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RESEARCH ARTICLE

The Distance to Reference Communities Index (DRCI): a new tool to assess communities' restoration success

Fontès Hugo^{1,2,3} , Marquis Christian¹, Torre Franck² , Patrick Grillas¹ , Thierry Dutoit² ,
François Mesléard^{1,2} 

The concept of a reference ecosystem is fundamental in restoration ecology, especially in assessing the success of ecological restoration projects. In response to criticism, it has undergone conceptual evolutions in its definition and use in the last decades. Even though there is still a need to develop statistical methods and analyses to account for reference variability. Here, we focus on two original and one literature-based calculation methods for designed indexes, which all aim to compare a community to be assessed (undergoing restoration) with a variable set of reference communities. These methods either use the average reference situation (species composition and abundance) as the restoration target or on the contrary, allow any reference site to be considered a relevant target. We compare the results of these methods by analyzing a simulated dataset. We then illustrate the application of the most relevant index by a real case study that compared a created Mediterranean temporary pond to a panel of 27 reference ponds located in the south of France. The results show that the Distance to Reference Communities Index (DRCI) correctly measures differences in species composition and abundance between an assessed and a reference panel of communities. It takes into account the variability of the reference communities, while the use of other indexes focuses on unrealistic average and fixed reference values. DRCI is complementary to a detailed ecological interpretation and to the use of other commonly used indexes, by giving a synthetic metric.

Key words: communities, ecosystem variability, Mediterranean temporary ponds, reference ecosystem, restoration assessment

Implications for Practice

- Stakeholders should consider the spatio-temporal variability of reference communities when defining a reference model.
- Distance to Reference Communities Index is a helpful tool to evaluate restored sites in relation to multiple reference sites. It can compare the communities of many sites against the same reference sites and track their progress. It considers that all positive references are considered equally valid.
- Using a dynamic reference (reevaluating the reference sites year by year or predicting future reference models) can lead to a continual decline in conservation and restoration goals. Stakeholders should consider this risk so as not to overestimate the success of restoration, e.g. by exploring historical data.

Introduction

Evaluating the success of ecological restoration requires beforehand a clear definition of its goals and objectives, as well as relevant medium- and long-term success indicators (Prach et al. 2019). To do so, the reference state is a key concept (Balaguer et al. 2014; Gann et al. 2019). It was originally defined as the state of an ecosystem prior to its degradation and the objective of ecological restoration action “sensu stricto” (Aronson et al. 1995). This is commonly referred to as a

historical reference. Nevertheless, since the 1990s, some authors have charged this reference concept as a fixist vision of ecosystems (Pickett & Parker 1994; White & Walker 1997). The historical reference has also been criticized due to the lack of knowledge about these past ecosystems (Guerrero-Gatica et al. 2019; Rodrigues et al. 2019), to the difficulty of distinguishing between natural and human influence on ecosystems over time (Millar & Brubaker 2006; Bennion et al. 2010), and the impossibility of returning to a previous stage in the context of global change, for socio-economical or practical reasons (Hobbs et al. 2009; Jackson & Hobbs 2009). Nowadays, the

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necessity to consider the spatio-temporal variability of ecosystems to define references achieves consensus, and its methodological importance is widely shared (Ruiz-Jaen & Aide 2005; Balaguer et al. 2014; Gann et al. 2019; Shackelford et al. 2021; Oliver et al. 2022). Although the concept of reference has evolved since the 1990s, examples of assessment using multiple reference sites with a broad consideration of spatio-temporal variability are largely ignored. Reference data are rarely recorded for longer than 2 years or over more than two sites; when they exist, multiple reference conditions are usually expressed by an average and not by a range of variable states (Shackelford et al. 2021; Oliver et al. 2022).

While vegetation richness and abundance are among the most commonly used indexes to assess restoration success (Ruiz-Jaen & Aide 2005; Benayas et al. 2009; Wortley et al. 2013), species composition is a key criterion (Gann et al. 2019). With this in mind, similarity/dissimilarity indexes and multivariate analysis as ordination are commonly used tools to assess restoration success (Urban 2006). Indeed, ordination analyses including multiple reference situations are possible ways to take into account the variability of a reference ecosystem. Hiers et al. (2012) propose the “dynamic reference concept,” which consists of comparing each site to be assessed with the barycenter of reference sites on an ordination (three first axes of an ordination) while reevaluating the reference panel and the sites to be assessed over time. Jaunatre et al. (2013) proposed synthetic indexes to assess community integrity by taking into account community composition and species abundance, using also a theoretical average reference situation as the restoration objective. Fengler et al. (2017) used numerical hierarchical classifications to assess the restoration success, allowing to attach or not a community to be assessed to a cluster of reference communities. Insofar as these classification methods can be automated by mobilizing large datasets (Oliver et al. 2013), this approach seems potentially promising for assessing restoration success. However, classification approaches give a binary answer as to whether or not a survey to be assessed belongs to a reference panel, and we have not identified any authors in the literature who propose a continuous metric based on clustering and enabling a restoration trajectory to be assessed in relation to a reference panel. Oliver et al. (2022) propose to use an “acceptable range of variation” to evaluate the success of the restoration, which allows us to take into account the variability of reference sites. However, the use of a range, in this case, is limited to a quantitative variable and does not measure the change in community composition.

There is no single best way to assess restoration success, as evidenced by the wide variety of analyses already available. However, methods taking into account the variability of reference communities are still underdeveloped, especially methods non-focusing on the average community. We therefore propose:

- (1) To compare the performance of three indexes designed to assess the restoration of communities against a variable reference panel: (1) an index derived from bibliography based on an average reference community, (2) an original index

based on the most similar reference community, and (3) an original index using both the most similar and the average reference community. For this purpose, we take a theoretical approach using a simulated dataset.

- (2) To illustrate the use of the more relevant index selected. For this purpose, we analyze a real community dataset from a Mediterranean temporary pond restoration project (southern France).

Methods

Statistical Formulation of Indexes

The three proposed indexes correspond respectively to three calculation methods for comparing a community or a site to be assessed (assessed point) with a reference panel, made up of several reference communities or sites (reference points). These methods use similarity/dissimilarity measures or ecological distances between communities.

Method Based on the Closest Reference Community: Distance to Reference Communities Index. Here, each reference point is considered a relevant objective (Fig. 1). So, to evaluate restoration success, we measured the distance between an assessed point and its closest reference point (as a single linkage distance). This distance thus takes into account the variability of the cloud of reference points, which is not represented by its barycenter location. We normalized the index by the internal variability of the reference panel, that is by the pairwise average distance between all the reference points. The Distance to Reference Communities Index (DRCI) is thus defined as the measurement of the distance between the point to be assessed and the closest reference point, divided by the mean distance between the reference points.

For A , a point to be assessed and R , a set of n reference points,

$$\text{DRCI}(A, R) = \frac{\text{Distance from } A \text{ to the closest reference point}}{\text{Pairwise average distance within the reference set}}$$

DRCI ranges from 0 (A is confounded with any of the reference points) to infinity.

Method Based on the Average (or Barycenter) Reference Community: Distance to Reference Barycenter Index. Using an average reference situation as the restoration target is a common way of assessing restoration success. In this case, the average or barycenter (ordination) of the reference communities is the sole restoration objective. Following Hiers et al. 2012, we therefore measure the distance between a point to be evaluated and the average or barycenter reference point (Fig. 1). We chose to normalize this distance by the average distance of the reference points from their barycenter, which allows us to take into account the average dispersion of the reference points around their barycenter. The Distance to Reference Barycenter Index (DRBI) is thus defined as the measurement of the distance between the point to be assessed and the reference barycenter,

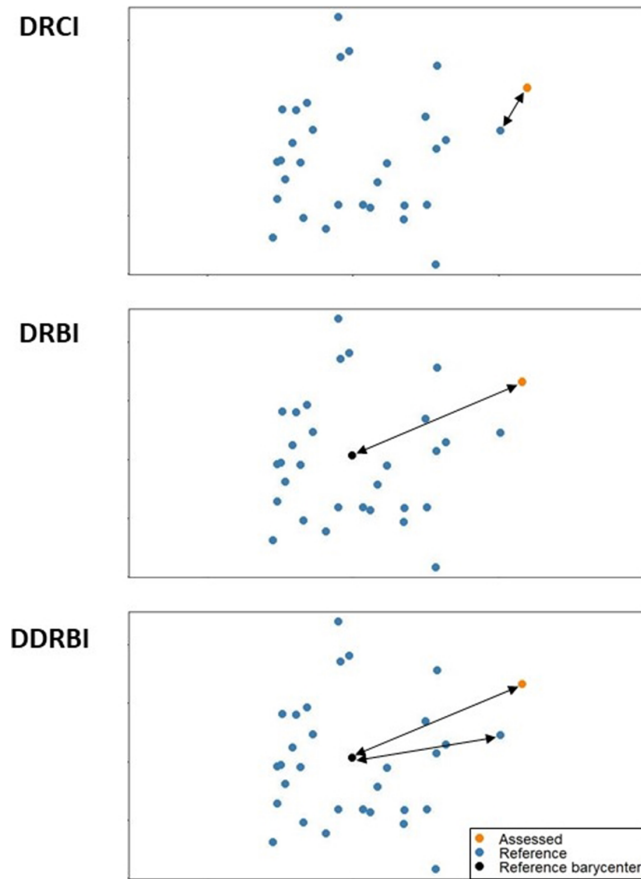


Figure 1. Two-dimensional illustration of measurements corresponding to three indexes designed to assess restoration success in relation to a variable reference set. DRCI = Distance to Reference Communities Index, based on the closest reference situation, DRBI = Distance to Reference Barycenter Index, based on the barycenter distance, and DDRBI = Differential Distance to Reference Barycenter index, based on the comparison of assessed and closest reference point to barycenter.

divided by the average distance between the reference points and their barycenter.

For A , a point to be assessed and R , a set of n reference points,

$$DRBI(A, R) = \frac{\text{Distance from } A \text{ to the reference barycenter}}{\text{Average distance between reference points and reference barycenter}}$$

DRBI ranges from 0 (A is confounded with the reference barycenter) to infinity.

Method Based on the Comparison of Assessed and Reference Community to Average (or Barycenter) Reference Community: Differential Distance to Reference Barycenter Index. Here, the distance of a point to be evaluated from the reference barycenter is compared with the distance of its closest reference point from the reference barycenter (Fig. 1). In other

words, we want to know whether the point to be evaluated is more or less close to the barycenter than the closest reference point.

For A , a point to be assessed, R a set of n reference points, and R_i the closest reference point from A

$$DDRBI(A, R) = \text{Distance from } A \text{ to the reference barycenter} \\ - \text{Distance from } R_i \text{ to the reference barycenter}$$

The Differential Distance to Reference Barycenter Index (DDRBI) is unbounded and equals zero if the point to be evaluated (A) is the same distance from the barycenter as its closest reference point (R_i). The DDRBI is negative if A is closer to the reference barycenter than R_i is.

Whatever the method of calculation, these three indexes can be calculated from different matrices: distance matrices, similarity/dissimilarity matrices, results from ordination analysis (e.g. following Hiers et al. 2012) or numerical classification (e.g. following Fengler et al. 2017) which all correspond to different metrics (e.g. Bray–Curtis, Chi-square, Gower, Jaccard, and Mahalanobis). The choice of the metric, which may affect results, should be made for each study case according to the dataset and the objective of the analysis (Legendre & Gallagher 2001; Borcard et al. 2011; Ricotta & Podani 2017). These three indexes (DRCI, DRBI, and DDRBI) are a way of calculating a continuous metric from an existing statistical analysis. The obtained results make it possible to compare, one by one, a large number of sites to be evaluated, on the same reference panel and to follow the ecological trajectory of these sites. They are therefore complementary to the multivariate analyses already in common use. Also, these indexes are not designed to give a binary answer on whether or not a community belongs to a reference panel (outside or included in the reference panel), but to provide a continuous and comparable metric between sites that share the same reference panel. Whether or not the community to be evaluated belongs to a reference panel must therefore be dealt with by a complementary clustering-type analysis (Oliver et al. 2013; Fengler et al. 2017) or the graphical interpretation of an ordination.

Simulated Dataset

We simulated a theoretical dataset to compare the three indexes. To this end, we generated a reference communities panel and two sets of communities to be evaluated, corresponding to two scenarios: (1) a set whose samples gradually converged toward a randomly chosen reference sample, (2) a set whose samples gradually converged toward the average reference situation (i.e. the reference barycenter).

Reference Communities ($n = 30$). We generated 30 reference samples composed of up to 10 species (then considered as reference species). Five species were systematically present in the reference samples to ensure the presence of shared reference species. We assumed that reference sites in the same ecosystem had several shared species. The five other species had a probability of being present in 50% of each sample. Abundances were randomly (uniform law) assigned values between 1 and 100 within each community. We then normalized these abundance values so that the sum of species abundances within a reference community did not exceed 100.

Assessed Communities, Scenario Trajectory to Reference Barycenter ($n = 30$). Thirty assessed samples were composed of up to 10 species among the 10 reference species and/or up to 10 non-reference species (absent from communities of reference). Here, the assessed samples were generated in such a

way as to form a trajectory toward the reference barycenter. To do this, we created an assessed sample corresponding to the average of the reference communities in terms of species composition and abundance (sample A30). The other samples were generated in such a way that the abundance of reference species decreased linearly until all species were absent (sample A1). The abundance of nontarget species also increased linearly, from community A30 (only reference species) to community A1 (only non-reference species) (Fig. 2).

Assessed Communities, Scenario Trajectory to a Reference Sample ($n = 30$). Assessed communities were generated in the same way as in the previous scenario but from a randomly selected reference sample (Fig. 2).

In both scenarios, the first sample (A1) had no reference species and the last sample (A30) was composed exclusively of

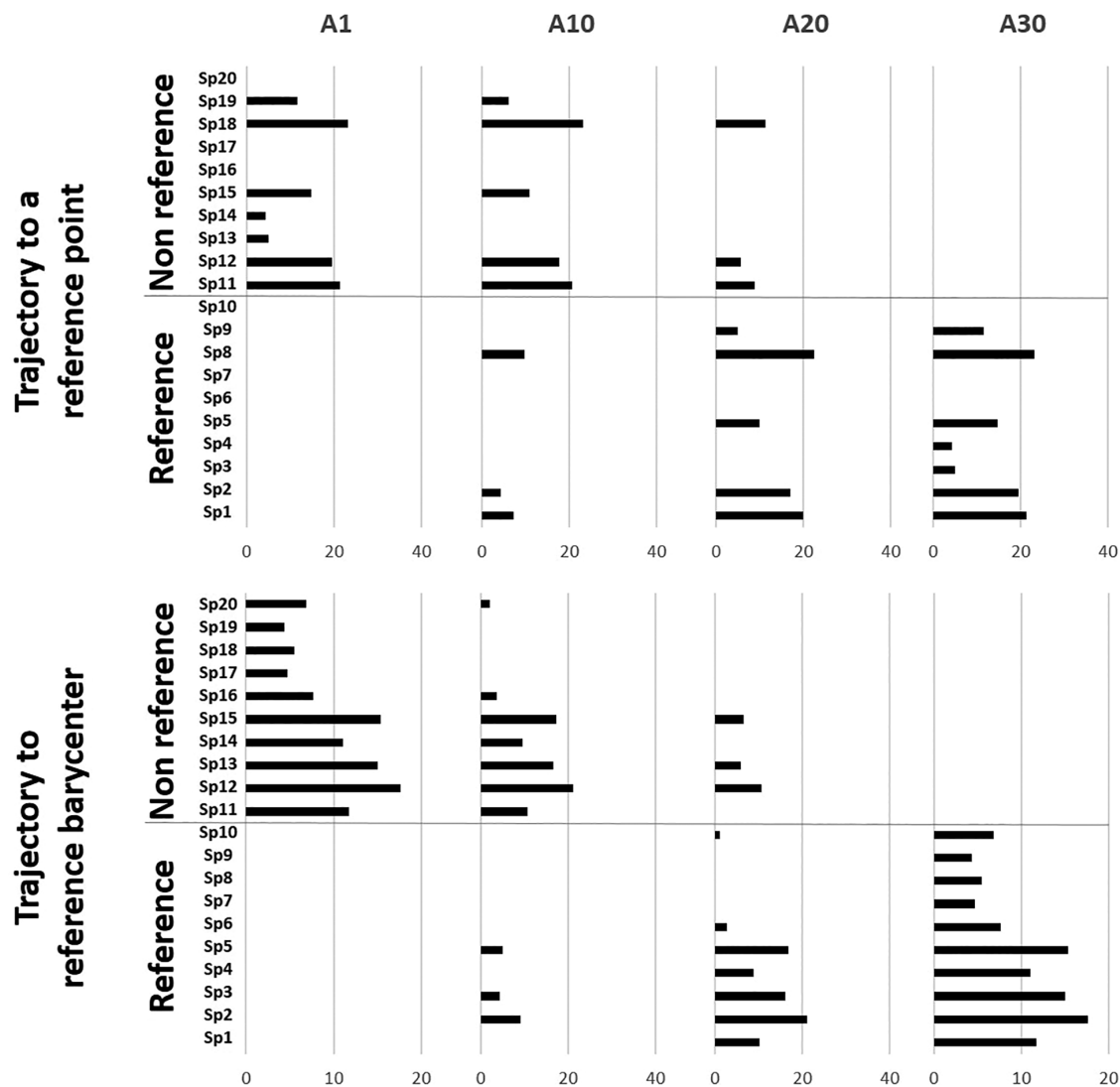


Figure 2. Abundance plots of reference or non-reference species for two scenarios. Sample A1 had no shared species with the reference and sample A30 was identical to a random reference sample (trajectory to random reference sample) or similar to the barycenter of the reference samples (trajectory to reference barycenter). A10 and A20 had intermediate situations between A1 and A30.

reference species, so the sample number corresponded to a favorable restoration trajectory (1–30).

All statistical analyses were performed with R software v.3.6.1 (R Core Team 2017). For each of these communities, we calculated the values of the DRCI, DRBI, and DDRBI (see R function in Supplement S1). The three indexes were calculated from the Bray–Curtis dissimilarity measure (Vegan package; Oksanen et al. 2022), a metric commonly used to compare community data (Legendre & Gallagher 2001; Ricotta & Podani 2017). The results of the three indexes were compared by Spearman correlation tests performed using the PerformanceAnalytics package (Peterson et al. 2018). The relationship between the restoration trajectory (i.e. sample number) and the values of the three indexes for the two scenarios was tested with a linear model (lm() function). Principal Coordinate Analysis (PCoA, using Bray–Curtis dissimilarity) were produced to graphically illustrate the positioning of each point to be evaluated in relation to the reference point cloud and their barycenter.

Real Case Study Dataset

To illustrate the use of the DRCI, we studied plant communities from natural (reference) or artificial (to be assessed) Mediterranean temporary ponds. Mediterranean temporary ponds are a particularly important conservation target due to their ecological importance and their vulnerability (degradation and destruction) (Rhazi et al. 2012). They require ambitious conservation and restoration actions, such as the creation of new ponds (Médail et al. 1998; Grillas et al. 2004; Zacharias & Zamparas 2010; Muller et al. 2013; Bagella et al. 2016; Taylor et al. 2021). The impoundment of these temporarily flooded ecosystems depends on inter- and intra-annual rainfall, which is highly variable under the Mediterranean climate (Grillas et al. 2004). The alternation between aquatic and terrestrial phases (Fig. 3), with significant inter- and intra-annual hydrological variability (Van den Broeck et al. 2015), implies the development of highly specialized plants that express themselves differently according to hydrological conditions (Grillas et al. 2004; Rhazi et al. 2009; Javornik & Collinge 2016). The high spatio-temporal variability of these communities and the knowledge of the main associated explanatory variables (Grillas 1990; Bonis 1993; Rhazi et al. 2009; Van den Broeck et al. 2015) make temporary ponds a particularly relevant study model here.

Our study was carried out in Camargue, in the southeast of France, where many marshes and ponds are the remains of the

Rhône River's activity, which created depressions disconnected from the mainstream through its ramifications and divagations (Muller et al. 2008). To select reference ponds, we listed as exhaustively as possible reference temporarily flooded sites accessible in Camargue (located in a protected natural area or under agreement with an organization involved in nature conservation) with a low water salinity (<5.5 psu measured in February). A temporary pond was considered a reference site if it had a natural geomorphological origin and was free from hydraulic management. All the identified reference ponds were considered to be well-preserved relict environments by the site managers (Fig. 3). We randomly selected 27 ponds, which corresponds to the maximum achievable sampling effort in the allocated time.

Cassaïre pond (lat 43°31'58.8"N; long 4°44'41.9"E), created in 2012 in the Camargue, was used as an evaluated pond. This pond was artificially managed and designed to mimic the hydrology of reference Mediterranean temporary ponds. (Muller et al. 2013, 2022). We selected it for its recent age to best illustrate the differences between this pond and the vegetation of the reference ponds.

Three parallel transects were located in each pond, the first one overlapping the deepest point of the pond, and the two others located at an equal distance between the first one and the edge of the pond. Floristic and in situ environmental measurements were set at regular intervals with a GPS (Global Positioning System) along the three transects. The interval was set depending on the length of the transects (3, 5, and 10 m) to limit the difference in the number of observations between ponds of different sizes and to avoid spatial autocorrelation between observations. Each observation was made within a 30 × 30 cm quadrat and clipped in nine 10 × 10 cm cells to obtain a good representativeness of the composition and structure of these communities due to the repetition along the three transects. We chose to use a survey size smaller than the minimum area (4 m²; Grillas 1990) but more frequently repeated, allowing for a better representation of the spatial heterogeneity of the vegetation and more practical for submerged vegetation. A list of all the species (tracheophytes, charophytes, and bryophytes identified at the species or genus level depending on their state of development) was recorded before measuring their respective frequencies (number of occurrences in the nine cells). This intra-quadrat frequency is an estimate of species abundance, unlike the inter-quadrat frequency, which corresponds most commonly to species frequency (i.e. the number of species present in

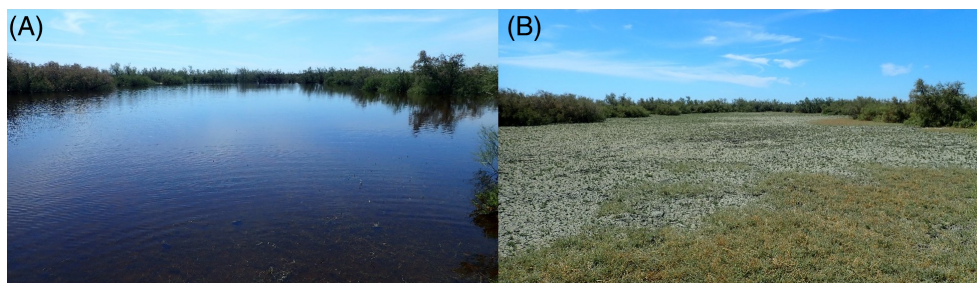


Figure 3. Pond of Cerisière sud, a temporary reference pond in Camargue, south of France, impounded in May 2020 (A) and dry in August 2020 (B).

all quadrats divided by the total number of quadrats in a habitat). Sampling was carried out at four different periods (April, May, June, and August) in 2019 and 2020 for reference ponds (eight dates per pond in total), and in 2020 for the Cassaïre pond (four dates in total). Thus, we explored the inter- and intra-annual variability of reference ponds and assessed the restoration success of Cassaïre ponds for a given year while considering their inter-annual variability. These sampling periods enabled the exploration of intra-annual variabilities, abiotic properties, and plant communities. They encompassed the aquatic phase of early plant growth (April) and late plant growth (May to June), but also the summer dry phase (June to August). Taking into account its spatial, seasonal (intra-annual), and inter-annual temporal variability, we explored the different possible states of this contemporary ecosystem on a regional scale.

The data were compiled by averaging each species' abundance in any given pond for each session and each year in order to generate composite surveys. From the 4321 reference surveys and the 160 surveys realized in the Cassaïre pond, we obtained, respectively, 216 and 4 composite surveys.

We used a Chi-square distance matrix (based on the relative frequencies of similar species) to calculate DRCI. This distance allows for comparing the distribution profiles of each species among surveys, by giving strong weight to rare species without being influenced by the double-absences of species (Legendre & Gallagher 2001; Borcard et al. 2011). We chose to add weight to rare species because many rare and opportunistic species contribute to the plant community of temporary Mediterranean ponds (Rhazi et al. 2009). Some species specific to these settings are indeed uncommon (Grillas et al. 2004), including, e.g. in our samples, *Cressa cretica*, *Damasonium polyspermum*, *Lythrum tribracteatum*, *Pulicaria sicula*, *Trifolium ornithopodioides*, and *Zannichellia obtusifolia*.

Here, each calculation of the DRCI was done using a distance matrix calculated from a dataset that combines the sampling of a pond to be assessed with all reference samples (lines) and species (column) (see the R script in Supplement S1). We therefore calculated four distance matrices and four DRCI values, corresponding to the four sampling sessions for the Cassaïre pond. In complement, we calculated other commonly used indexes, such as the proportion of exotic and native species abundance (%), the relative abundance of two functional groups (% of submerged hydrophytes and emergent species abundance). We also calculated two indices of ecological integrity proposed to evaluate the success of restoration by Jaunatre et al. (2013): the Community Structure Integrity Index (CSII) which "measures the average proportion of species' abundance in the reference communities represented in the assessed community" and the Higher Abundance Index (HAI), which "measures the average proportion of species' abundance in the assessed community higher than the reference communities." The results of these indexes were compared with DRCI values using Pearson correlation tests.

Distance matrices for DRCI calculations were run with the Vegan package (Oksanen et al. 2022). Correlations tests were performed using the PerformanceAnalytics package (Peterson et al. 2018). Both indexes of ecological integrity were performed with the CSII package (Jaunatre et al. 2013).

Results

Simulated Dataset

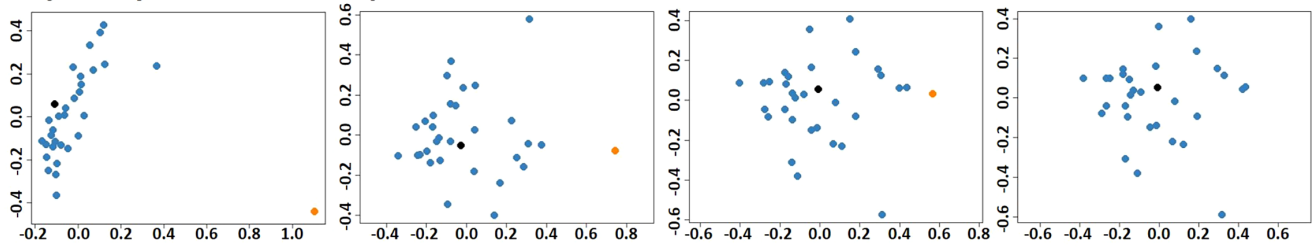
The positioning of each point (sample) to be assessed in relation to the cloud of reference points and their barycenter on the first two axes of a PCoA is shown in Figure 4. Point A1 (the only non-reference species) was correctly located away from the reference cloud for both scenarios, points A10 and A20 were progressively located closer to their targets, and point A30 perfectly overlapped its target, depending on the scenario. In the case of the scenario targeting a reference point, the point to be assessed moved progressively closer to a randomly selected point until it reached it, thus fulfilling one of the possible restoration targets. In the case of the scenario targeting the reference barycenter, the point to be evaluated crossed the reference point cloud until it reached it, thus fulfilling the only possible restoration objective.

The values of the three indexes for the two scenarios were very strongly and significantly correlated with each other (p value <0.001 , $\rho >0.98$). They were also very strongly and significantly correlated with the restoration trajectory (p value <0.001 , $\rho >0.98$), that is, with the number of sample to be evaluated (from the first sample, A1, completely different to the reference, to the last sample, A30, identical to one of the two target references depending on the scenario). The three calculation methods were therefore consistent with each other, and provided good information on the favorable restoration trajectory for the sample to be evaluated, whatever the scenario.

However, depending on the calculation method and scenario chosen, restoration was considered to have been achieved or not. (index value = 0 for sample A30) (Fig. 5). The DRCI value for sample A30 was equal to 0 for the randomly selected reference point scenario. Here, the DRCI indicated the similarity between the sample to be assessed and a reference sample, regardless of the reference sample reached. The DRCI value for A30 was greater than 0 for the barycenter scenario, so it did not indicate total success when a point to be evaluated reached the barycenter of the reference points. However, the DRCI value remained low in this scenario (DRCI = 0.27 for A30). The DRBI value for the A30 sample was zero for the barycenter scenario, which was the only objective to be achieved here. It was greater than zero for the scenario targeting a randomly selected reference point, in which case the DRBI was relatively high (DRBI = 1.12 for A30) and therefore did not indicate restoration success. The DDRBI value for sample A30 was zero for the randomly selected reference point scenario, so the restoration objective was achieved if the sample to be assessed reached any of the reference samples. The DDRBI value became negative when the point to be evaluated was closer to the barycenter than its closest reference point.

Both scenarios were designed in such a way that the samples to be evaluated were gradually brought closer and closer to a reference point or reference barycenter (Figs. 4 & 5). The relationship between the values of the three indexes and the restoration trajectory (i.e. the sample number from A1 to A30) was highly significant and strongly linear for all three calculation methods and both scenarios (p value <0.001 and adjusted r^2 between 0.99 and 0.95) (Fig. 5). For DDRBI, this relationship in the scenario targeting the reference barycenter was less linear than the

Trajectory to a reference point



Trajectory to reference barycenter

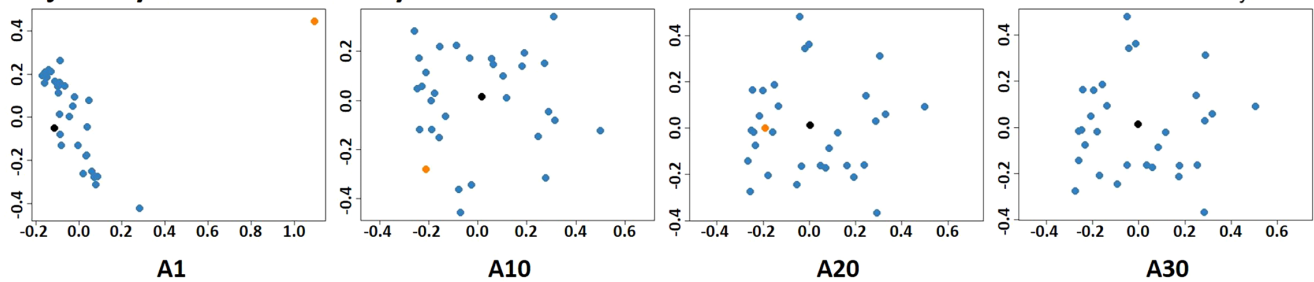


Figure 4. PCoA (axes 1 and 2) performed on the reference dataset, the reference barycenter, and the datasets to be evaluated according to two scenarios (simulated dataset). Sample A1 had no shared species with the reference and sample A30 was similar to a random reference point (trajectory to random reference point) or similar to the reference barycenter (trajectory to barycenter). A10 and A20 had intermediate situations between A1 and A30.

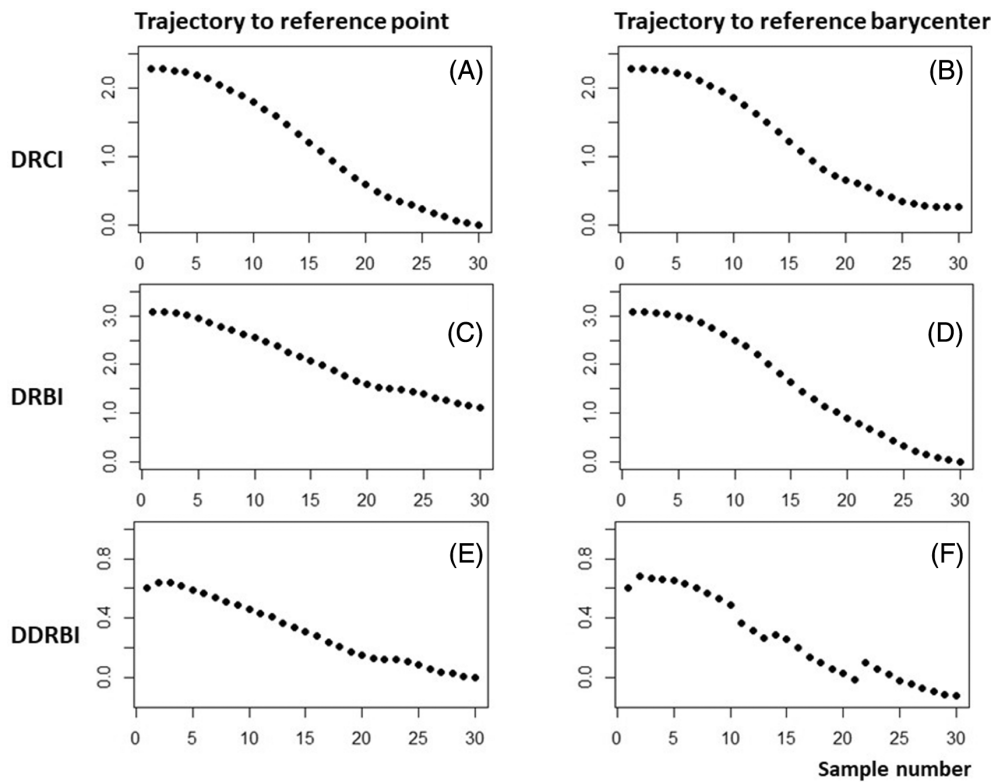


Figure 5. Results of the three calculation methods studied: (A and B) Distance to Reference Communities Index (DRCI, based on the closest reference situation), (C and D) Distance to Reference Barycenter Index (DRBI, based on the reference barycenter distance) and (E and F) Differential Distance to Reference Barycenter Index (DDRBI, based on the comparison of assessed and closest reference point to reference barycenter), along a restoration trajectory (sample number in abscissa). Sample A1 has no shared species with the reference, and sample A30 is (A, C, and E) similar to a reference sample in the marginal position of the reference cloud (scenario trajectory to random reference point), or (B, D, and F) similar to the barycenter of reference points (scenario trajectory to reference barycenter).

others (adjusted $r^2 = 0.95$) (Fig. 5F). This is because the value of the DDRBI increased punctually, while the curve decreased overall. This situation arose because the trajectory of the points to be evaluated was taking place inside the reference cloud. When the point to be evaluated was moving closer to the barycenter while approaching a reference point, the value of the DDRBI was decreasing, which is an expected result. But if the point to be evaluated changed its closest reference point while moving closer to the barycenter, the value of DDRBI could rise sharply, which is a counter-intuitive result. Similarly, the DDRBI could change from negative to positive as the trajectory was approaching the reference barycenter, another counter-intuitive result. This situation did not arise in the case of a trajectory aimed at a point on the edge of the reference cloud (Fig. 5E).

Cassaïre Case Study

The DRCI (Chi-square distance) of the Cassaïre pond was 1.61 in April, 1.74 in May, 2.38 in June, and 2.85 in August. This means that the Cassaïre vegetation pond was 1.64–2.85 times further away from the reference panel than the reference vegetations were from

each other on average. So, Cassaïre communities differed from the reference communities and increasingly diverged from them over this period. During the aquatic phase (April and May), when DRCI values were the smallest, the community was dominated by *Chara vulgaris* and *Ranunculus peltatus*, which were respectively scarce and often abundant hydrophytes in reference ponds. During the same period, other species present in reference ponds were punctually observed in the Cassaïre pond (e.g.: *Callitriche truncata* subsp. *occidentalis*, *Ranunculus trichophyllus*, *Riella notarisi*, and *Zanichellia pedunculata*). From June, *Paspalum distichum* was notably observed. It is an invasive alien species absent from reference ponds, which is boosted by summer freshwater supplies (Mesléard et al. 1993). The abundance of this species increased gradually until reaching its maximum in August. It was the most frequent species in the pond from June, when DRCI values were the highest. The CSII was low overall and decreased from April (0.36) to August (0.11), meaning that the abundance of reference species was low and decreased over this period (Fig. 6). The HAI remained high and stable overall, meaning the overabundance of reference or non-reference species during this period (0.8 in April to 0.88 in August). DRCI was significantly and positively correlated with the

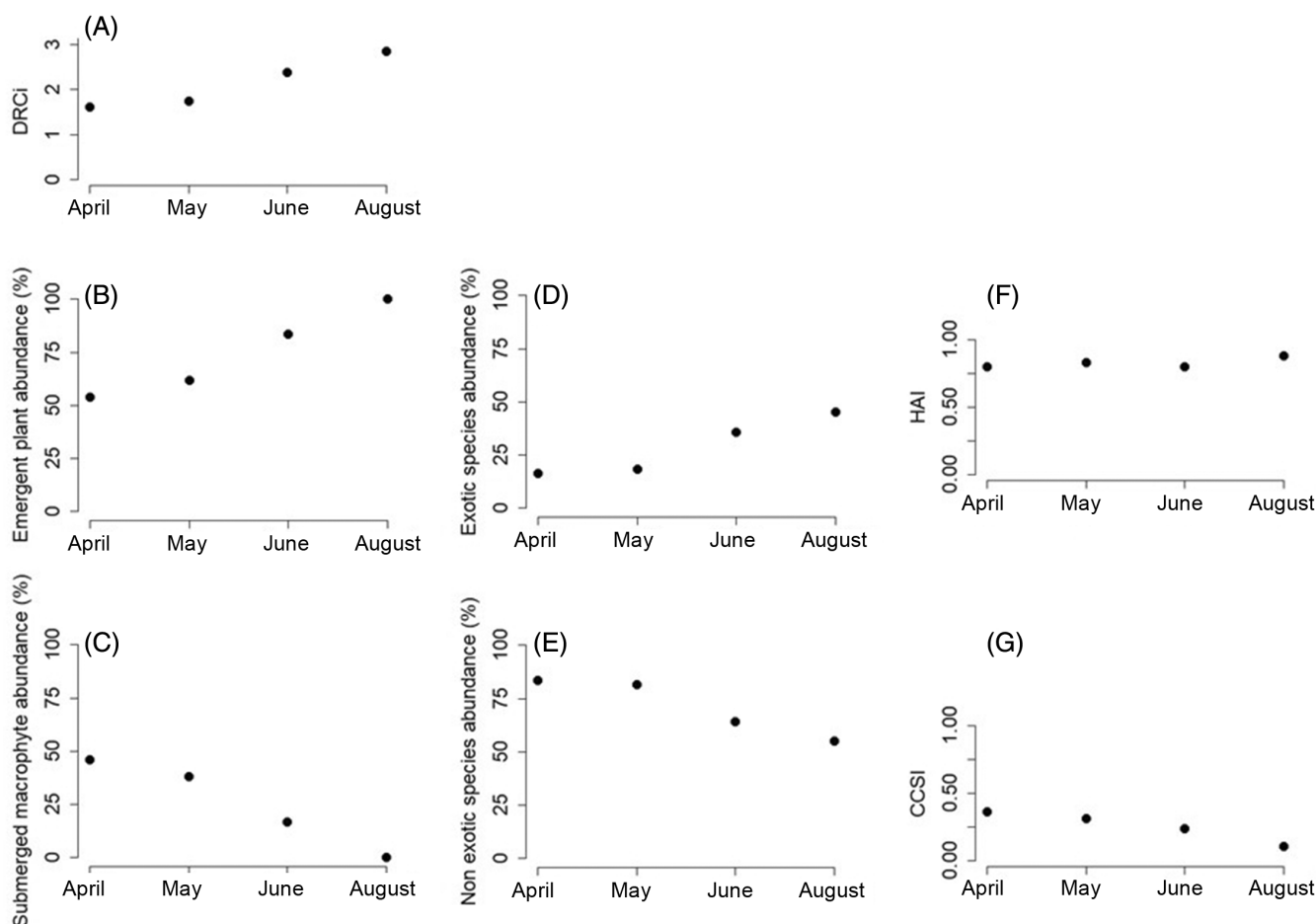


Figure 6. Plot of indicators of restoration success for the Cassaïre site in April, May, June, and August 2020: (A) Distance to Reference Communities Index, (B) emergent plants abundance (%), (C) submerged hydrophytes abundance (%), (D) exotic species abundance (%), (E) native species abundance (%), (F) Community Structure Integrity Index (CSII), and (G) Higher Abundance Index (HAI).

abundance of emergent plants (p value = 0.002, r = 0.99), and with the abundance of exotic species (p value = 0.002, r = 0.99). It was significantly and negatively correlated with submerged macrophyte abundance (p value = 0.002, r = -0.99), with nonexotic species abundance (p value = 0.002, r = -0.99), and with CSII (p value = 0.02, r = -0.97).

Discussion

Comparison of the Three Calculation Methods

Three indexes have been proposed to compare a restoration trajectory with a variable reference panel, giving similar results and enabling a restoration trajectory to be measured. However, there were several differences between the results obtained using these three methods.

The DRCI measured the distance from a point to be evaluated to the closest reference point. It is therefore considered that all reference communities as potential and equally relevant objectives, taking into account the variability of all reference sites.

The DRBI measured the distance from a point to be evaluated to the barycenter of reference points; these values indicated a complete restoration success only when the community to be evaluated was identical to the barycenter or average reference community (species composition and abundance). This corresponds to a theoretical situation that may never exist because a restored site has a probability close to zero of containing all the species of all the reference sites, with for each species an abundance corresponding to their average abundance in the reference sites. Setting the barycenter or a theoretical average situation as the unique restoration objective does not take into account the diversity and variability of reference situations. We therefore recommend not using it as such when assessing restoration success.

The DDRBI measured the difference between the distance of a point to be evaluated from the reference barycenter and the distance of its closest reference point from the barycenter. As with the DRCI, this index allowed each reference point to be considered as a relevant objective. The DDRBI also provided additional information, becoming negative when the point to be evaluated moved from outside to inside the reference cloud (i.e. the point to be evaluated was closer to the barycenter than its closest reference point). However, as seen in the results, by moving within the reference point cloud, it was possible that the reference point closest to the point to be evaluated changed, possibly leading to a re-increase in the DDRBI value or even a return to a positive value. This counter-intuitive result may lead to a misinterpretation of restoration success and restoration trajectory. Finally, trying to get closer to the barycenter of the reference points than to one of the reference points, even a marginal one, is not necessarily a more relevant objective. We therefore also recommend against this method of calculation, which is open to misinterpretation and considers the barycenter to be preferable to any reference situation.

Ecological Interpretation of Cassaïre Case Study

In the Cassaïre case study, DRCI (using Chi-square distance) values provided information that well reflects the differences

between the communities that developed over time and the reference ones. Indeed, the presence of a large number and high abundance of non-reference species, among which some were exotic invasive species (such as *Paspalum distichum*), well explained the unsuccessfulness of this current restoration situation. Also, the increase in DRCI values over the season reflected the greater similarity of the vegetation in April and May to the reference panel than in June and August. This can be explained by an increase in the abundance of exotic species (non-reference species), but also by the decrease in abundance and disappearance of reference species (CSII decrease), particularly aquatic species. The restoration of aquatic-phase communities was better than that of terrestrial-phase communities. We may hypothesize that aquatic conditions, which imply a very high degree of specialization for plants, have acted as an ecological filter, limiting the presence and abundance of nontarget species because they are not specialists in this constraining environment. This incomplete restoration situation was partly explained by the strong development of *P. distichum* linked to water management choices that reduced salinity and favored it. The high abundance of this species might also be the result of past cultivation practices (rice fields and irrigated hay meadows). This situation of incomplete restoration of the newly created Cassaïre pond (2012) matches the results of Moreno-Mateos et al. (2012), who showed that wetlands (a meta-analysis of 621 restored sites) take approximately 30 years for plant communities to converge more or less with reference.

Limits of the Approach

The DRCI is not a direct tool for concluding the success or failure of restoration. Restoration processes are often long, gradual, and uncertain (Black & Zedler 1998, Collinge et al. 2013), so the relevance of a single index to conclude restoration success (fully restored or not restored) would be questionable and needs more nuance in our view. For restoration assessment, DRCI must be supported by the interpretation of a range of complementary analyses on environmental conditions and communities, such as ordinations, clustering, trait analysis, etc., including both reference and under-restoration sites. Because the values of the DRCI index depend on the metric used, it is advisable to choose the distance or dissimilarity index best suited to the dataset, taking into account, e.g. the effect of rare species, the effect of many zeros in the species data table, or the nesting effect of assemblages (there is a large literature on the choice of distance, similarity or dissimilarity indices in community ecology; see, e.g. Legendre & Gallagher 2001, Baselga 2013, Ricotta & Podani 2017). We also recommend using other metrics to complement the DRCI results. In our case, the use of the Chi-square distance for the calculation of the DRCI at Cassaïre did not inform us about the absolute abundance of the (reference or non-reference) species. It was therefore relevant to complete the results of the DRCI with, e.g. the CSII or the HAI (Jaunatre et al. 2013) which informed us in greater detail about reference and non-reference species abundance. Regardless of the distance index used, the DRCI does not differentiate between a change in species composition or abundance or in both. A more detailed

approach, species by species, may then be relevant to refine the interpretation of the synthetic result of the DRCI, as we saw with the increase of *P. distichum* abundance in the results of the Cas-saire case study. Similarly, it may be useful to use the acceptable range of variation (Oliver et al. 2022) for an environmental variables analysis or a species-trait approach to support the ecological interpretation of the restoration assessment. Then, all species sampled in the reference sites were here considered target species, while some were more characteristic of the reference ecosystem and others, more common or even indicative of a degradation. Weighting or considering only the characteristic target species could complement the overall result given by the DRCI.

The relevance of the DRCI obviously requires that the reference panel is representative of the entire variability of the reference sites and it cannot be calculated with only one reference sample. Also, including substantially different sites (outliers) in the reference panel leads to an incorrect and too-flexible restoration objective. Study cases where reference sites are few and highly contrasted severely limit the use of the DRCI, which may not be relevant. In particular, we recommend not using the DRCI if the restoration assessment uses “twin” or “showcase” reference sites rather than a “multi-site” reference approach (sensus Rollet et al. 2022).

DRCI Inputs to Restoration Ecology

The methodological approach proposed in this study responds to some of the criticisms addressed to the reference state, in particular, related to its fixist aspect. (Pickett & Parker 1994; White & Walker 1997). However, in our case study, DRCI does not escape criticism related to the definition of a historical reference (Millar & Brubaker 2006; Hobbs et al. 2009; Jackson & Hobbs 2009; Bennion et al. 2010) because it was only based on contemporary reference sites and did not take account of their historical trajectory. Here, as in many cases, the choice of using a contemporary reference (when available) enables us to explore the ecosystems’ spatio-temporal variability without being limited by historical data availability. Nevertheless, the DRCI can also be used with historical data when available (e.g. phytosociological data), thus taking into account the historical variability of reference sites. As contemporary reference integrates variations related to current environmental factors, this enables the definition of an objective for contemporary restoration, potentially achievable. Reevaluating the ecological reference over time or even anticipating future paths of ecosystems would help define a “moving” or “dynamic” restoration objective in the context of global change (Clewel 2009; Hiers et al. 2012; Shackelford et al. 2021). This approach is compatible with the use of DRCI by mixing data from older and younger references or by reevaluating the reference panel over time. However, such an approach entails risks and pitfalls, especially that of a “shifting baseline syndrome” (Pauly 1995). Societal and scientific perceptions of ecosystems are indeed not necessarily fixed baselines (i.e. reference), they can shift (Papworth et al. 2009; Guerrero-Gatica et al. 2019; Rodrigues et al. 2019). The use of a contemporary reference might then consider degraded states as acceptable restoration goals. In the same way, reevaluating the ecological

reference over time can lead to a continual decline of conservation and restoration goals in the context of global biodiversity erosion (Balmford 1999; Rodrigues et al. 2019). We therefore recommend the use of DRCI when historical or contemporary multi-site references are used, provided that the limitations and risks of shifting baseline syndrome are assessed.

The DRCI can be used in a variety of ways, according to different conceptions of ecological reference:

- (1) using historical reference data that are representative of pre-disturbance conditions. This corresponds to a fixed long-term vision, but it can make it possible to include the historical variations of the well-preserved ecosystem according to the available data, thus defining a positive reference that is not degraded and not subject to the shifting baseline syndrome;
- (2) using contemporary reference data considered to be representative of the natural variation of the contemporary reference ecosystem. It is also a fixed long-term vision, but makes it possible to explore the spatio-temporal variability of the contemporary reference sites and thus to define a potentially more realistic restoration target;
- (3) reevaluating the reference over time (as Hiers et al. 2012), which makes it possible to compare the trajectories of restored sites in relation to the reference trajectory, which is potentially under the influence of global change and therefore subject to the shifting baseline syndrome.

However, the DRCI was not designed to use predicted reference communities, which generally involve functional rather than taxonomic approaches.

In addition, the DRCI calculation method does not lead us to target only exceptional heritage reference sites, as each reference site is considered a valuable positive reference. In particular, it allows defining multiple targets that better reflect the natural diversity of the reference ecosystem (“multi-site” approach vs. “showcase” approach, sensus Rollet et al. 2022), thus making restoration targets more realistic.

Ecological Application and Transfer to Practitioners

The DRCI provides a continuous metric for tracking the restoration trajectory of a site against a reference panel, or for evaluating a large number of restored sites against the same reference panel in a comparable way. It is therefore a synthetic and relevant tool for evaluating the restoration of multiple sites for an ecosystem or community in a given region. This approach could therefore have useful implications in a context where ecological restoration is targeted by ambitious international public policies, which should incorporate standardized assessment procedures that enable the comparison of numerous restored sites. Also, comparison with a reference panel is an issue that is also linked to the assessment of habitat conservation status (e.g. Natura 2000 habitat). The DRCI is therefore a tool that can be used for this purpose by comparing well-preserved habitats (reference habitats) with habitats to be assessed and monitored. From this perspective, identifying data from reference sites in databases would provide a useful source

of information for assessing the restoration success of many sites, for many targeted ecosystems.

In addition, the simplicity of the DRCI calculation combined with the ease of interpretation in ecological terms makes it a suitable tool for communication with practitioners. Finally, the general approach of taking into account the variability of reference states in the assessment of restoration success is an approach not often used in practice (Shackelford et al. 2021; Oliver et al. 2022) that we hope to encourage through this new index use.

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Supporting Information

The following information may be found in the online version of this article:

Supplement S1. R function for DRCI, DRBI, and DDRBI calculation using Bray-Curtis dissimilarity.

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