing, Visualization. L.A.G., T.M.K., P.E.A.M.O., A.K.O., A.M.S., L.R.T., and R.Y.T.: Conceptualization, Writing – review and editing, Visualization.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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