12 June 2025 | González, D.A., Sica, Y.V., and Solari, L.M., 5th World

BIOREGEN INDEX:

Pampas As a Case Study

5thWorld

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Abstract

Biodiversity loss driven by agricultural intensification presents a significant challenge to achieving sustainable food systems. The BioRegen Index is introduced as an outcome-based, multi-metric assessment tool designed to evaluate the impacts of farm management practices on biodiversity at the property scale. By integrating ecological indicators across structural, compositional, and functional components, the Index provides a standardized yet adaptable approach to quantify ecological integrity within agricultural landscapes.

The methodology encompasses remote sensing, field surveys, and quantitative ecological metrics to capture the complexity of agroecosystems. Implemented as a pilot in central Argentina's Pampas region, the Index was applied to eight farms representing a spectrum of management practices from conventional to regenerative and agroecological systems. Biodiversity monitoring focused on five taxonomic groups—birds, anurans, vegetation, pollinator arthropods, and ground-dwelling arthropods—using standardized protocols. Indicators were selected based on their responsiveness to management practices, and targets were established using observed values, ensuring context-specific relevance.

Results demonstrated the Index's ability to differentiate between management types, with regenerative farms exhibiting consistently higher biodiversity scores. The approach revealed variability within land use categories, highlighting critical areas for targeted interventions.

Despite some data limitations, particularly in vegetation and anuran surveys, the Index proved practical for use within moderate resource inputs. Moreover, its flexible structure allows for regional adaptation and possible integration of emerging technologies such as acoustic monitoring.

The BioRegen Index advances the toolkit available for biodiversity monitoring in agricultural systems, supporting adaptive management and policy-making. By linking biodiversity outcomes with land stewardship practices, the Index has the potential to guide transitions toward regenerative agriculture and contribute to global biodiversity targets.

Introduction

Biodiversity loss and human activities

Biodiversity, which encompasses a vast array of different species of plants, animals, fungi, and microorganisms, as well as their genetic diversity and the ecosystems and ecological processes they are a part of (Noss 1990, IPBES, 2019), is in rapid decline. More than one million plants and animals are threatened with extinction, and the average abundance of native species in most major land-based habitats has fallen by at least 20%, mostly since 1900 (IPBES, 2019). This loss is a direct result of human activity, where land and sea use changes have the largest global impacts.

A critical portion of changes in land use is due to activities linked to food production. Croplands and pastures have become one of the largest terrestrial biomes on the planet, occupying 40% of land surface (Ritchie 2019, Ellis et al. 2010, Foley et al. 2005). Although these activities have successfully increased food production, they have become the main cause of biodiversity loss due to processes that operate at different scales: From the reduction of the diversity of cultivated species and the standardization of their growth to the consolidation of large areas under the same crop and/or production system (Benton et al. 2003).

Preserving biodiversity is not only a matter of environmental responsibility but is also essential for human well-being and the prosperity of future generations, since biodiversity supports our food and health systems. It is directly and indirectly linked to the fulfillment of all 17 Sustainable Development Goals of the 2030 Agenda for Sustainable Development (Blicharska et al. 2019) and it is the basis for the provision of ecosystem services such as climate regulation, nutrient cycling, water purification, and recreation and ecotourism (Harrison et al. 2014). Furthermore, ecosystem services crucial for food production rely on biodiversity such as crop genetic variation, pollination, regulation of undesirable species, and soil health maintenance (Altieri 1999, Harrison et al. 2014).

Biodiversity-friendly practices to halt biodiversity loss

Food production does not necessarily mean biodiversity loss. There are many options to reach win-win solutions that protect farmland biodiversity while increasing the production of food and fibers (Fischer et al, 2017, Cunningham et al., 2013). An array of management strategies varying from land sharing (food production with the least impact on biodiversity integrated on the same land) to land sparing (high-yield farming areas combined with protected areas) can be implemented at both local and landscape levels (Phalan et al. 2011). Such strategies could involve intensifying food production in specific areas while preserving others as natural habitats (Phalan, 2018), maintaining natural habitats in less productive farm sections (Garibaldi et al, 2023), maintaining small elements interspersed in the agricultural matrix (Garibaldi et al., 2014), and practicing intercropping (Li et al., 2020), among others. Different strategies should be applied and adapted to local conditions as landscapes vary greatly in inherent biodiversity and the production systems they can support (Cunningham et al., 2013).

Regenerative agriculture is an agricultural movement that proposes alternative means of producing food to the conventional system in a way that may have lower or even positive environmental impacts (O'Donoghue et al, 2022, Rhodes, 2017). Regenerative agriculture is framed within the concept of regenerative sustainability, which sees humans and the rest of life as one self-organizing system that seeks to flourish and prosper (Gibbons, 2020). It involves the adoption of practices that increase biodiversity, improve soil health and carbon sequestration, and increase the provision of ecosystem services. Some commonly mentioned practices are the low use of external inputs (e.g., synthetic pesticides and fertilizer), livestock integration in crop systems, and tillage reduction or elimination (Newton et al, 2022). Though, any of the previously mentioned practices could also be used within this type of production system.

The importance of adopting biodiversity-friendly and sustainable agricultural practices is recognized as a global policy. More than 196 countries have agreed to these principles by adopting the Kunming-Montreal Global Biodiversity Framework as part of the Convention on Biological Diversity. It is also becoming relevant in the private sector, as shown by the growing number of international certifications that incentivize such practices, including the Global GAP (Global GAP 2022), Round Table for Responsible Soy (RTRS, 2022), Rainforest Alliance (Rainforest Alliance, 2022), and Smithsonian Bird Friendly certification (Smithsonian Bird Friendly, 2023). Whatever the biodiversity-friendly management strategies adopted and the reasons for incorporating them, simple tools that measure and report their success towards biodiversity conservation are crucial in the decision-making process.

Measuring outcomes of management practices

Two possible approaches exist when designing the implementation of biodiversity-friendly management strategies at the farm scale: Action-based (where the effort of implementing such a strategy is valued) and outcome-based (where the results of the strategy are under evaluation, requiring tools to measure biodiversity response) (Crowther et al. 2024). While the first has the advantage of not requiring biodiversity data, which might not be easily accessible, it could be very prescriptive, restricting the possibilities to adapt to particular contexts, subjective, and discouraging innovation. By focusing on evaluating measurable biodiversity results (e.g., species diversity, habitat quality), outcome-based approaches ensure that conservation efforts lead to tangible ecological benefits (Zimmert et al. 2024). Furthermore, as outcome-based metrics have varying degrees of dependency on landscape factors, they could incentivize cooperation between farms and landowners.

An important aspect of outcome-based tools is the use of biodiversity metrics that are sufficiently sensitive to changes in management practices at the temporal and spatial scale in which they are applied (Geldmann et al., 2021, Addison et al., 2018). For example, population size metrics of short-lived species (such as plankton) will respond more quickly than metrics measuring population trends of long-lived species (such as large fish or marine birds and mammals) (McQuatters-Gollop et al. 2019). In addition, the effectiveness of biodiversity interventions can be gauged through specific metrics that track progress against goals set at various levels or for different objectives. For instance, if our goals are related to improving a farm's functional aspects (e.g., water filtration or pollination) then measuring water quality or richness of pollinator species can be a good tool to assess progress. However, they may not be useful if our target focuses on extending non-productive areas or improving landscape heterogeneity.

Multi-metric land assessment tools

To understand biodiversity status on the field and identify its change, we need quantitative and qualitative ways to measure it. It is challenging to measure such a broad concept as biodiversity (i.e., all biotic variation from the level of genes to ecosystems) in useful ways (Purvis & Hector, 2000). Hence, Noss (1990) proposed to measure its different components in parallel: Structural (physical organization or pattern of elements in a farm), compositional (identity and variety of elements in a farm, including species lists and measures of species diversity and genetic diversity) and functional (involving ecological and evolutionary processes, such as gene flows, disturbances, and nutrient cycling). These components or facets encompass multiple levels of organization (e.g. landscape, community, species) and cannot be summarised using a single metric. Hence, a set of multiple complementary metrics is necessary to provide insight into the ecosystem's overall functioning.

Multimetric indices (MMIs) integrate multiple measurements of different biodiversity aspects simultaneously (Hughes et al., 1998) and have been used to evaluate ecological conditions globally (Buss et al., 2015, Ruaro & Gubiani, 2013). MMIs synthesize data, often from multiple levels of biological organization, to derive a single index that reflects the overall effects of land management impacts. MMIs are robust tools for assessing aquatic and terrestrial ecosystem status and trends (Buss et al., 2015, Ruaro & Gubiani, 2013, Tasser et al. 2019, Blumetto et al. 2019, Quinn et al. 2013).

Objective

We developed and tested an outcome-based multi-metric land assessment tool, the BioRegen Index, with the objective of providing a practical tool to measure agricultural land management impacts on biodiversity at a farm level. This tool includes: 1) a simplified field survey protocol, 2) the identification of outcome-based metrics, and 3) the integration of such metrics into a comparable, scalable index. We implemented the BioRegen Index in central Argentina as a case study to evaluate the feasibility of implementing and interpreting such an index.

Methods

Development of BioRegen Index

Complementary indicators

To achieve the goal of measuring land management impacts on biodiversity, and because no single metric is able to provide insight into the overall functioning of an ecosystem, the BioRegen Index uses a set of complementary indicators to form a composite index. In the context of this document we use indicator as a quantitative measure that estimates the current state or trend of any biodiversity component, such as richness of habitat specialists birds or natural vegetation coverage. We distinguish an indicator from an index, which is an aggregation of indicators into a single representation or a standardization, like the diversity of specialist birds, which would be composed by this group's richness and the abundance of this group. Finally, we use metric as a general term to describe any sort of measurement.

We use a three-level approach to assess ecological integrity, from remote sensing imagery (land cover), to rapid field assessments (planned biodiversity surveys), and detailed quantitative assessments (selected biodiversity indicators). The Index was designed to measure outcomes of practices on lands under a broad range of management objectives, and to be independent of land steward-provided information.

Scope and scale

The BioRegen Index was developed to be implemented in farming systems. We defined these as an area of land managed by a steward with the principal objective (although not the only one) of producing food, fiber, timber, and other goods (e.g. agriculture, ranching, forestry, fruticulture, horticulture). Despite this, the Index has enough flexibility to be adapted to systems with other main objectives.

The Index is designed to be calculated at the property scale, rather than a wider landscape scale, because it is at that scale where management decisions are usually made and implemented (Sietz et al, 2022). Albeit, it can also provide information on the different plots or land covers that make up the property. This is key for evaluating trade-offs between conservation and production, and directing management strategies towards the most critical areas. Furthermore, its flexibility allows for potential comparability between different properties and across regions.

Index structure

Global index

The global index for the property, based on Blumetto et al. (2019), incorporates a set of scores that are weighted by each land cover area and land cover weight, as shown in Eq. (1). Both the global index and the scores range from zero, in the worst scenario for biodiversity, to one, where the indicators are equal or greater than the target value.

$$\mathbf{BRI} = \frac{\sum_{n=i}^{n} \left(\frac{\sum_{n=m}^{n} S_{mi}}{°m} \times LCW_i \times LCA_i \right)}{\sum_{n=i}^{n} \left(LCW_i \times LCA_i \right)} \qquad (1)$$

S_{mi} = score for indicator *m* in land cover *i*, calculated by $Indicator_{mi}$ / $Target_m$
°m = total number of indicators
LCA_i: area of land cover *i*
LCW_i: weight of land cover *i*

The Index considers different ecosystem components that are evaluated through a set of scores that are created with an indicator pondered by a target value. The scores are summed and divided by the total number of scores, which corrects the Index in the event that some indicator could not be measured. It also adjusts for both the surface area and the land cover type to create a final Index representative of the entire property.

Components

The ecosystem's structural, compositional and functional components were considered when developing the Index. We included the functional component by measuring taxonomic groups that contribute to pollination and soil quality (e.g., pollinator arthropods and ground-dwelling arthropods). The compositional aspect was included by measuring taxonomic groups whose composition is sensitive to changes both at large and local scale (birds, anurans, arthropods). Lastly, we incorporated the structural aspect by considering the different land covers and their coverage (all indicators were assessed in each land cover).

For each component multiple indicators are included. The selection of particular indicators depends on the location of the land under evaluation (biome, ecoregion) and the land managers' goals, but should always incorporate the components measured. The Index's application involves the qualitative evaluation of each land cover of the farm through field sampling with a protocol tailored for each component.

All components have equal weight and are added in a linear regression fashion. In cases where more than one sampling point, and therefore more than one value exists for a land cover, the median of the values for that land cover for abundance indicators are used, as this avoids extreme values from distorting the data's representation, while mean values are used for richness indicators.

Land cover weighting

The Index was built so that the scores are calculated for each land cover class. These minimal application units depend on each property, but should represent an area with relatively homogeneous vegetation cover and affected by similar management practices. Using homogeneous patches instead of administrative field parcels allows the combination of similar areas and simplifies fieldwork. Each land cover has its own weight in the Index, allowing for areas of greater value for biodiversity conservation like areas spared from production (linear elements, woody areas, grasslands, etc.) or wetlands to be highly valued.

Setting targets

In an index's calculation, the target is the goal value for each selected indicator. This could be either the value observed under pristine conditions, or one determined by the land owner according to their particular objectives. In the first case, it can be obtained from bibliographic references, databases specific to the area or a similar ecosystem, or based on the farm data. It is important to ensure that the sampling effort of this reference number is similar to the one used for the indicator's calculation, to allow for comparability. For example, if the number of arthropods in a pitfall trap is used as an indicator, the number of days the trap is active should be similar to the one in the reference value. For each score, the same target is used for all land covers. In cases where an indicator's value exceeds the target, the score is adjusted to one, which limits that metric's ability to compensate for shortcomings in other metrics.

Sampling design

The goal is to represent the biodiversity present across the entire property, which is why it is necessary to create a land cover map. Once the land covers present on the property are identified, a stratified sampling is carried out where sampling points are placed based on each cover's area. Productive covers with smaller areas will receive less sampling effort than those with larger areas, while natural covers will receive greater sampling effort due to their higher heterogeneity in structure and composition.

An implementation case in Argentina

To show a potential implementation of the BioRegen Index, we used Central Argentinian agroecosystems as a case study. In the following section, we describe its calculation including which indicators were chosen according to the ecoregion and how the sampling design was implemented.

Study area

The BioRegen Index's testing phase focused on eight farms with an array of management practices. These farms are located in central Argentina, in the Pampas phytogeographical province (Cabrera, 1971), one of them was located in the Flooding Pampa while the rest were located in the Rolling Pampa (Figure 1) (Matteucci, 2012). The original vegetation of this area was dominated by grasslands, with a predominance of Stipa sp., Briza sp., Bromus sp. and Poa sp. However, this is now highly modified due to agricultural intensification, with annual crops being the main land cover, interspersed with cattle ranching in less fertile areas (Baldi and Paruelo, 2008; Viglizzo et al., 2011). The climate is humid and temperate, with mean annual temperatures between 17°C and 19°C (mean min. annual temperatures of 10°C and mean max. annual temperatures of 23°C), and mean annual precipitation around 900 mm (SMN, 2020).

While the total size of the properties varied between 40 and more than 1000 hectares, a portion of the larger farms was selected for sampling. This determined that the final sizes were between 40 and 328 hectares. The main activity of the farms was the production of cereals and oilseeds, to which was added the raising of livestock in four of them. Some of the farms also had a portion dedicated to fruticulture (pecan trees) and horticulture production. In cases where a portion of the farm was selected, it was taken into account that the selected portion represented the diversity of productions of the entire property. Furthermore, three of the farms claimed to have conventional management (Farms 1, 2 and 3, Figure. 1), two were described as regenerative. (Farms 4 and 5), and three presented agroecological management and organic certification (Farms 6, 7 and 8). While three of the farms were located in an area with intense crop production (Farms 1, 4 and 5), one was located in an area of mixed production (livestock and agriculture), and the remaining four were located in an area with greater urban influence (Farms 3, 6, 7 and 8).

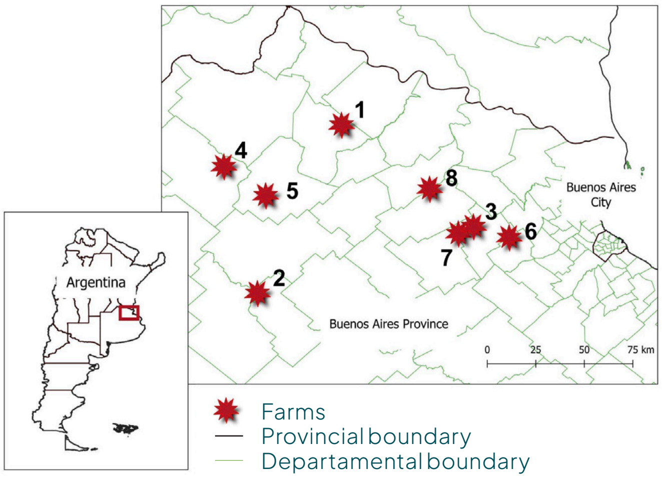

Figure 1: *Study area (Buenos Aires, Argentina)*

Sampling design

As the project's goal is to quantify the impact of the farm management as a whole, a stratified random sampling design was used to capture all possible sources of biodiversity variation. For this, a Land Use/Land Cover (LULC) map was generated from a partly-supervised classification of sentinel images from the year 2023, and later corrected with previous knowledge of each farm and input of the land managers. These corrections included the reclassification of plots with annual and fruit crops, and fallow, and the elimination of patches of less than 0.1 hectares.

All detected LULC classes were categorized in two types: Productive, including all plots that involved the production of a good, and non-productive, these being all patches with natural or semi-natural vegetation that did not have a direct productive purpose. Furthermore, LULC classes of productive plots were classified in rangelands, annual crops, and perennial crops (Table 1).

LULC class	LULC category	Type
Closed forest Open forest Peridomestic Windbreak Herbaceous Water bodies	Natural or semi-natural vegetation	Non-productive
Pasture Grassland Lowland	Rangelands	Productive
Corn Early soy Late soy Bean Fallow	Annual crops	
Pecan Festuca crop	Perennial crops	

Table 1: *LULC classes, LULC categories and types identified in the sampled farms*

BioRegen Index components

To quantify the components included in the BioRegen Index, fieldwork was carried out in March 2024. The sampled taxonomic groups and the protocol used for each are described below:

a. Birds

Birds play multifaceted roles as ecosystem health indicators, for instance, contributors to pest control and pollinators of plants (Whelan et al. 2008, Sekercioglu 2017, Mekonen 2017). By tracking the presence of rare, imperiled, and habitat specialists species we can assess the impacts of regenerative practices on habitat restoration and overall biodiversity status (Michels 2022).

The bird sampling was carried out in all LULC categories by an ornithologist and a secondary observer who recorded all species seen or heard for five minutes at each sampling point (Figure 2). This was done during the first three hours after sunrise, and the last three hours before sunset.

Figure 2: Auditory and visual sampling of birds

b. Ground-dwelling arthropods

Ground-dwelling arthropods mainly comprise beetles (Coleoptera, Carabidae), rove beetles (Coleoptera, Staphylinidae) and spiders (Araneae) (Montgomery et al. 2021, Lami et al. 2023). Monitoring ground-dwelling arthropods in regenerative systems holds significant importance as these small organisms play a pivotal role in the ecosystem's health and functioning. As key components of soil biodiversity, they contribute to nutrient cycling, pest control, and soil structure improvement. Regularly measuring arthropod populations allows us to assess the overall ecological balance, gauge the impact of regenerative practices on their abundance and diversity, and make informed management decisions (de Pedro et al. 2020, Oettel and Lapin 2021, Triquet et al. 2022, Chowdhury et al. 2023).

The ground-dwelling arthropods sampling was carried out in productive LULC categories as metrics derived from this biological group are heavily related to management practices in agricultural settings (de Pedro 2020, Lami et al. 2023). Each sampling point comprised a pitfall trap (Montgomery et al. 2021) formed by a 250 ml transparent plastic container placed in the soil with its opening level with the soil surface (de Pedro 2020, Montgomery et al. 2021, Hohbein et al. 2018) and covered by a 15-centimeter diameter plastic green cover, placed five centimeters above the top of the pitfall trap (Figure 3). The plastic container was 90% filled with a 70% alcohol mixture and 10% filled with propylene glycol, enabling sample conservation for later laboratory analysis. The plastic cover prevented rain from filling the traps, leaf litter, and other organic material from falling into the traps, and slow evaporation of the preservative (Hohbein et al. 2018).

The traps were active between approximately 36 and 48 hours (Mcnamara Manning et al. 2021), after which each container was closed, removed, and stored until it was sent for taxonomic identification. This taxonomic identification was done down to the family level by an experienced entomologist.

Figure 3: Pitfall traps for ground-dwelling arthropods sampling

c. Pollinator arthropods

Pollinator arthropods, such as bees, butterflies, and other insects, play a vital role in plant reproduction and fruit and seed production. By tracking their populations and diversity, we can assess the effectiveness of regenerative practices in providing suitable habitats and resources for these essential pollinators (Aguilera 2020, Drunen et al. 2022, Chowdhury et al. 2023).

The pollinator arthropods sampling was carried out in all LULC except for very closed forest and corn fields as pan traps are not suited for environments where the traps are not visible from a distance (Montgomery et al. 2021). Each sampling point consisted of a pan-trap formed by three bowls of a white, blue, and yellow color. It was 90% filled with a 70% alcohol mixture and 10% filled with propylene glycol, and held by a wooden stick one meter above the ground (Morandin et al. 2013, McCravy 2018, Montgomery et al. 2021) (Figure 4).

The traps were active between approximately 36 and 48 hours (Mcnamara Manning et al. 2021), after which the three bowls' contents were placed in a 500-meter plastic container and stored until it was sent for taxonomic identification. This taxonomic identification was done down to the family level by the laboratory of the National University of Luján's Zoology Department.

Figure 4: Pan traps for pollinator arthropods sampling

d. Vegetation

Naturally growing vegetation plays a fundamental role in long-term sustainability and productivity. Vegetation, both structurally and functionally, serves as a key ecosystem health indicator, reflecting soil quality, biodiversity, and resilience to disturbances. By consistently tracking vegetation, it becomes possible to assess the impact of implemented regenerative practices and make necessary adjustments (Oettel and Lapin 2021).

The vegetation sampling was carried out in all LULC categories by a botanist and a field assistant. At each sampling point, vegetation structure and composition were measured in three one-by-one meter quadrats, divided in four sections by two nylon threads placed at the 50-centimeter mark, that were placed randomly near a pitfall trap (Figure 5). The division of the quadrat in four sections was done to facilitate the visual estimation of coverage for each species. In each quadrat the following measurements were registered:

- Species present and approximate coverage percentage of each
- Bare soil approximate coverage percentage
- Mulch approximate coverage percentage
- Dominant species height in each stratum present (arboreal, shrubby, subshrub, and herbaceous), considering the median value of three consecutive measurements
- Litter depth, considering the median value of three consecutive measurements

To add the data from the three quadrats, the mean was used for litter depth, and all coverage measures. For richness measurements, the total value of the three quadrats was used.

Figure 5: 1x1 meter quadrats, divided in four sections, for vegetation sampling

e. Anurans

Monitoring anurans in productive areas within the context of regenerative management practices serve as sensitive ecosystem health indicators due to their reliance on both aquatic and terrestrial habitats. By tracking their populations and diversity, we can assess the effectiveness of regenerative practices in providing suitable habitats and minimizing environmental disturbances (Agostini et al. 2021). Monitoring anurans helps us gauge the success of conservation efforts, ensure water quality, and maintain a balanced ecosystem, contributing to the overall resilience and sustainability of regenerative agricultural systems.

The anurans sampling was carried out by a herpetologist plus a secondary observer, with one or two different methods depending on the type of land cover class, which will allow a comprehensive assessment of the anuran community:

- **Auditory sampling:** The herpetologist plus the secondary observer registered all species and approximate number seen and/or heard during a 15-minute period (Pierce & Gutzwiller 2004).
- **Visual plot sampling:** The herpetologist plus the secondary observer carried out an exhaustive search of anurans for 15 minutes on an eight by eight meters plot, covering the entire plot and recording the number of individuals and the species.

The samplings were conducted from sunset to midnight, approximately between 19 hours and 01 hours (Vonesh et al. 2023). The visual plot sampling was conducted in all LULC categories except for annual crops and some LULC plots where it was determined that did not provide an appropriate habitat for anurans. Complementary anuran sampling points were placed in water bodies and sampled with a visual plot sampling and an auditory sampling.

Biodiversity monitoring stations

In order to facilitate the fieldwork and improve resource use, all the field measurements were clustered in biodiversity monitoring stations (BMS) that had a predefined spatial layout (Figure 6). Every BMS had one sampling point for birds and anurans, three quadrats that constitute a vegetation sampling point, and up to three independent sampling points for pollinator and ground-dwelling arthropods. In the later cases a separation of 30 meters between traps guaranteed their independence (Montgomery et al. 2021, Hohbein et al. 2018). BMS were separated a minimum of 500 meters in order to make the bird (Siriwardena et al. 2006, Boscolo & Metzger 2009, Rechetelo et al. 2016) and anuran (Suárez et al. 2016, Semlitsch & Bodie 2003) samplings independent.

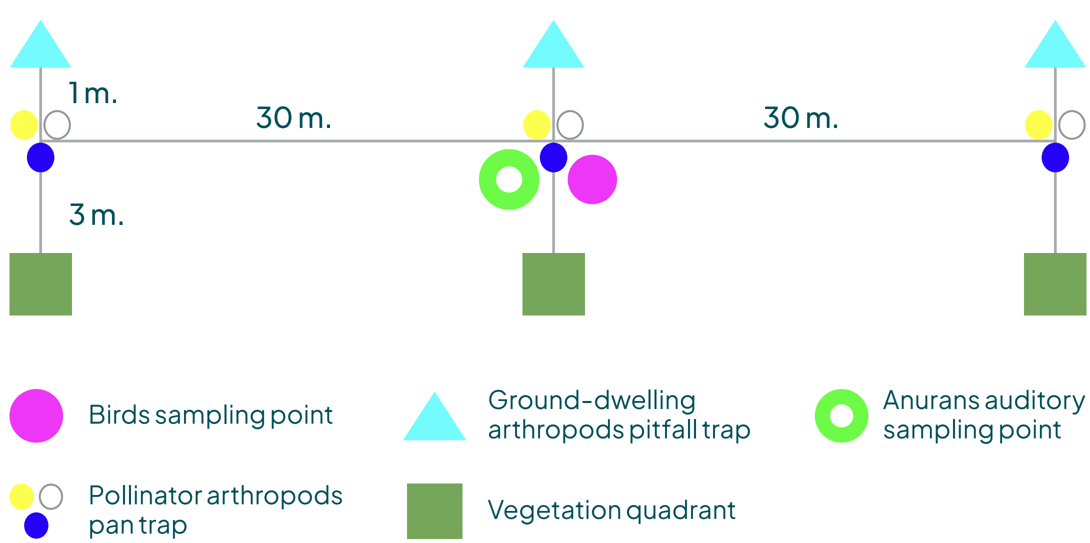

Figure 6: Biodiversity monitoring station design

A BMS was placed every 30 hectares of a LULC class, which was achieved by establishing the cut-off point every 45 hectares. This meant a sampling effort of 10% for birds (considering a sampling radius of 100 meters) and of ~2% for ground-dwelling and pollinator arthropods.

The criteria for the BMS placement depended on the LULC type: For productive types, the number of BMS was calculated over the total area of that class, while for non-productive types, the number of sampling points was calculated over the size of each patch. This guaranteed that all non-productive patches, that are usually more heterogeneous, were sampled. The number of BMS had a saturation point at five stations, that is, classes of more than 150 hectares had five stations. For non-productive types, a BMS was placed in every patch of the same LULC class up to three patches, over which only one every two patches were sampled. Complementary, exclusive anuran sampling points were added in water bodies, where a visual plot sampling and an auditory sampling was conducted. Table 2 summarizes the components measured in each LULC category and the BMS location criteria.

Type	LULC class	Components					BMS quantity calculation
		Birds	Ground-dwelling arthropods	Pollinator arthropods	Vegetation	Anurans	
Non-productive	Closed forest	x			x	x	A BMS every 30 ha of a patch
	Open forest	x		x	x	x	
	Peridomestic	x		x	x	x	
	Windbreak	x		x	x	x	
	Herbaceous	x		x	x	x	
	Water bodies					x	
Productive	Pasture	x	x	x	x	x	A BMS every 30 ha of a class
	Grassland	x	x	x	x	x	
	Lowland	x	x	x	x	x	
	Corn	x	x		x		
	Early soy	x	x	x	x		
	Late soy	x	x	x	x		
	Bean	x	x	x	x		
	Fallow	x	x	x	x		
	Pecan	x	x	x	x	x	
	Festuca crop	x	x	x	x		

Table 2: Groups sampled in each LULC classes

Development of indicators

A variety of indicators can be used to describe and quantify the characteristics of ecological communities, which provide insights into their composition, structure, and function. The first step in selecting the indicators to be included in the Index was the development of possible metrics to explore, for which an exhaustive bibliographic search was carried out and experts in the area in each biological group were consulted. Through this process, nine possible indicators of birds, 30 of pollinating arthropods, 19 of ground-dwelling arthropods, 26 of vegetation, and 1 of anurans were generated. These indicators were based on richness, abundance, and diversity (measured through the Shannon Diversity Index), which are commonly used metrics to describe ecological communities. For vegetation, abundance was estimated through coverage.

During the sampling period, a population explosion of Astylus atromaculatus occurred which is not necessarily related to farm management but responds to regional processes. To prevent this overgrowth from distorting abundances in the pollinator arthropods indicators, the Melyridae family was excluded from the calculation of those indicators.

The values of each indicator were explored through boxplot graphs, which allowed an initial selection of the ones that showed variation between conventional and regenerative establishments. The final selection of indicators was done by analyzing significant differences between managements with Kruskal-Wallis test followed by Dunn's test (Potvin & Roff 1993), because most of the indicators didn`t follow a normal distribution. Finally, correlation between significant indicators was explored. Whenever two significant indicators were highly correlated (Pearson correlation coefficient >70), the indicator with the greatest ease of calculation was selected. Through this process, the objective was not to select indicators that showed better results in regenerative fields, but rather those that were sensitive to the type of management (conventional or regenerative).

To further simplify the Index's calculation, the previously mentioned analyses were performed for each LULC category. This allowed us to identify the categories where the indicators actually showed differences in management.

Selecting targets

To establish the targets for each indicator, the entire dataset collected during sampling were used. The highest value found at an independent sampling point was set as the target for the richness scores, and the value corresponding to the 90th percentile was used for the abundance scores. The latter was done in order to prevent abnormally high values distorting the scores.

Selecting weights

Natural and semi-natural habitats interspersed in the agricultural matrix have a determining effect on sustaining biodiversity in agroecosystems (Fahrig et al. 2011, Benton et al. 2003). Research shows that in the Pampas region these can help maintain bird populations, mammals, and anurans (Codesido & Bilenca, 2011, Weyland et al. 2014, Suárez et al. 2016, Bilenca et al. 2007) and boost ecosystem services like weeds and pest control (Garibaldi et al. 2023, Gonzalez et al. 2020). For this reason, higher weight was given to non-productive areas over productive ones.

Results

BioRegen Index in Argentina

During the fieldwork 166 pitfall traps and 189 pan traps were deployed, and 62 bird points, 33 anuran points, and 40 vegetation points were sampled. It involved 15 people in the field at different times (up to six at a time, adding professionals and two assistants) during 25 days, and 1257 hectares were sampled. It took three days to complete the surveys on the larger farms, and two for the smaller ones.

Various unforeseen events prevented us from obtaining vegetation data from Farms 3, 6, 7 and 8, ground-dwelling arthropods and pollinator arthropods data from Farm 7 and anurans and birds data from Farm 2. In this last case, data from a similar sampling carried out in February 2023 was used. In some cases where traps were vandalized by wildlife or a sampling point could not be accessed, the portion of the property represented by the Index was adjusted.

Indicators, targets, and weights

Ten four-component indicators that showed significant differences between management types were selected to be part of the final Index. Figure 7 shows boxplots for the data's distribution for each indicator in conventional and regenerative farms, and p-values of that difference. Table 3 summarizes the final selection of components and indicators, the target values and the LULC category selected to measure each.

As weights, a value of two was used for the non-productive category while one was used for the productive ones.

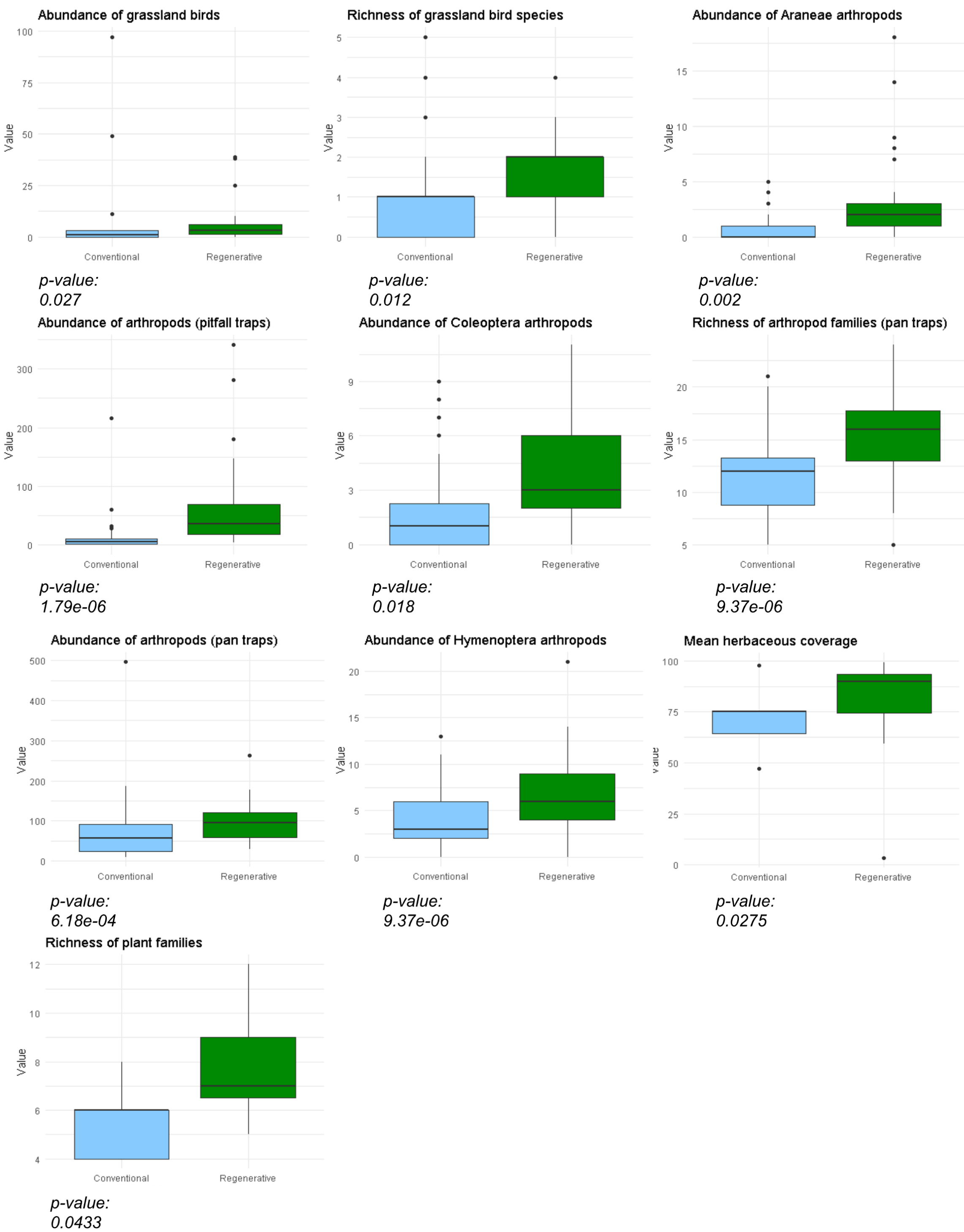

Figure 7: Differences for each selected indicator in regenerative (green) and conventional (blue) management

Component	Indicator	LULC category	Target
Birds	Abundance of grassland birds *(nGrasslandBirds)*	All	10.5
	Richness of grassland birds species *(nSpeciesGrasslandBirds)*	All	5
Ground-dwelling arthropods	Abundance of Araneae arthropods *(nAraneaePitfallTrap)*	Annual crops	3
	Abundance of Coleoptera arthropods *(nColeopteraPitfallTrap)*	Annual crops	6.5
	Abundance of arthropods *(nArthrPitfallTrap)*	Annual crops	70.5
Pollinator arthropods	Abundance of arthropods *(nArthrPanTrap)*	Annual crops, perennial crops	123
	Richness of arthropod families *(nFamiliesArthrPanTrap)*	Annual crops, perennial crops, rangelands	25
	Abundance of Hymenoptera arthropods (excluding the Formicidae family) *(nArthrHymenoptera)*	Annual crops, perennial crops	9
Vegetation	Mean herbaceous coverage *(meanHerbStratumCoverage)*	Natural or semi-natural vegetation,perennial crops, rangelands	100
	Richness of plant families *(nFamiliesVeg)*	Natural or semi-natural vegetation, perennial crops, rangelands	12

***Table 3:** Final indicators and the LULC categories where they were included, target values used*

BioRegen Index in Argentinian farms

Scores for components and the final BioRegen Index for the eight farms are presented in Table 4 and Figure 8. In the studied farms the BioRegen Index ranged from low to intermediate, varying from 0.065 to 0.565. The higher values corresponded to the two regenerative farms (Farm 4 and 5), while conventional and agroecological farms showed varied results.

The LULC category scores showed a wide range of values, ranging from 0 to 0.69. In general, the highest values were seen in rangelands (0.429 to 0.691), while natural or semi-natural vegetation showed the lowest values (0 to 0.477). Regenerative farms had less variable scores between their different LULC categories than conventional fields.

Figure 9 illustrates the LULC category scores for the four farms where all components could be measured. While the BioRegen Index provides a general value for the entire property, the analysis of each LULC category allows us to understand the improvement potential for each farm area. For example, conventional farms (Farms 1 and 2) should improve their annual crop management, while all farms would benefit from creating or restoring natural vegetation areas.

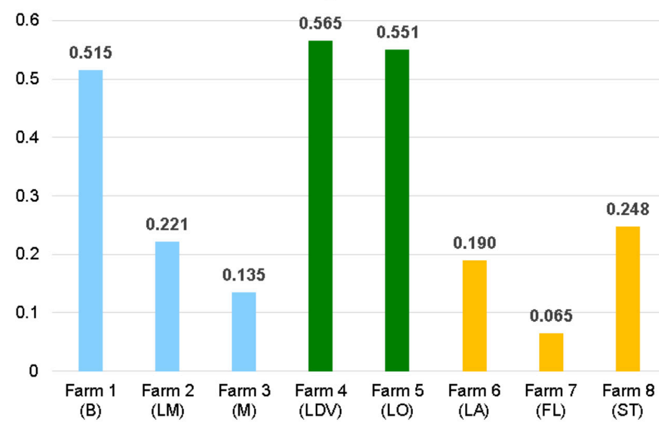

Figure 8: BioRegen Index for conventional (blue), regenerative (green) and agroecological (yellow) farms in the Pampean region, Argentina

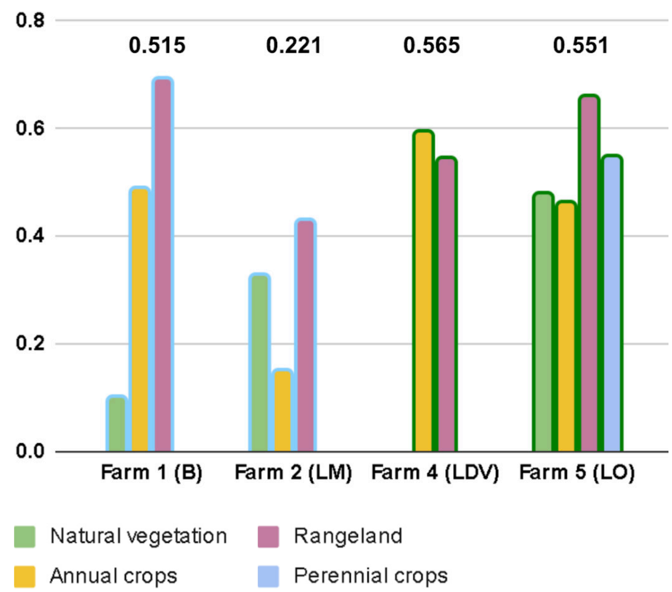

Figure 9: BioRegen Index and LULC category score for conventional (blue outline) and regenerative (green outline) farms in the Pampean region, Argentina

Management type	Farm	LULC category	Area (ha)	Weight	meanHerbStratumCoverage	nFamiliesVeg	nSpeciesGrasslandBirds	nGrasslandBirds	nFamiliesArthrPanTrap	nArthrPanTrap	nArthrHymenoptera	nAraneaePitfallTrap	nColeopterPitfallTrap	nArthrPitfallTrap	LULC category value	Max value	LULC category score	BioRegen Index
				Target values	100	12	5	10.5	25	123	9	3	6.5	70.5				
					Score (indicator/target)													
Conventional	Farm 1 (B)	Natural or semi-natural vegetation	4.4	2	0.020 (2)	0.375 (2)	0.000 (2)	0.000 (2)							0.867	8.778	0.099	0.515
		Annual crop	194.3	1			0.160 (5)	0.095 (5)	0.549 (15)	0.607 (15)	0.667 (15)	1.000 (15)	0.462 (15)	0.369 (15)	94.804	194.310	0.488	
		Rangeland	50.3	1	0.643 (3)	0.500 (3)	0.800 (2)	1.000 (2)	0.511 (15)						34.748	50.300	0.691	
	Farm 2 (LM)	Natural or semi-natural vegetation	7.4	2	0.602 (2)	0.708 (2)	0.000 (2)	0.000 (2)							4.846	14.800	0.327	0.221
		Annual crop	202.9	1			0.200** (1)	0.095** (1)	0.350 (8)	0.126 (8)	0.111 (8)	0.000 (10)	0.231 (10)	0.085 (10)	30.390	202.900	0.150	
		Rangeland	62.3	1	0.753 (2)	0.417 (2)	0.300 (4)	0.143 (4)	0.533 (6)						26.744	62.300	0.429	
	Farm 3 (M)	Annual crop	44.0	2			0.000 (1)	0.000 (1)	0.360 (3)	0.203 (3)	0.222 (3)	0.333 (3)	0.000 (3)	0.227 (3)	7.393	43.950	0.168	0.135
		Natural or semi-natural vegetation	11.7	1	*	*	0.100 (2)	0.048 (2)							1.722	23.326	0.074	
Regenerative	Farm 4 (LDV)	Annual crop	187.3	1			0.200 (2)	0.190 (2)	0.592 (15)	0.821 (15)	0.778 (15)	0.667 (18)	0.615 (18)	0.730 (18)	107.556	187.300	0.574	0.565
		Rangeland	79.2	1	0.794 (4)	0.521 (4)	0.440 (5)	0.381 (5)	0.587 (15)						43.137	79.200	0.545	
	Farm 5 (LO)	Natural or semi-natural vegetation	12.9	2	0.899 (2)	0.375 (2)	0.300 (2)	0.333 (2)							12.333	25.864	0.477	0.551
		Annual crop	68.9	1			0.300 (2)	0.238 (2)	0.647 (6)	1.000 (6)	0.833 (6)	0.333 (5)	0.154 (5)	0.170 (5)	31.660	68.911	0.459	
		Rangeland	80.9	1	0.873 (4)	0.8125 (4)	0.480 (4)	0.381 (4)	0.740 (12)						53.206	80.940	0.657	
		Perennial crop	104.3	1	0.898 (3)	0.611 (3)	0.333 (3)	0.381 (3)	0.515 (9)						57.157	104.328	0.548	
Agroecological	Farm 6 (LA)	Annual crop	41.5	1			0.200 (3)	0.190 (3)	0.360 (9)	0.130 (9)	0.222 (9)	0.333 (9)	0.000 (9)	0.057 (9)	7.744	41.500	0.187	0.190
		Perennial crop	1.6	1			0.400 (1)	0.381 (1)	0.360 (3)	0.081 (3)	0.111 (3)				0.424	1.590	0.267	
	Farm 7 (FL)	Annual crop	24.6	1			0.200 (1)	0.095 (1)	*	*	*	*	*	*	3.636	24.630	0.148	0.065
		Natural or semi-natural vegetation	15.5	2	*	*	0.000 (3)	0.000 (3)							0.000	31.000	0.000	
	Farm 8 (ST)	Annual crop	34.1	1			0.300 (2)	0.238 (2)	0.340 (6)	0.171 (6)	0.222 (6)	0.333 (6)	0.538 (6)	0.085 (6)	9.483	34.050	0.278	0.248
		Natural or semi-natural vegetation	9.9	2	*	*	0.200 (1)	0.190 (1)							3.846	19.700	0.195	

*Table 4: Individual components and final BioRegen Index for eight farms in the Pampean region, Argentina. The number of sampling points is shown in brackets under each score. * Indicates lack of data for that indicator. **Data from 2023 sampling.*

Discussion

Applicability of the Index

To support landowners' capacity to track how their management practices influence biodiversity, we developed the BioRegen Index and illustrated its application to evaluate the outcome of management practices. We demonstrate how the BioRegen Index can be implemented following a documented field protocol and how it provides useful information about the farm's management as a whole, as well as providing spatially-explicit insights into the different land uses within the farm. The Index serves to assess the farm's current state, and its different land covers based on past management practices, but more importantly, to measure changes over time and evaluate the success of the practices implemented for biodiversity conservation within the framework of an adaptive management process.

This multi-metric assessment tool can be applied worldwide to multiple farming systems due to its flexibility and goal-oriented structure. Metrics more appropriate to different ecoregions can be incorporated, as well as specific metrics to capture changes in the structural, compositional, and functional components of biodiversity due to management practices. The BioRegen Index also represents an improvement in relation to other outcome-based indices that require the development of specific scores for each component in a region (Tasser et al. 2019, Blumetto et al. 2019).

Furthermore, the ability to set variable target values allows the Index to guide individual objectives, or to evaluate the progress towards goals set for different farms within a watershed or ecoregion.

BioRegen Index in Argentina

The BioRegen Index tested in farms in central Argentina representing a gradient from traditional farming to farms including biodiversity-friendly practices was able to differentiate the management systems. By following the field protocols included in the BioRegen Index toolbox, we were able to sample five biological groups on up to 320 hectares in three days. At the farm scale, the Index ranged from low to intermediate values, where higher values corresponded to the regenerative farms while lower ones corresponded to farms with conventional practices. At the land cover scale, the BioRegen Index varied among land covers, which helps identify parts of the farm that need more improvement (e.g., annual crops in conventional farms). The BioRegen Index, is also useful in monitoring the different taxonomic groups measured and identifying opportunities for improvement (e.g. ground-dwelling arthropods in Farms 2 and 3).

Even though selected indicators showed differences among management practices, other indicators that are commonly used to evaluate management practices, like vegetation structure or bare soil (Blumetto et al. 2019, Herzog et al. 2012), and that we had expected to reflect differences in management, did not. This may be attributed to an insufficient sampling effort. This limitation was particularly evident in vegetation and anurans. We observed high variability in vegetation metrics among quadrats within the same BMS, suggesting significant spatial heterogeneity. Given that identification to the family level, rather than species level, is sufficient to calculate the final indicators, increasing the number of quadrats or sampling points could improve representation without extending the total sampling time.

Interestingly, a low diversity of anuran species was recorded. As accurately representing this group requires a substantially high sampling effort, it was decided not to include this group in the final Index. Additionally, anuran species composition is highly dependent on the presence of water within the farm, which does not necessarily depend on the management, moving away from the Index's purpose of reflecting the outcome of management practices.

Nevertheless, in ecoregions dominated by wetland vegetation, anurans could be a key component for assessing practices that affect water conditions or the riparian zone (Suárez et al. 2016).

Optimization in the selection of indicators to incorporate in the Index lowered the burden on specialists in the field and the overall monetary costs. Such optimization involved the selection of indicators that do not imply a high degree of knowledge for sampling and analysis. Examples of this are choosing appropriate sampling techniques that do not require identification on the field, such as placing traps, or exploring abundance instead of richness indicators, which avoids the need for taxonomic identification.

What is next?

Landscape metrics

In this BioRegen Index version, complex landscape metrics, such as the connectivity of natural areas or the riparian buffer strip width were not included. Instead, we focused solely on the surface area of the four land-use types. To enhance the indicator's ability to capture landscape structure's influence on biodiversity, it would be valuable to identify and incorporate relevant landscape indicators for agroecosystem regeneration into the BioRegen Index. Including such metrics would allow improvements in land cover composition and configuration—such as increased heterogeneity and connectivity—to be reflected in the Index, providing a more comprehensive assessment of biodiversity-friendly management practices.

Targets

In the BioRegen Index, targets enable the use of the Index to track individual progress or assess the performance of different farms within a given region. However, if local targets were developed and standardized across regions, the Index could also be used for interregional comparisons. The importance of establishing region-specific targets for comparison becomes evident when analyzing the BioRegen Index of Farm 2 (LM, 0.221), which exhibited a particularly low Index. This result may be attributed to the fact that the targets used corresponded to values from the Rolling Pampa, and were not suitable for the specific characteristics of the Flooding Pampa, where Farm 2 was located.

Furthermore, if the difficulty of establishing targets were to hinder the Index's use, the development of indicators should consider the search for those that have pre-established target values. For example, using the Simpson's Index, that ranges from zero to one, the target naturally becomes the maximum value that this Index can take (Quinn et al., 2013). This approach would enhance the Index's applicability by reducing reliance on region-specific targets while maintaining its effectiveness in evaluating ecosystem conditions

Scalability

Technological initiatives for biodiversity monitoring are rapidly expanding. The convergence of AI, bioacoustics, image recognition, eDNA analysis, and drone-based monitoring, along with the increasing role of citizen science, is transforming how species and ecosystems are studied. These innovations enable scalable, cost-effective, and high-resolution monitoring of species distributions and habitat dynamics.

Further optimization in the fieldwork involves incorporating some of these techniques, which will allow the fieldwork and processing to be executed by laypeople, driving the fast adoption of the BioRegen Index as a tool to evaluate regenerative farm management. However, as Reynolds et al. (2025) highlights, while AI adoption in conservation holds great promise for improving effectiveness, it is not a cure-all and should not replace traditional methods, field-based research, and education. Careful planning is essential to ensure equitable access to these technologies and their responsible development and deployment.

To explore the potential of this, we conducted a pilot comparative analysis using acoustic sensors to identify bird species through audio recordings. The results of the point count survey carried out in a regenerative farm was compared with an expert's analysis of recorded bird songs from the same location. We used Wildlife Acoustics Song Meter Micro 2 sensors (www.wildlifeacoustics.com) to record the audio samples. When comparing the five-minute field survey with analysis of a five-minute audio recording, both methods detected approximately the same number of species (around 11). However, the use of sensors allows increased sampling effort at a much lower cost. By extending the expert's analysis from five to 20 minutes of audio, we were able to identify a total of 19 species. This highlights the immense potential of remotely sensing biodiversity and post-hoc bird song identification, especially when combined with artificial intelligence for automated species recognition. While AI-driven bird identification is already well-developed, anuran species detection remains less explored. It is only a matter of time before both groups can be fully surveyed using sensors. As these technologies continue to evolve and integrate, biodiversity monitoring is becoming more precise, automated, and globally accessible, opening new possibilities for conservation efforts.

Conclusions

The BioRegen Index is the first iteration of an outcome-based, multi-metric land assessment tool targeted to assess the impacts of biodiversity-friendly management practices. Its implementation provided useful insights regarding potential drawbacks but also showcased the usefulness of such a tool and its sensitivity to different management practices. We encourage land managers to test the Index and its whole set of tools to help us improve the current status.

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