Ecological equivalence assessment methods: what trade-offs between operationality, scientific basis and comprehensiveness?

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Abstract

In many countries, biodiversity compensation is required to counterbalance negative impacts of development projects on biodiversity by carrying out ecological measures, called offset when the goal is to reach "no net loss" of biodiversity. One main issue is to ensure that offset gains are equivalent to impact-related losses. Ecological equivalence is assessed with ecological equivalence assessment methods (EAMs) taking into account a range of key considerations that we summarized as ecological, spatial, temporal and uncertainty. When EAMs take into account all considerations, we call them "comprehensive". EAMs should also aim to be science-based and operational, which is challenging. Many EAMs have been developed worldwide but none is fully satisfying. In the present study, we examine 13 EAMs in order to identify i) their general structure and ii) the synergies and trade-offs between EAMs characteristics related to operationality, scientific-basis and comprehensiveness (called "challenges" in his paper). We evaluate each EAM on the basis of 12 criteria describing the level of achievement of each challenge. We observe that all EAMs share a general structure, with possible improvements in the choice of target biodiversity, the indicators used, the integration of landscape context and the multipliers reflecting time lags and uncertainties. We show that no EAM combines all challenges perfectly. There are trade-offs between and within the challenges: operationality tends to be favored while scientific basis are integrated heterogeneously in EAMs development. One way of improving the challenges combination would be the use of offset dedicated data-bases providing scientific feedbacks on previous offset measures.

Key-words

Biodiversity offset, ecological equivalence, ecological equivalence assessment methods, no net loss, mitigation hierarchy, compensation.

1. Introduction

Biodiversity erosion has accelerated in recent decades (Sala *et al.* 2000) and has become a major environmental concern as biodiversity loss is identified as a major driver of ecosystem change (Hooper *et al*. 2012). Alongside "classic" answers such as species and ecosystems protection and conservation, biodiversity compensation is increasingly used to counteract impacts from development. It is applied worldwide and has legal status in some countries (e.g., the United States, Canada, Australia, Germany, France and the United Kingdom). Compensation mechanisms remain country-dependent (McKenney & Kiesecker 2010; Commissariat Général au Développement Durable (CGDD) 2012) but are usually integrated in the mitigation hierarchy, after avoidance and reduction of impacts.

Efforts have been put into enhancing biodiversity compensation, and biodiversity offset in particular. Biodiversity offset is a way of compensating for biodiversity losses (Business and Biodiversity Offsets Programme, BBOP 2012a) with the aim of achieving "no net loss" (NNL) of biodiversity (ten Kate *et al.* 2004). Concerns about offset practices have been expressed in the literature for many years (Race & Fonseca 1996) as offset is the last lever on which it is possible to act in order to achieve NNL (Gibbons & Lindenmayer 2007).

Notably, frameworks have been established to guide offset measures design in order to achieve NNL of biodiversity (Business and Biodiversity Offsets Programme, BBOP). One of the main conditions is that biodiversity gains should be comparable, or equivalent to biodiversity losses (Gardner *et al.* 2013). When this happens, "ecological equivalence" is reached. Ecological equivalence is one of the most widely discussed conceptual challenges in the related scientific literature (Gonçalves *et al.* 2015). A particularly controversial aspect is how ecological equivalence should be assessed. A number of essential considerations that should be taken into account in order to evaluate equivalence have been identified (Quétier & Lavorel 2011; Bull *et al.* 2013; Quetier *et al.* 2014), which we summarize in four key groups: ecological, spatial, temporal and uncertainty considerations.

Ecological considerations gather (i) issues related to the choice of biodiversity components for which losses and gains are quantified, also called target biodiversity (Quétier & Lavorel 2011) and (ii) the set of indicators that is used to quantify those biodiversity components, also known as currency (Bull *et al.* 2013) or metrics (Business and Biodiversity Offsets Programme, BBOP 2012a).

Spatial considerations relate to the integration of impacted and compensatory sites landscape context in equivalence assessment. Landscape context gives information about landscape components influencing biodiversity (e.g., connectivity and metapopulation functioning; Beier & Noss, 1998) which are notably important to locate offset sites (Kiesecker *et al.* 2009; Saenz *et al.* 2013). According to the BBOP (2012b) "a biodiversity offset should be designed and implemented in a landscape context to achieve the expected measurable conservation outcomes".

Temporal considerations are related to the time lag (also called delay) between the moment when impact on biodiversity occurs and the moment when offset measures become fully effective (Maron *et al.* 2010), ensuing interim losses of biodiversity (Dunford *et al.* 2004). One current solution to avoid or reduce interim losses is to implement compensation ahead of impacts (e.g., by using mitigation banks; Wende *et al.* 2005). But when no bank system is available, assessment of equivalence should take into account temporal considerations (Laitila *et al.* 2014).

Finally, considerations on uncertainty refer to the lack of confirmed knowledge and hindsight when assessing equivalence, and particularly in this article we focus on the risk of failure when implementing offset measures (Moilanen *et al.* 2009; Curran *et al.* 2013). This risk mostly depends on the species or ecosystems concerned by offset (Tischew *et al.* 2010), the type of offset implemented (Anderson 1995) such as habitat restoration, protection, creation or enhancement (Levrel *et al.* 2012) and the ecological engineering techniques used (Jaunatre *et al.* 2014).

Equivalence Assessment Methods (EAMs) exist worldwide and are used by developers or authorities to evaluate biodiversity losses and gains (e.g., State of Florida 2004; Gibbons *et al.* 2009; Darbi & Tausch 2010). They are specifically conceived to ensure that offset measures are sufficient to reach ecological equivalence. Although every EAM seeks to ensure NNL of targeted biodiversity, none is fully satisfactory and principles underlying some EAMs have been discussed (McCarthy *et al.* 2004; Gordon *et al.* 2015). Notably, depending on the method used, calculations result in different offset surfaces for the same impact (Bull *et al.* 2014). It seems rather difficult or even impossible to move toward an unanimous worldwide method, mainly because of (i) diversity in offset policies between countries (McKenney & Kiesecker 2010), (ii) disparity between development projects and the resources committed to biodiversity conservation (Regnery *et al.* 2013b), and (iii) disparities in biodiversity status context and conservation issues. Nonetheless, exploring interactions between the characteristics underlying EAMs could highlight ways of improving equivalence assessment. Thus, we characterized existing EAMs regarding three "challenges" that we identified to be determinant in EAMs effectiveness to meet NNL. In this article, we call these three "challenges" operationality, scientific basis and comprehensiveness. On one hand, operationality is needed by developers and public authorities to carry out standardized assessments in a small amount of time, at reasonable costs (Laycock *et al.* 2013) and in consistence with the skills level of structures involved in mitigation studies. On the other hand, growing awareness comes from the scientific sphere that equivalence assessment should be grounded on scientific basis, including evidence based biodiversity evaluation, objective and transparent metrics and calculation (Gonçalves *et al.* 2015) and feedbacks from previous offset related experiences (Maron *et al.* 2010; Pöll *et al.* 2015). Despite the importance of both operationnality and scientific basis challenges, they are often seen as not fully compatible. Finally, comprehensiveness is a transversal challenge addressing the fact that EAMs development should take into account all four key equivalence considerations, as highlighted by Quétier & Lavorel (2011). We can hypothesize that it is an obstacle for operationality and that it is more compatible with scientific basis.

The objective of this paper is to provide elements of reflection for the development of future EAMs contributing to design offset measures that lead to NNL, by exploring two main questions:

(i) Is there a common structure underlying all EAMs and what elements of such structure could be used as basis when developing an EAM?

(ii) What are the synergies and trade-offs in achieving operationality, scientific basis and comprehensiveness. Particularly, is operationality necessarily in contradiction with both other challenges? Is it possible to combine all three challenges in one EAM accepted by both operational and scientific spheres?

2. Material and method

2.1 Analysis of EAMs structure

Thirteen EAMs developed in various offset policies were analyzed: Habitat Evaluation Procedure, Resource and Habitat Equivalency Analysis, Canadian method Fish Habitat, Habitat Hectare, Uniform Mitigation Assessment Method, Landscape Equivalency Analysis, Business and Biodiversity Offsets Programme (BBOP) pilot method, Land Clearing Evaluation, German Ökokonto, Californian Rapid Assessment Method, Pilot method in United Kingdom and Somerset Habitat Evaluation Procedure (Table 1; see Appendix A for description of these EAMs). EAMs are distinct from legislative frameworks and offset policies providing main principles on biodiversity offset (e.g., Brownlie & Botha 2009; Regnery *et al.* 2013a).

These EAMs were chosen because they were either published in a scientific journal or had accessible guidelines that could be used to understand how they were constructed and for what purpose. Only main EAMs were analyzed, but we are aware that there are variants adapted to specific cases and that different versions of guidelines are used simultaneously (Duel et al. 1995; Tanaka 2008). The EAM selection intended to give an overview of the current EAMs diversity and also of EAMs commonly used. Thus this is not an exhaustive sample but rather a representative one as it covers North America, Australia and Western Europe which are three main zones where offset policies are well-established (Madsen *et al.* 2010). The sample also covers all kind of ecosystems (terrestrial, aquatic, marine or wetlands).

In order to evaluate how EAMs are structured we first conducted a qualitative bibliographic study. We started from Quétier's & Lavorel's publication (2011) to described EAMs characteristics according to the four key equivalence considerations: (i) Ecological: what components of biodiversity do EAMs evaluate? (ii) Spatial: how do EAMs take into account the landscape context? (iii) Temporal: how do EAMs take into account time lags? And (iv) Uncertainty: how do EAMs take into account the risk of offset failure? Finally, we identified the "compensation unit" used in each EAM, which is the currency calculated for a site and then compared between impacted sites (loss of biodiversity units) and offset sites (gains of biodiversity units).

2.2 Synergies and trade-off between the three EAMs challenges

Twelve criteria were defined, covering a large range of characteristics related to how operationality, scientific basis and comprehensiveness are taken into account in EAMs. A description of those criteria and the working hypothesis underlying their choice are specified in Table 2.

In our work EAMs are considered operational when they have pre-defined indicators ("Indicators set up"), are rapid to implement ("Implementation rapidity"), when data needed are easily available ("Data availability") and when "like for unlike" offset designs (exchangeability between biodiversity impacted and compensated) are possible ("Exchangeability"). EAMs are considered to have scientific basis when all the indicators used to assess biodiversity are based on scientific documentation ("Biodiversity indicators"), when the metrics used are quantitative and appropriate to the biodiversity component being assessed ("Biodiversity indicator metrics"), when spatial considerations are taken into account with dedicated indicators ("Spatial considerations") and when uncertainty is taken into account based on previous feedbacks ("Uncertainty considerations"). Finally, EAMs are considered comprehensive when they include all key equivalence considerations (“Key equivalence consideration”), when they target species, habitats and ecosystem functions (“Biodiversity components”), when they require various types of data (from the literature, GIS, field data, etc., “Data type”) and when they evaluate biodiversity with a relevant set of indicators (“Indicators number”).

Each criterion was defined by 3 or 4 modalities (see Appendix B for modalities details). For most modalities, data could be derived from the published version of EAMs. However, to complete certain modalities (e.g., those relating to “Implementation Rapidity”) we interviewed experts who either use the EAM in the field or have contributed to its construction (see Appendix C, experts’ names and functions are given when they agreed to be cited). When divergent answers were obtained for a given EAM, priority was given to the answer obtained from EAMs developers which was the case for the UMAM, CRAM, UK pilot and German Ökokonto (see Appendix C). We found some mismatches between experts’ answers and theoretic guidelines, but this could be explained by differences in EAMs variants or case-by-case practices. In these cases, we decided to stick to the theoretical guidelines (see Appendix D).

A score from 1 to 3 or 4 (depending on the number of modalities) was then given to each criterion, where 1 is the lowest level of challenge achievement, and 4 the highest (see Appendix B). For example, an EAM that require only very easy to access data will receive a 4 for the “Data availability” criterion. This scoring system was deliberately simple and linear to give all modalities a similar weight. The aim of this scoring was to highlight synergies and trade-offs between these criteria, and beyond, between the three challenges.

We suppose that some correlations between particular criteria will occur, as for example, if large data collection (Data Type) is required, data availability may be low. Moreover, when users have to choose indicators (Indicators set up), they can a priori choose a combination of qualitative and quantitative discrete or continuous metrics (Biodiversity indicator metrics) which would imply a correlation between these criteria. However, it remains theoretical as in practice users could very well choose only indicators with qualitative metrics.

2.3 Data analysis

A principal component analysis (PCA) was performed on all criteria scores (see Appendix C), in order to analyze how EAMs addressed operationality, scientific basis and comprehensiveness. Mean scores were calculated for each challenge (ScoreOp, ScoreScBs and ScoreComp) as the relative mean of the scores attributed to the four criteria describing the challenges, expressed as percentage challenge achievement. These mean scores were added as supplementary variables in the PCA (so that they do not contribute to PCA axis construction). Correlations between criteria were assessed by a nonparametric measure of rank correlation, Spearman rank coefficient (rho), as a complement to PCA, in order to identify oppositions and synergies between criteria underlying the challenges. Criteria were considered correlated for rho ≥ ±0.5 (Freckleton 2002). The PCA also allows identification of EAMs groups according to the challenge they best achieve. All analyses used R software version 3.1.2 with the corresponding FactoMineR package (Husson *et al.* 2015).

3. Results

3.1. EAMs general structure

The analysis of the 13 EAMs indicates that they all share a common structure to calculate losses and gains of biodiversity (Figure 1). They all consider two sites (impacted site and offset site) at two time points (before and after impact or offset measures). One or several indicators are chosen as surrogates to qualify or quantify the targeted biodiversity components, which differ from one EAM to another depending on the context. Two main EAM types can be identified according to the range of biodiversity they target: "specialized", using indicators for a specific ecosystems (for example Australian endemic vegetation for the Habitat Hectare method or Florida's wetlands for UMAM) and "generalist" using general indicators adapted to a wide range of ecosystems (e.g., terrestrial ecosystems for PilotUK) (Table 3).

A benchmark can be used if there is an identified reference state for the targeted biodiversity (e.g., for Habitat Hectare the benchmark is "the same vegetation type in a mature and long-undisturbed state", and for UMAM it is a "reference standard wetland" considered as in good ecological quality). A quantitative value based on these indicators is attributed to the site before and after impacts (to calculate biodiversity losses) or offset (to calculate biodiversity gains) and is multiplied by the related site areas. This combination of biodiversity "quality" and "quantity" constitutes the "compensation unit". A tiny majority of EAMs (8 out of 13) evaluate ecological equivalence by attributing "compensation units" to impacted and offset sites (Table 3), allowing biodiversity losses and gains to be assessed and compared on the same basis. There are no specific rules for offsetting one compensation unit by another, only that the number of units exchanged in the offsetting process must be at least equal. The other five EAMs go one step further by using specific rules to size offset measures. This can be done by integrating temporal or uncertainty related ratios to increase the compensatory site area (e.g., Habitat Evaluation Procedure, UMAM; Table 3), or by assessing losses and gains every year during impacts and offset (Figure 1) from the moment impacts occur and the moment when offset measures are considered as effective with a discounted rate (Resource, Habitat, Landscape Evaluation Analysis and Habitat Evaluation Procedure).

In all cases, the only values that were calculated based on real measures of the current state of the sites are the one related to the impacted site before impact and to the offset site before offset measures. All other values (after impact or offset measures) are calculated based on predictions. Some EAMs provide a basis for such predictions (i.e. Resource, Habitat, and Landscape Evaluation Analysis), but most of the time, the user has to find a way to make predictions as accurate as possible.

3.2. Trade-off and synergies between the three EAM challenges

3.2.1. Correlations among criteria between and within challenges

The relationship between criteria and EAMs can be correctly summarized by the two first PCA axes according to the amount of variation explained by these two first axes (64%). There is no clear opposition between scores of operationality, scientific basis and comprehensiveness (calculated as the relative mean of the related criteria scores, see Appendix E), as shown with their projection on Figure 2a. However, when considering each criterion separately, negative and positive correlations between criteria related to different challenges or within a single challenge occur.

As we expected, criteria related to operationality are negatively correlated to criteria related to scientific basis and also comprehensiveness. Some of these correlations are quite intuitive and confirm what we assumed (Implementation Rapidity ~ Data Type, rho = -0.74; Data Availability ~ Data Type, rho = -0.58; and Indicator Setup ~ Biodiversity Indicator Metrics, rho = -0.87). Using large data collection leads to low implementation rapidity and low data availability. The other correlations constitute less expected results: data needed for filling in indicators with qualitative metrics is more available than for filling in indicators with quantitative metrics (Data Availability ~ Biodiversity Indicator Metrics, rho = -0.83); furthermore spatial considerations are more taken into account when assessing equivalence in a “like for like” perspective (Exchangeability ~ Spatial Consideration, rho = -0.65). As any individual criteria within scientific basis and comprehensiveness are not correlated, those challenges could be combined. Surprisingly, positive correlations also occur between criteria related to operationality and scientific basis (Implementation Rapidity ~ Biodiversity Indicators, rho = 0.66) and between operationality and comprehensiveness (Indicators Setup ~ Number of Indicators, rho= 0.64). In other terms, using scientifically based indicators do not slow down the implementation rapidity and using a set of several well adapted indicators is easier if they have been previously pre-defined.

Positive correlations between criteria related to the same challenges also occur. It is the case for three out of four criteria related to operationality (Data Availability ~ Indicators Setup, rho = 0.86; Indicators Setup ~ Implementation Rapidity, rho = 0.78; and Data Availability ~ Implementation Rapidity, rho = 0.54). This means that it is easy to combine these criteria in order to obtain a good level of operationality. However there is no positive correlation between criteria related to comprehensiveness and negative correlation for criteria related to scientific basis Biodiversity Indicator Metrics ~ Biodiversity Indicators, rho = - 0.64) implying difficulties to develop scientific basis in every aspects.

3.2.2. Groups of EAMs defined by the challenge they best achieve

The PCA highlights the existence of a few groups of EAMs characterized by similar scores for a small number of criteria. Because three criteria (out of the four) related to operationality contributed the most to axis 1, EAMs on the right side of the PCA graph on Figure 2b can be considered as operational ones (HabHect, PilotUK, SomersetHEP, UMAM, CRAM, Ökokonto, LdClEval, and FishHab). They have pre-defined indicators, are rapid to implement (less than 1 week or between 1 week and 6 months) and data used are free and quick to collect, or specific data-bases exist for these methods.

On the left side of axis 1, a group of five EAMs (HEP, PilotBBOP, HEA, REA, LEA, Figure 2b) was defined mainly by two other criteria that contribute to axis 1: BiodivIndMc (90%) and DataTp (73%) (Figure 2a). These EAMs need complex data to be implemented (data can come from the literature, GIS, simple field visits, field inventories or field monitoring and modeling) and indicators metrics can be a combination of qualitative and quantitative data (both discrete and continuous).

Criteria contributing the most to axis 2 (Figure 2a) are Uncertainty Consideration (86%) and Exchangeability (76%) on the upper side and Spatial Consideration (68%) on the lower side. Quite surprisingly, no EAM combines very well both spatial and uncertainty considerations. Furthermore, EAMs trouble making the integration of uncertainty science based: only the Canadian Fish Habitat method (isolated on axis 2 upper extremity) uses a ratio based on existing data-bases providing scientific feedbacks on previous offset measures (highest score for Uncertainty Consideration) in order to adjust the offset surface areas.

A group of three EAMs (HabHect, CRAM and LdClEval) appears clearly on Figure 2b being characterized by high scores for Spatial Consideration, meaning that spatial indicators (e.g., connectivity) are taken into account in the calculation of the compensation unit. Indeed, it make less sense to evaluate impacted and compensatory sites values within a particular landscape context when equivalence is assessed in a “like for unlike” perspective.

Finally, no group of EAMs can be characterized by high scientific basis as every criterion related to scientific basis contributes to the PCA graph in a different direction (Figure 2a) involving high scores for this challenge apportioned among EAMs.

4. Discussion

We analyzed the structure of existing EAMs and assessed the possible synergies and trade-offs between criteria underlying the way EAMs address operationality, scientific basis and comprehensiveness. The studied EAMs share a common structure to evaluate sites biodiversity and to size offset although they handle ecologic, spatial, temporal considerations and uncertainty in various ways. There is no clear trade-off in challenge achievement but some criteria within or between challenges are negatively correlated. No EAM perfectly addressed all three challenges and groups of EAMs were identified according to criteria or challenge they best achieved.

4.1. EAMs general structure

We identified three main aspects of EAMs common structure that should be considered when developing an EAM and discuss the way they could be improved.

Target biodiversity

All EAMs evaluated biodiversity losses and gains by combining biodiversity “quality” and area. Biodiversity “quality” is expressed in terms of three main components: species (e.g., threatened, endemic, patrimonial), habitat (e.g., protected ecosystems, wetlands, species habitat) and functionalities (e.g., connectivity, wetland functions). Only 5 EAMs out of 13 focus on ecosystem functionalities in addition to species and habitats, while scientists currently strongly encourage assessing biodiversity functionality, notably in order to better integrate “ordinary” biodiversity in offset processes (Regnery *et al.* 2013b). Offsetting ecosystem functionalities and “ordinary” biodiversity is also beginning to appear in offset policies: for example, the French consultative process “*Grenelle de l’Environnement*” (2007) specifies that “ordinary” biodiversity should be evaluated by Environmental Impact Assessment (EIA), notably for the role played as ecological corridors, and be compensated for if impacted (Quetier *et al.* 2014). That is why at least part of the “compensation units” should be based on ecosystems functionalities. This should be done in consistency with offset policies which influence considerably the biodiversity components targeted (e.g., the US Wetland Mitigation policy requires offset for wetlands, in Europe the Birds and Habitats Directives requires offset for specific birds species or habitats (EEC, 1992, 2009) and the offset measures outcomes (e.g., wetland functionalities restoration, species population conservation). According to the targeted biodiversity (either imposed by offset policies or chosen as best surrogate for all biodiversity) the use of "specialized" or "generalist" EAMs is more or less appropriate. Specialized EAMs seem best indicated to maximize the accuracy of equivalence assessment when impacts concern a limited geographic zone composed of a single type of ecosystem. Generalist EAMs are probably more appropriate for projects impacting biodiversity over a large area including various habitat types such as wetlands, forests, rivers, meadows, etc., in order to embrace a global view of the site's biodiversity.

Indicators

Indicators chosen as surrogates of biodiversity are at the very heart of EAMs in a sense that they enable calculation of the "compensation units" (Bekessy *et al.* 2010). Even when the same type of ecosystem is targeted, the set of indicators is different from one EAM to the other, involving various approaches of ecosystem evaluation. This is for example the case for UMAM and CRAM for wetlands, and Habitat Hectare and Land Clearing Evaluation for Australian endemic forest. Moreover, depending on the type of ecosystem evaluated, indicators can reflect one aspect more than the others: ecosystem structure (e.g., forest ecosystem in Habitat Hectare), composition (e.g., species population in Landscape Equivalency Analysis) or functionalities (e.g., wetlands functioning in UMAM). Therefore, careful consideration should be given to the choice of indicators. Notably, indicators found in specialized EAMs can hardly be used to evaluate other ecosystems; doing so would require a range of adaptations (Gaucherand *et al.* 2015). Bas *et al.* (2016) provide an example of such promising adaptation as they combined two EAMs (UMAM and HEA) into a hybrid method in order to improve offset in European marine and costal environment. Nonetheless, we recommend that indicators (for ecological, spatial but also temporal and uncertainty considerations) should be specifically selected to embrace both target biodiversity and offset policies specificities before being adapted from EAM developed in another context.

Predictions

To assess biodiversity losses and gains, predictions have to be made, since offset measures have to be sized mostly before the project can be conducted in order to obtain permits. Predictions concern biodiversity state after impact (effect of habitat destruction or fragmentation on onsite and surrounding biodiversity) and after offset (biodiversity trajectory and likelihood of offset success). The fact that half of the assessment of equivalence is based on prediction means that this assessment is far from precise, especially since accuracy of forecasting is often low. Modeling techniques (e.g., Meineri *et al.* 2015) adapted to EAMs could greatly increase efficiency in assessing losses and gains (Resource/Habitat Evaluation Analysis already requires use of modeling, although quite simple). Another way to make more accurate predictions and reduce uncertainty would be for EAM users to take advantage of feedback from previous impacts or offset measures in similar habitats or for the same species or taxa (Walker *et al.* 2004; Tischew & Kirmer 2007; Tischew *et al.* 2010). This could be achieved by drawing tendencies from data (Specht *et al.* 2015) generated by all EIA individually for a large set of projects.

4.2. Trade-offs and synergies between the three EAM challenges: why do they exist and how could they be overcome (or not)?

Based on their average scores, the EAM challenges we identified as operationality, scientific basis and comprehensiveness are not incompatible but still no EAM combines all these challenges perfectly. This is due to some trade-offs occurring between few criteria within and between challenges.

4.2.1. *Compromises tend to favor operationality*

The majority of analyzed EAMs showed high operational scores (8 out of 13 EAMs have mean scores of operationality from 64% to 85%, see Appendix E). These more operational EAMs (HabHect, PilotUK, SomersetHEP, UMAM, CRAM, Ökokonto, LdClEval, and FishHab) use a system of predefined indicators, are mostly specialized and are quick to implement. They are reproducible and easy to use but are very context dependent. For project developers, one priority is to propose offset measures that will be accepted by decision-makers, and that can be rapidly implemented at a reasonable cost (Cuperus *et al.* 2001). To this end, operational tools are needed and EAMs with predefined indicators seem therefore more suitable, with a higher likelihood of acceptance if assessment is science-based. Most EAMs having predefined indicators with a scoring system rely on rapidly collected and inexpensive (or free) data, and therefore are rapid to implement (UMAM, CRAM, Habitat Hectare, UK Pilot method). However, this can imply compromising on some criteria related to other challenges as it precludes large-scale data collection and modeling, which are elements contributing to comprehensiveness. In addition, the use of rapidly collected data implies that indicator metrics are qualitative which leads to a lower level of scientific basis. Therefore, less operational EAMs (HEP, HEA, REA, LEA, PilotBBOP) which better combine both other challenges are often used for large-scale "voluntary" offset (BBOP 2014a, 2014b) or accidental impacts (Roach & Wade 2006) which should be subject to less temporal, financial and legislative constraints than "classic" development project.

4.2.2. *Heterogeneity in the integration of scientific basis*

Trade-offs between criteria within a challenge concern especially scientific basis (EAMs have high scores for one or some criteria related to this challenge but never all of them). Depending on the context and resources, scientific basis are integrated in EAMs either through development of scientifically documented biodiversity indicators (Land Clearing Evaluation) and landscape context integration (Habitat Hectare, CRAM), or through the use of ratios reflecting uncertainty based on feedbacks (e.g., Fish Habitat). The heterogeneity in the integration of scientific basis can be explained by differences in knowledge and resources available depending on the EAMs developer organism. Developing EAMs with solid scientific basis for every criterion requires researchers to be involved in EAMs design, alongside offset stakeholders and experts. Besides, both EAMs integrating best scientific basis (BBOP pilot method and Land Clearing Evaluation, see Appendix E) included researchers in their design phase. The number of research projects focusing on improving offset design is increasing (Gonçalves *et al.* 2015) but there is still a gap between complex and technically advanced tools developed by researchers, such as software implemented for identifying important areas for connectivity (e.g., "*Graphab*", Foltête *et al.* 2012 or "*Circuitscape*", Koen *et al.* 2014) and what is actually used in practice by consultancies and developers. Therefore we strongly encourage researchers to publish or propose research tools and methods available for developers and authorities in the context of biodiversity offset.

4.2.3. *Improving synergies between scientific basis and comprehensiveness*

There are neither trade-offs nor strong synergies between criteria related to scientific basis and comprehensiveness. Existing knowledge could largely benefit to a better combination of these challenges achievement in order to better assess equivalence in the design phase of offset measures. Notably, key equivalence considerations are well identified in literature (Norton 2009;

Bull *et al.* 2013; Gardner *et al.* 2013) and science-based solutions have already been suggested to integrate delay and uncertainties in offset design (Moilanen *et al.* 2009; Laitila *et al.* 2014; Cochrane *et al.* 2015). Both ecological and spatial considerations should be addressed using the multiplicity of existing indicators covering a wide range of species and habitats (e.g., Andreasen *et al.* 2001; Biggs *et al*. 2006; Regnery *et al.* 2013d).

4.2.4. Combining operationality, scientific basis and comprehensiveness

Finally, our study aimed to identify if all challenges could be combinable in one EAM accepted by both operational and scientific spheres. One issue that affects all 3 challenges is data: operationality relies on data availability, comprehensiveness on data diversity which influences the accuracy of biodiversity assessment (e.g., species conservation status, Bensettiti *et al.* 2012), and scientific basis on data provenance (data updating is notably crucial and even more important with global changes modifying ecosystems dynamics, Vitousek *et al.* 1997). We therefore suggest one main avenue to develop EAMs combining the three challenges: the creation and use of biodiversity offset dedicated data-bases gathering relevant information concerning key equivalence considerations (e.g., risks associated to offset failure based on previous feedback) for at least species and ecosystems frequently targeted in offset procedures. In this way, EAMs implementation could be based on a large amount of data which would be available for users and which could be regularly updated with recent knowledge. This would require a certain investment both in time and money, but would also make information coming from scientific documentation available (for example ecological corridor identification based on the species dispersal ability). An important aspect remains the data interpretation, and tendencies should be established (some data could, for instance, be contradictory) so that the data is used in the most efficient way.

Such data-bases could be developed by public authorities at regional or national level (French government intend to create such data base gathering data from all EIA). Moreover, some companies (Virah-Sawmy *et al.* 2014) own a large amount of land and therefore have the possibility to offset their impacts on biodiversity on their own land. In this purpose, biodiversity issues (e.g., ecosystems maps or species lists) can better be identified in advance for their offset needs (e.g., French biodiversity observatories in alpine ski resorts). In this way, offset measures could be anticipated and launched before impacts occur to reduce time lags, and the offset site location could be made consistent with biodiversity issues improving sites integration in landscape context.

Conclusion

All studied EAMs share a general framework to assess ecological equivalence where equivalence key considerations (ecological, spatial, temporal and uncertainties) are taken into account in different ways, which influence EAMs operationality, scientific basis comprehensiveness. The analysis of these three “challenges” revealed that operationality tends to be favored in EAMs development, while there is heterogeneity in the integration of scientific basis in EAMs. No EAM is fully satisfying as none combines all challenges perfectly. One way of better combining operationality, scientific basis and comprehensiveness is to develop and use offset dedicated data-bases providing hindsight on local context and previous offset measures. The common structure underlying EAMs suggests that, even though some aspects could be improved, no better solution has yet been found. In developing EAMs, it might be useful to think “out of the box” and invent new structures. Finally, demonstrating ecological equivalence does not guaranty alone offset measures design that reaches the “no net loss” objective. Some issues related to what is really done in practice like offset long-term duration, maintenance and governance, remain of great importance.

EAM name, code and reference	Structure and Country where EAM was implemented initially	Offset policy in which EAM can be implemented	Type of impacts for which EAM can be implemented
Habitat Evaluation Procedure (HEP) (US Fish and Wildlife Service (USFWS) 1980)	US Fish and Wildlife Service, United States	US Conservation Banking	Development project impacting terrestrial or aquatic biodiversity
Resource and Habitat Equivalency Analysis (REA / HEA) (NOAA 1995, 1997)	National Oceanic and Atmospheric Administration, United States	Damage Assessment and Restoration Program	Accidental impacts on biodiversity
Canadian method Fish Habitat (FishHab) (Minns *et al.* 2001)	Department of Fisheries and Oceans, Canada	Canada's National Fish Habitat Compensation Program	Development project impacting lacustrine habitats
Habitat Hectare (HabHect) (Parkes *et al.* 2003)	Victorian Department of Natural Resources and Environment, Australia	BushBroker Program	Projects impacting native vegetation.
Uniform Mitigation Assessment Method (UMAM) (State of Florida 2004)	Florida Department of Environmental Protection, United States	US Wetland and Stream Mitigation Banking	Development project impacting wetlands and wetlands mitigation banks
Landscape Equivalency Analysis (LEA) (Bruggeman *et al.* 2005)	Department of Fisheries and Wildlife, Michigan State University, United States	US Conservation Banking	Credits for endangered species mitigation banks
BBOP pilot method (PilotBBOP) (Business and Biodiversity Offsets Programme (BBOP) 2009)	Business and Biodiversity Offsets Programme, international	Every non-constraining offset policy	Development project impacting biodiversity
Land Clearing Evaluation (LdClEval) (Gibbons *et al.* 2009)	New South Wales Government, Australia	BioBanking	Proposals to clear native vegetation
German Ökokonto (Ökokonto) (Darbi & Tausch 2010)	Baden-Württemberg Region, Germany	Nature Conservation Law	Development project impacting biodiversity
Californian Rapid Assessment Method (CRAM) (California Wetlands Monitoring Workgroup (CWMW) 2013)	California Wetlands Monitoring Workgroup, United States	US Wetland and Stream Mitigation Banking	Development project impacting wetlands and wetlands mitigation banks
Pilot method in United Kingdom (PilotUK) (Department for Environment, Food & Rural Affairs 2012)	Department for Environment, Food & Rural Affairs, England	UK Environmental Impact Assessment	Development project impacting terrestrial biodiversity
Somerset Habitat Evaluation Procedure (SomersetHEP) (Burrows 2014)	Somerset County Council. England	National Planning Policy Framework (NPPF)	Development project impacting terrestrial biodiversity

Table 1: Context of selected EAMs implementation

Table 2: Description of criteria related to operationality, scientific basis and comprehensiveness and working hypothesis underlying criteria choices.

EAM challenge	Criteria	Description and working hypothesis
Operationality (Op)	Indicators set up (IndSetup)	The way indicators are defined in the method. Predefined indicators make EAMs more standardized and lead to repeatable and comparable equivalence evaluation (Quétier & Lavorel 2011).
	Data availability (DataAv)	Level of data cost and time to collect data that are needed to fill in indicators. Inexpensive and rapid to collect data will provide more guaranties that EAMs will be widely used than expensive and long to collect data (a parallel can be drawn with river health assessment (Boulton 1999)
	Implementation rapidity (ImpRp)	Cumulative time needed to both collect data and implement EAMs. Rapid method implementation notably reduces the risk of biodiversity losses related to delay in offset measures design (Bas *et al.* 2016). .
	Exchangeability (Exchg)	EAMs adaptation to allow a certain degree of exchangeability between biodiversity impacted and compensated (*like for like* or *like for unlike* offset). Developers have more flexibility in designing offsets with *like for unlike* (or *similar*) offsets (Quétier & Lavorel 2011; Quétier *et al.* 2014; Bull *et al.* 2015).
Scientific basis (ScBs)	Biodiversity indicators (BiodivInd)	On which basis biodiversity indicators were set up in EAMs. The use of indicators based on defensible scientific documentation provides more guaranties that biodiversity evaluation is rigorous (indicator has been demonstrated to be a good surrogate of targeted biodiversity component) and consensual (there is a global agreement among scientific community) (McCarthy *et al.* 2004; Gonçalves *et al.* 2015).
	Biodiversity indicator metrics (BiodivIndMc)	Type of metrics (qualitative, quantitative discrete or continuous) used to inform biodiversity indicators. Quantitative metrics (e.g. number of bat species, height of vegetation) give losses and gain calculation more accuracy and transparency (Noss 1990) whereas qualitative metrics are more subject to interpretation bias and subjective judgment.
	Spatial consideration (SpCd)	The way spatial consideration (impacted or compensatory sites insertion in landscape) is taken into account in the method. Measuring landscape components (connectivity, fragmentation…) with appropriate indicators is essential for integrating the effect of surrounding landscape on sites biodiversity (e.g. significance of species richness) to losses and gain comparison (Quétier & Lavorel 2011; Gardner *et al.* 2013).
	Uncertainty consideration (UnCd)	The way uncertainty (probability of offset failure) is taken into account in the method. As all offsets have a chance of failing to meet expectations, uncertainty can be considered by weighting gains calculation according to the probability of offset success (Moilanen *et al.* 2009). In this purpose, using of area-based offset multipliers is frequent but they are relevant only when based on feedbacks about previous offset measures (Tischew *et al.* 2010).
Comprehensiveness (Comp)	Key equivalence considerations (EqCd)	Number of key equivalence considerations (ecological, spatial, temporal, uncertainty) taken into account in the method. These four considerations have been identified in the literature to be essential when calculating equivalence in order to design offset achieving “no net loss” (Moilanen *et al.* 2009; Quétier & Lavorel 2011; Bull *et al.* 2013; Gardner *et al.* 2013)
	Target Biodiversity (TgBiodiv)	Target biodiversity components evaluated in EAMs. In order to capture biodiversity complexity, losses and gains should be evaluated for a maximum of biodiversity components: species populations, ecosystems (or habitats) and functionalities (Noss 1990; Pereira *et al.* 2013).
	Data type (DataTp)	Type of data needed to fill in indicators (data from literature, GIS, simple field visit, inventories…). Using all kind of data provides various types of information at different scales and accuracy leading to a more comprehensive losses and gains assessment.
	Number of indicators (NbInd)	Number of indicators used to evaluate biodiversity at impacted and compensatory sites. The multidimensional nature of biodiversity makes it complicated to evaluate and using one single indicator (or proxy) has been demonstrated to be insufficient (Bull *et al.* 2013). Multiple indicators are preferable to capture a maximum of biodiversity components (diversity, functionality…) (Andreasen *et al.* 2001).

Table 3: Key equivalence considerations taken into account in EAMs and "compensation unit" used.

EAM name and code	Key Ecological Equivalence Considerations				Metric used as "compensation unit" for losses and gains calculation
	Ecological: What is the target biodiversity?	**Spatial:** How does EAM take into account landscape context?	**Temporal:** How does EAM take into account interim losses?	**Uncertainty**: How does EAM take into account risk of offset failure?	
Habitat Evaluation Procedure (HEP) (US Fish and Wildlife Service (USFWS) 1980)	Suitable habitat for species population (HSI)	No general rule, consideration treated on a case by case basis.	HSI is calculated for each year of the analysis	No general rule, consideration treated on a case by case basis.	***Habitat Unit (HU)=****HSI* habitat areal extent* HSI is the observed indicator compared to the optimal condition.
Resource and Habitat Equivalency Analysis (REA / HEA) (NOAA 1995, 1997)	Habitat resource (e.g., species population) or service (e.g., primary production)	No general rule, consideration treated on a case by case basis.	Resource or service is calculated for each year of the analysis, and at least during all impact duration, and until offset effectiveness.	No general rule, consideration treated on a case by case basis.	***Discounted Resource/ Service Acre Year*** *= proxy value * discounted rate * site area*
Canadian method Fish Habitat (FishHab) (Minns *et al.* 2001)	Lacustrine habitats condition for fish productivity	No general rule, consideration treated on a case by case basis.	Not taken into account in offset sizing	No general rule, consideration treated on a case by case basis.	***Habitat Suitability Index (HIS)*** as surrogate of fish habitat productivity. Calculated from an Habitat Suitability Matrix (HSM) model
Habitat Hectare (HabHect) (Parkes *et al.* 2003)	Native vegetation condition	Indicators of landscape context	Not taken into account in offset sizing	No general rule, consideration treated on a case by case basis.	***Habitat Hectare****=Habitat Score (HS) * site area* HS is the sum of each indicator score
Uniform Mitigation Assessment Method (UMAM) (State of Florida 2004)	Wetland integrity and functionality	Indicators of landscape context and location	Multiplier to size offset related to offset effectiveness delay.	Multiplier to size offset related to probability of offset success	***Delta****= mean of the three indicators final category score* Indicators are scored from 0 to 10 (10 is the benchmark)
Landscape Equivalency Analysis (LEA) (Bruggeman *et al.* 2005)	Species population	Species population is modeled for different landscape evolution scenarios.	Species population is calculated for each year of the analysis.	No general rule, consideration treated on a case by case basis.	***Discounted Landscape Service Year*** *= indicator value * discounted rate*
BBOP pilot method (PilotBBOP) (Business and Biodiversity Offsets Programme (BBOP) 2009)	"Key biodiversity component"	Spatial indicators (e.g. connectivity) related to the site "key biodiversity component"	No general rule, consideration treated on a case by case basis.	Multiplier to size offset related to offset success probability and offset effectiveness	***Habitat Hectare****=Habitat Score * site area* Habitat score is the sum of all indicator values
Land Clearing Evaluation (LdClEval) (Gibbons *et al.* 2009)	Native vegetation condition	Landscape Value calculated with indicators of site insertion in the landscape.	Not taken into account in offset sizing	No general rule, consideration treated on a case by case basis.	***Site Value*** ***Landscape Value*** ***Regional Value*** Calculated with predefined indicator scores
German Ökokonto (Ökokonto) (Darbi & Tausch 2010)	Biotope naturalness, distinctiveness and role for endangered species	No general rule, consideration treated on a case by case basis.	Not taken into account in offset sizing	Probability of offset success taken into consideration in the biotope value	***Biotope value*** *in EcoPoints/m²*

Californian Rapid Assessment Method (CRAM) (California Wetlands Monitoring Workgroup (CWMW) 2013)	Wetland integrity and functionality	Indicators of buffer and Landscape Context	Not taken into account in offset sizing	No general rule, consideration treated on a case by case basis.	***CRAM Scores*** *= sum of each indicator's final category score* Indicators are scored from 3 to 12 (12 is the benchmark)
Pilot method in United Kingdom (PilotUK) (Department for Environment, Food & Rural Affairs 2012)	Habitat condition and distinctiveness.	Multiplier to size offset related to offset location compared to impacts (i.e., same ecological network)	Multiplier to size offset related to offset effectiveness delay.	Multiplier to size offset related to probability of offset success	***Habitat Hectare****=Habitat Score * site area* Habitat Score=Condition* Distinctiveness
Somerset Habitat Evaluation Procedure (SomersetHEP) (Burrows 2014)	Suitable habitat for species population.	Multiplier (Density Band) takes into account impacted site location from a species distribution point of view.	Multiplier to size offset related to offset effectiveness delay.	Multiplier to size offset related to probability of offset success	***Habitat Unit (HU)*** *= (HSI* Density Band)*Area* HIS is calculated with predefined scores for habitat, matrix, formation and management.

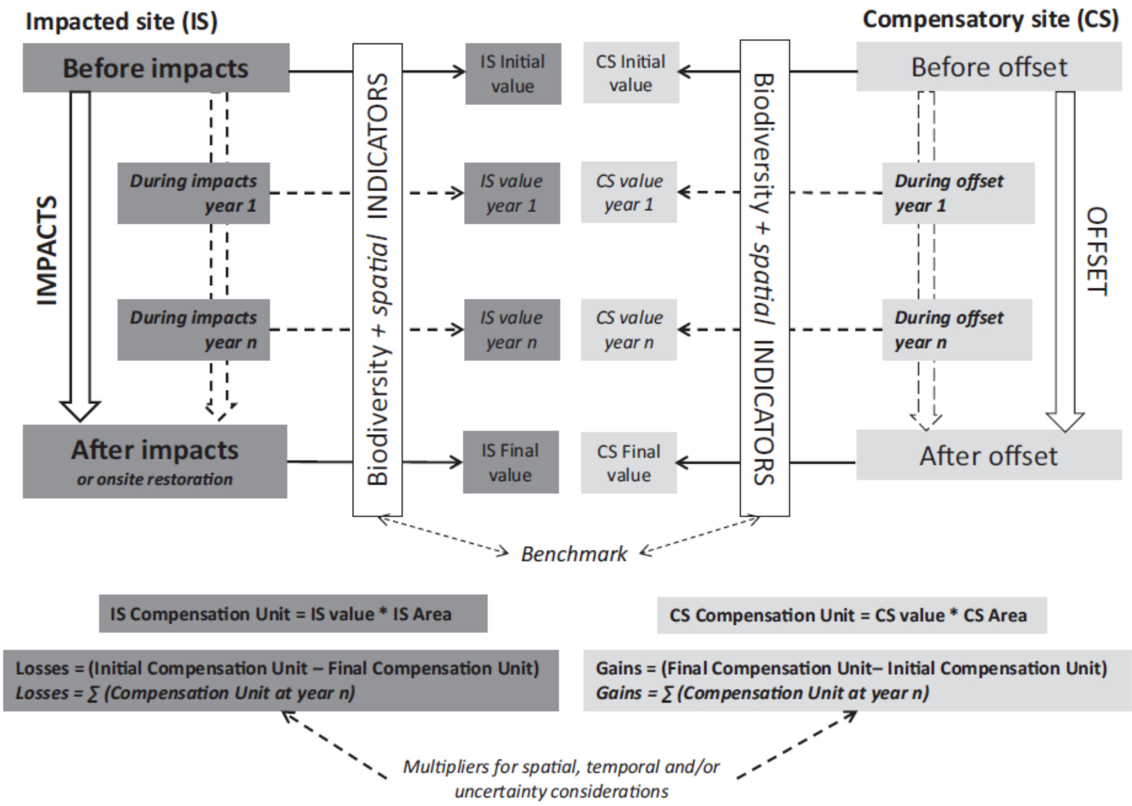

Fig 1: Equivalence Assessment Method (EAM) general structure. Two sites are considered: the impacted site (dark grey boxes) and the potential offset site (light grey boxes). Site values are calculated for each site (center boxes) thanks to various indicators, and "compensation units" are obtained by multiplying these values by the site areas. Solid arrows and regular font correspond to features shared by most EAMs. Dotted arrows and italics correspond to main options for EAMs.

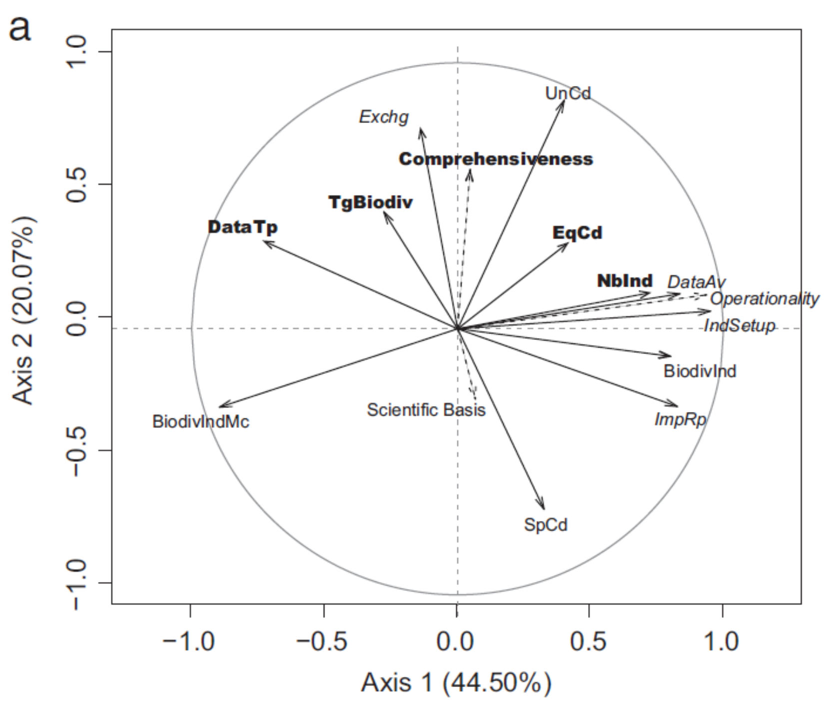

Fig 2a*:* Principal Component Analysis (PCA) variable graph. Criteria relative to operationality are in italic, criteria relative to scientific bases are in regular and criteria relative to comprehensiveness are in bold. Average scores for each challenge (Operationality, Scientific Basis and Comprehensiveness) are represented with dotted arrows.

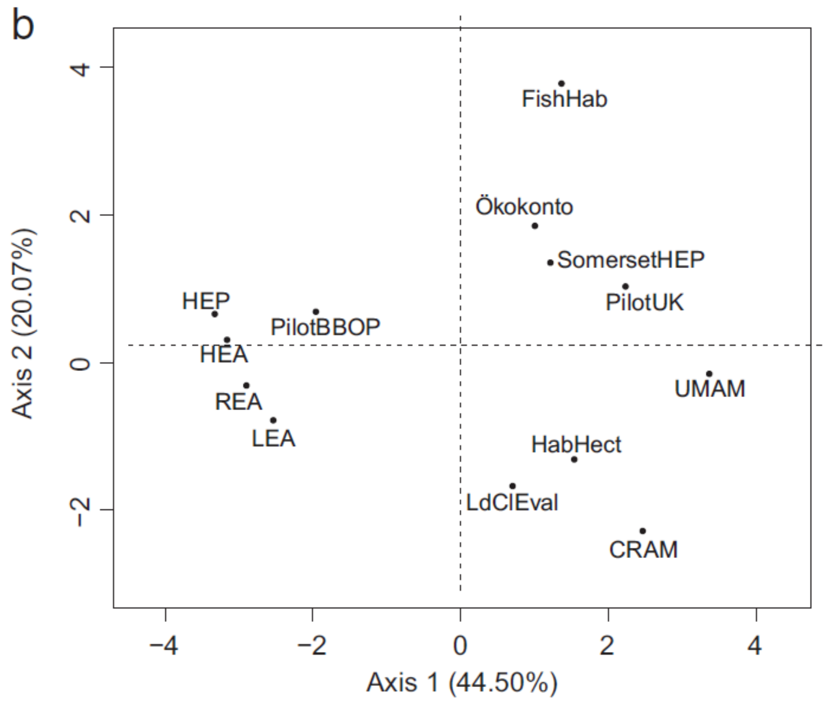

Fig 2b*:* Principal Component Analysis (PCA) individuals graph.

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Supplementary material

<u>Appendix A</u>: EAMs description

- **Synthetic table**

EAM	Year of EAM development	Structure and country	Biodiversity targeted and "compensation unit"	Key equivalence considerations taken into account		
				Spatial	Temporal	Uncerta inties
Habitat Evaluation Procedure	1976	US Fish and Wildlife Service, USA	Species population terrestrial habitats Habitat Unit (HU	No	Yes	No
Resource and Habitat Equivalency Analysis	1994	National Oceanic and Atmospheric Administration, USA	Terrestrial habitat resource / service Discounted resource/service year	No	Yes	No
Canadian method Fish Habitat	2001	Department of Fisheries and Oceans, Canada	Lacustrine fish habitats Habitat Suitability Index	No	No	No
Habitat Hectare	2003	Victorian Department of Natural Resources and Environment, Australia	Australian vegetation Habitat Hectare	Yes	No	No
Uniform Mitigation Assessment Method	2004	Florida Department of Environmental Protection, USA	Florida wetlands Delta	Yes	Yes	Yes
Landscape Equivalency	2005	Endangered species banking agencies, USA	Species metapopulations Discounted landscape service year	Yes	Yes	No
BBOP pilot method (PilotBBOP)	2009	Business and Biodiversity Offsets Programme, international	Terrestrial habitats Habitat Hectare	Yes	No	Yes
Land Clearing Evaluation	2009	New South Wales Government, Australia	Australian vegetation Site Value, Landscape Value and Regional Value	Yes	No	No
German Ôkokonto	2010	Consultancies, Gerrmany	Terrestrial habitats Biotope Value	No	No	Yes
Californian Rapid Assessment Method	2006	California Wetlands Monitoring Workgroup, USA	California wetlands CRAM Score	Yes	No	No
Pilot method in United Kingdom	2011	Department for Environment, Food & Rural Affairs, UK	Terrestrial habitats Habitat Hectare	Yes	Yes	Yes
Somerset Habitat Evaluation Procedure	2014	Somerset County Council, England	Terrestrial habitats Habitat Unit	Yes	Yes	Yes

- **Habitat Evaluation Procedure** (US Fish and Wildlife Service (USFWS) 1980)

The Habitat Evaluation Procedure (HEP) was developed in the late seventies in USA by the US Fish and Wildlife Service, in order to calculate comparable Habitat Units (HUs) and use them as a basis for sizing optimal offsets. This EAM focuses on habitats. It is stipulated in HEP that an area can have various habitats (with measurable areal extents) and that they can have different suitability for species that may occur in that area. The habitat suitability is quantified in HEP via Habitat Suitability Index Models (HSIs).
To calculate HSIs, user has first to select species of interest (they can be patrimonial and endangered species, umbrella species etc. depending on the issues on the site). Then, for each species, a HIS has to be chosen to best reflect species condition in its habitat (or the habitat suitability for this species). It must be in an index form:

$$Index\ value\ = \frac{Value\ of\ interest}{Standard\ of\ comparaison}$$ so for an HSI it will be:

$$HSI = \frac{Study\ area\ habitat\ condition}{Optimum\ habitat\ condition}$$

The “Optimum habitat condition” is a benchmark found in literature or measured in the field. Metrics for “Study area habitat condition” can be for example species abundance or biomass/unit area, but must reflect the habitat suitability for this species.

The next step consists in calculating cumulative Habitat Units (HU’s) for the species, for each year of the evaluation (e.g. each year of project):

$$Cumulative\ HU's = \sum_{i=1}^{p} HSI_a * habitat\ areal\ extent_a$$

Where:
HSI_a is the species’ HSI at year i
$areal\ extent_a$ is the area of available habitat for species at the year i. It is calculated in different ways depending whether the species habitat include only one vegetation cover type, or more than one. There three possibilities: (i) species habitat includes one cover type (e.g. forest), (ii) species habitat includes several cover types, but each one provides all of species requirements (i.e. shelter, food), (iii) species habitat includes several cover types, but each one provides only one species requirement (e.g. forest/shelter and meadow/food).
If HSI value is not available for every year, user can decompose the period of analysis in smaller period and calculate Cumulative HU with a specific formula.

Finally, Average Annual Habitat Units (AAHU’s) are calculated as follow for each year of the evaluation (e.g. each year of project):

$$Average\ Annual\ Habitat\ Units\ (AAHU's) = \frac{Cumulative\ HU's}{Period\ analysis\ number\ of\ years}$$

This value is the one used in the losses and gains calculation, as follow:

$$Losses\ or\ Gains\ \ = AAHU's_{with} - \ AAHU's_{without}$$

Where:
$AAHU'_{with}$ is the AAHU’s for the impacted site or the compensatory site with impact or offsets.

$AAHU'_{without}$ is the AAHU's for the impacted site or the compensatory site without impact or offsets (initial state of area before impact and before offsets).

This evaluation takes into consideration the natural evolution of both impacted and compensatory site (without any impact or offset).
There are two main equations to size offsets, depending on the compensation goal:
-<u>In-kind</u>: the HU lost are offset for each evaluation species (the list of target species is identical to the list of negatively impacted species).

$$Optimum\ compensation\ area = -A * \frac{\sum_{i=1}^{n} Losses(i) * Gains(i)}{\sum_{i=1}^{n} Gains(i)^2}$$

-<u>Equal replacement</u>: the HU lost are offset through a gain of an equal number of HU's (the list of target species may or may not be identical to the list of negatively impacted species).

$$Optimum\ compensation\ area = -A * \frac{\sum_{i=1}^{n} Losses(i)}{\sum_{i=1}^{n} Gains(i)}$$

Where:
A is the size of candidate compensation study area
i is the species number, and *n* is the total number of identified species.

- **<u>Resource and Habitat Equivalency Analysis</u>** (NOAA 1995, 1997)

Resource Equivalency Analysis (REA) and Habitat Equivalency Analysis (HEA) are EAMs developed initially to size offset for accidental impacts on resource (REA) or service (HEA) (i.e. oil spill on salt marsh) by the National Oceanic and Atmospheric Administration, in the United States. These EAMs are based on two restoration actions: one primary restoration on the impacted site, and one compensatory restoration on the compensatory site. The latest aims to offset the impacted site's interim losses. Only one proxy is needed to represent the level of resource or service lost.
In REA, it is understood by "resource" a particular species population. So the proxy chosen by the user can be abundance for example. In HEA, it is understood by "service" a particular function of a habitat. The proxy is also chosen by the user and can be the primary productivity of salt marsh for example.
First, user has to determine the benchmark, which is the level of resource or service on the impacted site before the accident occurred. Then, losses are calculated according to a "recovery function" representing the evolution of resource or service level from the accident to the benchmark on the impacted site with primary restoration. The same way, gains are calculated according to a "maturity function" representing the evolution of resource or service level from the beginning of offsets to the benchmark for the compensatory site. Losses and gains are calculated each year for a certain amount of time, which at minimum must last until the level of resource or service has reached the benchmark. A discounted rate is used in these EAMs in order to take in consideration the relation the public has with the resource or service losses and gains. In Environmental policies, this discounted rate is often 3% (Commissariat Général du Développement Durable (CGDD) 2011). With the application of a discounted rate, losses have an increasing value over time, and in the contrary, gains have a decreasing value over time.

Losses and gains are calculated as follow (the unit is discounted resource or service acre year).

$$Losses = \sum_{n=i}^{b} (R_t * D) * area_1$$

$$Gains = \sum_{n=j}^{b} (R_t * D) * area_2$$

Where:
i is the year when primary restoration starts on the impacted site (area 1)
j is the year when offsets start on the compensatory site (area 2)
b is the year when the calculation is stopped (benchmark level have to be reached).
R is the % of resource or service lost or gained compared to the benchmark in average at the nth year.
D is the discounted rate

Ecological equivalence is achieved when losses = gains.
The equations to size offsets that achieve equivalence is as follow:

$$Area_2 = \frac{\sum_{n=i}^{b} (R_t * D) * area_1}{\sum_{n=j}^{b} (R_t * D)}$$

- **<u>Canadian method Fish Habitat</u>** (Minns *et al.* 2001)

In Canada, the Department of Fisheries and Oceans provide tools for managing and protecting Canada's fishery resources. Section 35 of the Fisheries Act is a general prohibition forbidding the Harmful Alteration, Disruption or Destruction (HADD) of fish habitats. If all mitigation measures cannot prevent a HADD, an authorization is required and proponents are then obligated to develop a set of compensatory actions that will result at least in no net loss of fish productivity. The Fish Habitat method is an EAM allowing to size offset so they can achieve no net loss. The method is mainly intended to be used to assess development projects occurring in large inland lakes. It involves the use of a "Habitat Suitability Matrix" (HSM) model implemented as a software package with many features (but regulatory users only use basic elements).

"*The essence of the approach is the idea that the habitat preferences of individual fish species and life stages can be quantified and aggregated into habitat suitability indices* [HSI] *that in turn can be used as surrogate measures of fish habitat productivity*" (Minns *et al.* 2001). To calculate HSI's, the HSM model uses pooled matrices representing the aggregate habitat preferences of many species. Species lists are identified and are grouped by life stage, trophic level regime and thermal preference. HIS values are generated for specific combinations of water depth, substrate and vegetation cover that can be assigned to individual habitat patches. HIS values range between 0 and 1, which represent a percentage of the benchmark (1 is the benchmark value).
HIS's as surrogates of fish productivity are calculated for three areas:
-the area of habitat lost due to development activity (A_{Loss})
-the area modified, directly and indirectly, as a result of the development activity (A_{Mod})
-the area created or modified elsewhere to compensate for the development activity (A_{Comp})

To achieve ecological equivalence, the result of the following equation has to be neutral (no net loss of biodiversity) or positive (net gain):

$$\Delta P_{now} = [(P_{Mod} - P_{Now}) * A_{Mod}] - (P_{Max} * A_{Loss}) + [(P_{Com} - P_{Now}) * A_{Com}]$$

Where:
ΔP_{now} is the net change of natural productivity of fish habitat
P_{Max} is the maximum potential unit area productivity rate (or productive capacity)
P_{Now} is the present unit area productivity rate
P_{Mod} is the modified unit area productivity rate in affected areas
P_{Com} is the compensation unit area productivity rate in affected areas.

- **<u>Habitat Hectare</u>** (Parkes *et al.* 2003)

The "Habitat Hectare" approach has been first developed by (Parkes *et al.* 2003) for the Victorian Department of Natural Resources and Environment in Australia. Here we will name "Habitat Hectare" this particular EAM, even though other EAMs are based on the same principle (e.g. UK pilot method, BBOP pilot method). This principle consists in multiplying a value reflecting the quality of the site with the site area.

Habitat Hectare focuses on terrestrial biodiversity related to native vegetation. A site is evaluated according to several indicators (listed below), some related to the site condition, and others related to landscape context. Each indicator is scored as a percentage of a benchmark (Pre-European vegetation condition). A pre-defined weight is attributed to each indicator. The sum of all indicators maximal values equals 100.

Indicators and their maximal scores:

Site condition	Large trees	10
	Tree (canopy) cover	5
	Understorey (non-tree) strata	25
	Lack of weeds	15
	Recruitment	10
	Organic litter	5
	Logs	5
Landscape context	Patch size	10
	Neighbourhood	10
	Distance to core area	5

The site final score is called the "Habitat Score" (HS) and it is calculating summing all indicators scores. It must be multiplied by the site area (in hectare). Four Habitat Scores are calculated:

HS_A for the current score of the habitat that will be impacted (area 1)

HS_B is the predicted score for the habitat after impacts (area 1)

HS_C is the current score of the habitat proposed for offsets (area 2)

HS_D is the predicted score of the habitat after offsets (area 2)

Ecological equivalence is achieved when:

$(HS_A * area_1) - (HS_B * area_1)$ (losses) = $(HS_D * area_2) - (HS_C * area_2)$ (gains).

The equations to size offsets that achieve equivalence is:

$$Area_2 = \frac{HS_A * area_1 - HS_B * area_1}{HS_D - HS_C}$$

This calculation has to be done for each impacted habitat.

- **<u>Uniform Mitigation Assessment Method</u>** (State of Florida 2004)

The Uniform Mitigation Assessment Method (UMAM) is a "rapid assessment method" developed specifically for Florida's wetlands in order to assess their functionality.

Indicators are predefined and classified in three categories:

-*Location and landscape*

8 indicators

-*Hydraulic environment*

12 indicators

-*Community structures*

Vegetation and structural habitat

10 indicators

Benthic and Sessile Communities"

7 indicators

User have to score each indicator between 0 and 10 depending on the indicator condition (the guidance help the user defined it). An average score is calculated by category and the average of these score is the site final score called Delta. Four Deltas are calculated.

Δ_A for the current score of the site that will be impacted (area 1)

Δ_B is the predicted score for the site after impacts (area 1)

Δ_C is the current score of the site proposed for offsets (area 2)

Δ_D is the predicted score of the site after offsets (area 2)

The method includes two multipliers for gains calculation:

-the *T-factor* reflects the time lag associated with mitigation (the period of time between when the functions are lost at an impact site and when those functions are replaced by the mitigation), and the additional mitigation needed to account for the deferred replacement of wetland or surface water functions. It determined with a correspondence grid between years and scores.

-The mitigation *risk*, evaluated to account for the degree of uncertainty that the proposed conditions will be achieved, resulting in a reduction in the ecological value of the mitigation assessment area. The risk is scored on a scale from 1 (for no or de minimus risk) to 3 (high risk), on quarter-point (0.25) increments.

Losses and gains are calculated as follow:

$$Losses = (\Delta_A - \Delta_B) * area_1$$

$$Gains = \left[\frac{(\Delta_D - \Delta_C)}{T-factor * risk}\right] * area_2$$

Ecological equivalence is achieved when losses = gains

The equations to size offsets that achieve equivalence is as follow:

$$Area_2 = \frac{(\Delta_A - \Delta_B) * area_1}{(\Delta_D - \Delta_C)} * (T - factor * risk)$$

- **Landscape Equivalency Analysis** (Bruggeman *et al.* 2005)

This EAM has been developed to calculate ecological credit for species mitigation bank in the United States. It is elaborated on the same principles than REA and HEA. The method aim to assess a landscape conservation value (service) for metapopulation, evaluated through two main indicators: abundance and genetic variance. Those indicators are calculated for three landscape evolution scenario. A landscape is modeled as "*habitat patches* [which] *are distinguished by greater habitat quality than surrounding areas. Area outside of the habitat patch that allow low occupancy rates (lower habitat quality) are classify as the matrix*" (Bruggeman *et al.* 2005). As in REA and HEA, a discounted rate is used.

Abundance and genetic variance are modeled for:

-the B scenario (benchmark) where there is no habitat loss

-the M scenario (mitigation) where a conservation bank is added

-the W scenario (withdrawal) where impacts sites in the landscape require the withdrawal of credit from the mitigation bank (several choices are possible).

Ecological credits (E) for conservation bank are calculated as follow (the unit is discounted landscape service year): With the abundance indicator:

$$E = \sum_{t=i}^{x} \frac{1}{(1+D^2)} \left(\frac{Nm_t - Nw_t}{Nb_t}\right)$$

With the genetic variance indicator:

$$E = \sum_{t=i}^{x} \frac{1}{(1+D)} \left(\frac{Gb_t - Gw_t}{Gb_t}\right) - \sum_{t=c}^{x} \frac{1}{(1+D)} \left(\frac{Gb_t - Gm_t}{Gb_t}\right)$$

Where:
i is the year when impacts occurred and when credits are bought to a conservation bank.
x is the year when calculation is stopped
Nb, Nw and Nm are the abundance calculated in scenario B, W and M respectively, in average for the tth year
Gb, Gw and Gm are the abundance calculated in scenario B, W and M respectively, in average for the tth year
D is the discounted rate

The credits are calculated so that the "*landscape configurations that provide equivalent levels of services despite changes in landscape structure that result from losing a patch or changing matrix quality*" (Bruggeman *et al.* 2005).

- **BBOP pilot method** (Business and Biodiversity Offsets Programme (BBOP) 2009)

The BBOP has proposed a methodology detailed in the *Biodiversity Design Offset Handbook* Apendix C. It has been designed for voluntary biodiversity offsets, and it based on "Habitat Hectare" principles. There are two versions of the method, one focusing on habitats, and the other focusing on species. It is recommended to use in priority the habitat version and the species version as a complement. All terrestrial habitats can be assessed.
For the habitat version, no indicators are imposed, they are to the choice of user, but the methodology provides guidance in this choice. The 10 to 20 indicators used to assess both impacted and compensatory sites have to be chosen according to ecological, spatial (e.g. connectivity), political (e.g. protected species) and social (e.g. emblematic species) issues. First, they have to be informed for a "benchmark area", chosen as well by the user for its ideal habitat condition. Each indicator value found in the "benchmark area" will be its maximum value. Each indicator has also to be weighted depending on the importance it has in the habitat assessment (the sum of weights equals 100).
Four Habitat Scores are calculated.
HS_A for the current score of the site that will be impacted (area 1)
HS_B is the predicted score for the site after impacts (area 1)
HS_C is the current score of the site proposed for offsets (area 2)
HS_D is the predicted score of the site after offsets (area 2)

$$HS_A = \sum_{n=1}^{x} [\left(\frac{V_A}{V_b}\right) n * C_n]$$

$$HS_B = \sum_{n=1}^{x} [\left(\frac{V_B}{V_b}\right) n * C_n]$$

$$HS_C = \sum_{n=1}^{x} [\left(\frac{V_C}{V_b}\right) n * C_n]$$

$$HS_D = \sum_{n=1}^{x} [\left(\frac{(V_D * L) + V_D}{V_b} \right) n * C_n]$$

Where:
x is the number of chosen indicators
V_A, V_B, V_C, V_D are the values of the nth indicator
C_n is the weight of the nth indicator
L is the % of the nth indicator increase thanks to offset * offset success probability

Ecological equivalence is achieved when:
$(HS_A * area_1) - (HS_B * area_1)$ (losses) = $(HS_D * area_2) - (HS_C * area_2)$ (gains).

The equations to size offsets that achieve equivalence is as follow:

$$Area_2 = \frac{HS_A * area_1 - HS_B * area_1}{HS_D - HS_C}$$

This calculation has to be done for each impacted habitat.

For the species version, only one indicator has to be chosen, representing the species population (e.g. abundance). A benchmark value is also fixed. The calculation is the same as the one in the habitat version.

- **Land Clearing Evaluation** (Gibbons *et al.* 2009)

The Land Clearing Evaluation (LCE) is the EAM behind the calculation of credits in the context of Biobanking in the New South Wales state in Australia (Department of Environment Climate Change and Water 2009).
LCE focuses on terrestrial biodiversity related to native vegetation which will be cleared. A site (whether a proposal site for clearance or a biobank site) is evaluated according to three values: the Regional Value (RV), the Landscape Value (LV) and the Site Value (SV). RV represents the site conservation significance of vegetation at the regional scale. The two latest are calculated using native vegetation biodiversity variables, scored as a percentage of a benchmark (Pre-European vegetation condition). The score goes from 0 to 3 according in which category the variable is. A pre-defined weight is attributed to each variable.
Each value calculation is detailed as follow:

- **Regional Value**:

It is the same equation for both clearing and offset sites.

$$RV = \sum_{z=1}^{n} [\left(1 - \left(\frac{R}{100}\right)^{0.25}\right) * \left(\frac{zone\ area}{total\ area}\right) * 100]$$

Where:
z is a zone with the same vegetation type and the same condition
R is the per cent of the vegetation type in the zth zone that is remaining relative to its predicted pre-European distribution

- **Landscape Value**:

The variables used are listed below. Each variable is scored from 0 to 3 according to which category its value stands.

Variables:

(1) % Cover of native vegetation within a 1.75 km radius of the site (1000 ha)

(2) % Cover of native vegetation within a 0.55 km radius of the site (100 ha)

(3) % Cover of native vegetation within a 0.2 km radius of the site (10 ha)

(4) Connectivity value

(5) Total adjacent remnant area

(6) % Within riparian area

$$LV_{clearing\ site} = \sum_{v=1}^{5}(S_v * W_v)_{current} - \sum_{v=1}^{4}(S_v * W_v)_{with\ proposed\ clearing}$$

$$LV_{offset\ site} = \sum_{v=1}^{6}(S_v * W_v)_{with\ proposed\ clearing\ and\ offsets} - \sum_{v=1}^{4}(S_v * W_v)_{with\ proposed\ clearing}$$

Where:

S_v is the score for vth variable (1-6)

W_v is the weighting for the vth variable (1-6)

- **Site Value:**

The variables used are listed below. Each variable is scored from 0 to 3 according to which category its value stands.

Variables:

(a) Native plant species richness

(b) Native over-storey per cent cover

(c) Native mid-storey per cent cover

(d) Native ground per cent cover (grasses

(e) Native ground per cent cover (shrubs)

(f) Native ground per cent cover (other)

(g) Exotic plant per cent cover

(h) Number of trees with hollows

(i) Proportion of over-storey species occurring as regeneration

(j) Total length of fallen logs

It is the same equation for both clearing and offset sites.

$$SV = \sum_{Z=1}^{x}\left(\frac{\sum_{n=a}^{j}(S_v * Wv) + A\left[(S_a * S_g) + (S_b * S_i) + (S_h * S_j) + (S_c * S_k)\right] * 100}{C} * zone\ area \right)_z$$

Where:

z is a zone with the same vegetation type and the same condition

S_v is the score for vth variable (a-j)

W_v is the weighting for the vth variable (a-j)

A is a constant weighting given to the interaction terms (authors used 5)

k = (sd + se + sf)/3

c is the maximum score that can be obtained given the variables that occur in the benchmark for the vegetation type

zone area is the total area of the nth vegetation zone in hectares.

Clearance is accepted only if the gain in each value on offset site is higher or equal than the losses in each value on clearing site (meaning if ecological equivalence is achieved):

$$RV_D \geq RV_A$$
$$LV_{offset\ site} \geq LV_{clearing\ site}$$
$$SV_D - SV_C \geq SV_A - SV_B$$

Where:
A is the current value of site proposed for clearing
B is the predicted value of site after proposed clearing
C is the current value of site proposed for offsets
D is the predicted value of site proposed for offsets.

The equations, metrics and variables detailed here, as well as the data that underpinned them, were codified into a computer software tool to facilitate LCE application for users.

- **German method *Ôkokonto*** (Darbi & Tausch 2010)

In Germany, mitigation modalities are settled in each Land for five environmental components: biotopes and species, water, soil, landscape, and air and climate. The general mitigation method is called Ôkokonto (it is not the only mitigation method used in Germany). Here the modalities for the Bade-Wurtemberg Land are detailed for the biotopes and species component. The method focuses on biotopes, with the assumption that species can be protected through their habitat protection. In Germany, a biotope is a uniform geographic unit from a vegetation typology and/or landscape point of view. The *Ökokonto-Verordnung* decree indexes and classifies the Land's biotopes (with a total of 223).
Each biotope is classified according to:
-a "normal" value expressed in EcoPoints/m² corresponding to the average biotope's condition
-a value range allowing to take into account the changing biotope's condition
In reality, there are two sets of value range with a "normal" value: one called "realistic" and the other elaborated to take into account certain environmental measures uncertainty.
For example, a biotope could be characterized as follow:
-with a "realistic" value range from 20 to 30 EcoPoints/m² and a 25 EcoPoints/m² "normal" value.
-with an "uncertainty" value range from 15 to 25 EcoPoints/m² and a 20 EcoPoints/m² "normal" value.

The number of EcoPoints/m² a biotope will get is determined depending on three criteria: its degree of "naturalness", the role it has for endangered or patrimonial species and its distinctiveness in the local scale.
A software allows these three criteria combination to calculate the different values above for each biotope. The values go from 1 to 64 EcoPoints/m².
To calculate biodiversity losses and gains, four biotope values (V) are needed:
V_A for the current value of the biotope that will be impacted (area 1)
V_B is the predicted value for the biotope after impacts (area 1)
V_C is the current value of the biotope proposed for offsets (area 2)
V_D is the predicted value of the biotope after offsets (area 2)

Ecological equivalence is achieved when:

$(V_A * area_1) - (V_B * area_1)$ (losses) = $(V_D * area_2) - (V_C * area_2)$ (gains).

The equations to size offsets that achieve equivalence is as follow:

$$Area_2 = \frac{(V_A - V_B) * area_1}{(V_D - V_C)}$$

- **Pilot method in UK** (Department for Environment Food & Rural Affairs 2012)

The UK pilot method has been developed by the Department for Environment, Food and Rural Affairs in England, in the context of a new legislation preparation (Department for Environment Food & Rural Affairs (DREFA) 2013).

This EAM is based on “Habitat Hectare” principles. It focuses on terrestrial habitat. Habitats are evaluated through two criteria: its condition and its distinctiveness. Condition is scored 1, 2 or 3 whether it is good, moderate or poor. Distinctiveness is scored 2, 4 or 6 whether it is low, medium or high. In England, guidelines are available for classifying habitat condition and distinctiveness (i.e. some condition assessment tools are available and used for specific purposes). Distinctiveness includes parameters such as species richness, diversity, rarity (at local, regional, national and international scales) and the degree to which a habitat supports species rarely found in other habitats.

The Habitat Score is calculated as (Condition * Distinctiveness). It must be multiplied by the site area (in hectare). Four Habitat Scores are calculated:

HS_A for the current score of the habitat that will be impacted (area 1)

HS_B is the predicted score for the habitat after impacts (area 1)

HS_C is the current score of the habitat proposed for offsets (area 2)

HS_D is the predicted score of the habitat after offsets (area 2)

Ecological equivalence is achieved when:

$(HS_A * area_1) - (HS_B * area_1)$ (losses) = $(HS_D * area_2) - (HS_C * area_2)$ (gains).

In addition, the UK pilot EAM includes four multipliers which aim to take into account spatial, temporal and uncertainty dimensions in offset sizing:

-R1: offset probability of success

-R2: duration for the offset to be effective

-R3: offset location (ecological network)

-R4: condition of hedgerows on impacted site

The equations to size offsets that achieve equivalence is as follow:

$$Area_2 = \frac{HS_A * area_1 - HS_B * area_1}{HS_D - HS_C} * (R1 * R2 * R3 * R4)$$

This calculation has to be done for each impacted habitat.

- **Californian Rapid Assessment Method** (California Wetlands Monitoring Workgroup (CWMW) 2013)

The Californian Rapid Assessment Method (CRAM) is a “rapid assessment method” like UMAM, but developed specifically for California’s wetlands. There are two primary purposes for using CRAM. It is used to assess the ambient condition of a population of wetlands or to assess the condition of an individual wetland or wetland project. Wetland type must be identified following the guideline classification. Indicators are predefined and classified in four categories:

-*Buffer and Landscape Context*

  Aquatic Area Abundance or Steam Corridor Continuity

    3 indicators

  Buffer

    3 indicators

-*Hydrology*

    3 indicators

-*Physical Structure*

    2 indicators

-*Biotic Structure*

  Plant Community:

    3 indicators

  Horizontal Interspersion

  Vertical Biotic Structure

User have to score each indicator with a letter from A to D (A=12, B=9, C=6, D=3) depending on the indicator condition (the guidance help the user defined it). The category score is calculated as an average of each indicator score except for *Buffer and Landscape Context* and *Biotic Structure* for which there is a specific formula.

The final CRAM Score (CS) is calculated as follow:

$$CS = \frac{score_{BLC}}{max_{BLC}} + \frac{score_{H}}{max_{H}} + \frac{score_{PS}}{max_{PS}} + \frac{score_{BS}}{max_{BS}}$$

Where:

$score_{BLC} = \ [buffer\ condition * (\%AA\ with\ buffer * average\ buffer\ width)^{0.5})^{0.5}]\ +\ aquatic\ area\ abundance$

$score_{BS}\ =\ mean(plant\ community) + horizontal\ interspersion + vertical\ biotic\ structure$

Four CS are calculated for each Assessment Areas (AA). The (AA) is the portion of the wetland that is assessed using CRAM. An AA might include a small wetland in its entirety. But, in most cases the wetland will be larger than the AA. Rules are therefore explained in the guideline to delineate the AA, which must only represent one type of wetland.

CS_A for the current score of the AA that will be impacted (AA 1)

CS_B is the predicted score for the AA after impacts (AA 1)

CS_C is the current score of the site proposed for offsets (AA 2)

CS_D is the predicted score of the site after offsets (AA 2)

Ecological equivalence is achieved when:

$(CS_A * AA_1) - (CS_B * AA_1)$ (losses) = $(CS_D * AA_2) - (CS_C * AA_2)$ (gains).

The equations to size offsets that achieve equivalence is as follow:

$$AA_2 = \frac{CS_A * AA_1 - CS_B * AA_1}{CS_D - CS_C}$$

CRAM Scores are comparable only between the same types of wetland.

- **<u>Somerset Habitat Evaluation Procedure</u>** (Burrows 2014)

This EAM has been adapted from the US Fish and Wildlife Service's method to be usable in the English context. It is based on the same principle: the calculation of Habitat Units (HU) which are the product of a Habitat Suitability Index (suitableness of habitat for species) and the total area of habitat affected or required for the species.
Habitats are classified into over 400 categories with an Integrative Habitat System (IHS) using hierarchical Habitat Codes. The IHS provides as well Matrix, Formation and Land Use/Management added to the Habitat Code. Each habitat category is scored on a scale from 0 (poor) to 6 (excellent), according to its condition to support species, no matter the distinctiveness (i.e. broadest, priority level). Then the Matrix score (from 0 to 6) is added or subtracted depending on the contribution the "matrix" has on habitat suitability. Matrix here represents certain elements like scrubs or single trees which can influence habitat suitability for species. Formation and Management are scored between 0 and 1, depending on their effect on habitat and are multipliers (e.g. a species could require grazed grassland). All these information are gathered in a database for each habitat (ongoing).
So IHS is calculated as follow:

$$IHS = [(Habitat\ Code\ \pm Matrix\ Code) * Formation\ Code * Management\ Code]$$

The IHS obtained is finally multiplied by the Density Band (scored 1, 2 or 3, according to the occurrence of the species in the habitat).
HUs on site are calculated as follow (area is in hectare):

$$HUs = (IHS *\ Density\ Band) * Area$$

The HUs calculation has not to be done necessarily for all species impacted, but some umbrella species should be chosen to represent a habitat.
Two HUs are calculated on each impacted and compensatory sites:
$HUs_{required}$ for HUs lost due to impacts and that have to be offset
$HUs_{retained/enhanced}$ for HUs retained or enhanced due to onsite or offsite offsets

$$HU_{required} = HUs\ before\ impact * Risks$$
$$HU_{retained/enhanced} = HUs\ after\ offset - HUs\ before\ offset$$

Where:
"$Risks$" include delivery and temporal risks about offset measures. They are scored with specific grids provide by DREFA, and depend on the type of habitat.

Ecological equivalence is achieved when:

$$HU_{required} - \ HU_{retained\ or\ enhanced}(losses) = HU_{retained\ or\ enhanced}\ (gains)$$

It is considered that any impact on a species population affected by the development must be replaced by habitat enhancement or creation that is accessible to that particular population.

<u>Appendix B</u>: Description of challenges, criteria and modalities used to characterize EAMs.

Challenge	Criteria	Modalities and Scoring
Operationality (Op)	Indicator set up (IndSetup)	- **IndSetup1**: user has to choose one or several indicators - **IndSetup2:** indicators are predefined without a scoring system - **IndSetup3:** indicators are predefined with a scoring system
	Data availability (DataAv)	**DataAv1:** data are costly in terms of both time and money **DataAv2:** data are costly in terms of time (e.g., repeated data collection in the field) but not money **DataAv3**: data are cost-free (e.g., open-access data-bases) and rapid to collect (e.g., simple indicators measured in the field) **DataAv4:** Specific data-bases exist for the method (e.g., giving biodiversity units for specific habitat) so data is free and rapid to collect
	Implementation rapidity (ImpRp)	The time to implement method is: - **ImpRp1**: greater than 1 year - **ImpRp2**: between 6 months and 1 year - **ImpRp3**: between 1 week and 6 months - **ImpRp4**: less than 1 week
	Exchangeability (Exchg)	**Exchg1**: EAM only allows calculation for "like for like" offset **Exchg2**: EAM allows calculation for "like for unlike" offset when "like for like" offset is not relevant **Exchg3**: The method can be adapted to compute "like for like" offset, or "like for unlike" offset when "like for like" offset is not relevant
Scientific basis (ScBs)	Biodiversity indicators (BiodivInd)	- **BiodivInd1**: Indicators have to be chosen by users, based on examples and advice given in the EAM guideline - **BiodivInd2**: Indicators are fixed in the method and based on expert opinion - **BiodivInd3**: Indicators are fixed in the method and based on scientific documentation
	Biodiversity indicator metrics (BiodivIndMc)	**BiodivIndMc1**: metric is qualitative **BiodivIndMc2**: metric is quantitative discrete only or combined with qualitative **BiodivIndMc3**: metric is quantitative continuous only or combined with quantitative discrete **BiodivIndMc4**: metric is a combination of the three
	Spatial consideration (SpCd)	- **SpCd1**: spatial consideration is not taken into account in the theoretical guidelines, but is used on a case-by-case basis in practice - **SpCd2**: a ratio is used to adjust the surface area that will need to be offset - **SpCd3**: some indicators include these issues directly (e.g., connectivity indicators)
	Uncertainty consideration (UnCd)	**UnCd1**: uncertainty is not taken into account in the theoretical guidelines, but is considered on a case-by-case basis in practice **UnCd2**: a ratio is used to adjust the offset surface area (this ratio is the result of expert opinion) **UnCd3**: some indicators include this consideration directly (e.g., contribution to a site value) **UnCd4**: a ratio is used to adjust the offset surface area. This ratio is based on scientific literature or an existing data-base which provides scientific feedback on previous restoration actions
Comprehensiveness (Exh)	Key equivalence considerations (EqCd)	-Key equivalence considerations taken into account are: - **EqCd1**: only ecologic - **EqCd2**: ecologic + one other - **EqCd3**: ecologic + two others - **EqCd4**: ecologic + three others
	Target Biodiversity (TgBiodiv)	Biodiversity targeted can be: **TgBiodiv1**: natural habitat or species population and/or ecosystem functions **TgBiodiv2**: natural habitat(s) + species population **TgBiodiv3**: natural habitat(s) + species population + ecosystem functions
	Data type (DataTp)	- **DataTp1**: data from literature and/or GIS data + Simple field data - **DataTp2**: data from literature and/or GIS data + Simple field data + field inventories and/or field monitoring - **DataTp3**: data from literature and/or GIS data + Simple field data + field inventories and/or field monitoring + modeling
	Number of indicators (NbInd)	**NbInd1**: One indicator (or proxy) is used **NbInd2**: Several indicators are used to evaluate one biodiversity components (e.g. species) **NbInd3**: Several indicators are used to evaluate several biodiversity components (e.g. species and habitats)

Appendix C: questionnaire sent to EAM experts

*obligatory questions

- **Please fill in your full name**
- **Please fill in your function and your organization or agency**
- **What method are you going to assess? ***
- If you wish to fill in the form for a method that is not already mentioned, please write its name and references in "Other". Please choose one answer

Habitat Hectare (Parkes et al., 2003
Pilot method in UK (Drefa, 2012)
BBOP pilot method (BBOP, 2009)
Resource Equivalency Analysis (NOAA, 1997)
Habitat Equivalency Analysis (NOAA, 1995)
Landscape Equivalency Analysis (Bruggeman et al., 2005)
Habitat Evaluation Procedure (USFWS, 1980)
Uniform Mitigation Assessment Method (State of Florida, 2004)
Californian Rapid Assessment Method (CWMW, 2013)
German Ökokonto (Darbi & Tausch 2010)
Land Clearing Evaluation (Gibbons et al., 2009)
Canadian method Fish Habitat (Minns et al., 2001)
Other: **(1)**

1-On which biodiversity component(s) does the method focus?
Please choose one answer. If your answer is not already mentioned, please precise it in "Other".

Species (e.g. protected species)
Natural habitat(s) (e.g. wetlands or old-growth forest)
Natural Habitat(s) + species (e.g. wetland with patrimonial species)
Natural Habitat(s) + species + ecosystem functions
Other:

2-How was the method developed?
Please choose one answer

It was developed by consultants
It was developed by researchers or by a governmental organization
It was developed by a collective group (e.g. researchers, consultants, administration...) at the regional (or state) level
It was developed by a collective group at the national (or federal) level

3-What is the kind of data used in the method?
You can choose several answers.

Bibliographic data
GIS data
Simple field data
Field inventories

Field monitoring
Modelling

4-How difficult is it to access or collect the necessary data?
Please choose one answer

Data are costly both in terms of time and money
Data are costly in terms of time (e.g. repeated data collection in the field) but they are not expensive
Data are costly in terms of money (e.g. data that need to be bought from specialized companies such as LIDAR data or laboratory analyses…) but rapid to collect
Data are free (e.g. open-access data-bases) and rapid to collect (e.g. simple indicators measured in the field)

5.a-How much time would you need to collect all the data?
For a site with an average surface and an average complexity.

< 2 days
Between 2 days and 2 months
Between 2 months and 1 year
> 1 year

5.b-Once the data collected, how much time would you need to calculate ecological equivalence, using the method?

6-On which basis were the indicators of biodiversity chosen?
Please choose one answer

Indicators have to be chosen by users, based on examples and advices given in the method
Indicators are fixed in the method and based on expert opinion
Indicators are fixed in the method and based on scientific documentation

7-What type of metric(s) is(are) used to assess indicators?
Example are given for the indicator "vegetation density". You can choose several answers.

Qualitative (e.g. not dense, quite dense, very dense)
Quantitative discrete (e.g. between 0 and 10 plants/m², between 11 and 20 plants/m² etc.)
Quantitative continuous (e.g. 33 plants/m²)

8- Does the method explicitly incorporate one or more of the following consideration?
You can choose several answers

Ecological consideration (biodiversity evaluation)
Spatial consideration (e.g. site insertion in the landscape, offset location)
Temporal consideration (e.g. offset effectiveness delay, interim losses)
Uncertainty consideration (e.g. offset success probability)

9.a-If the method takes into account spatial consideration, how is it incorporated in the method?
Please choose one answer

Some indicators include this consideration directly (e.g. connectivity indicators)
A ratio to adjust the surface area that will need to be offset is used

9.b-If the method takes into account uncertainty consideration, how is it incorporated in the method?
Please choose one answer

A ratio is used to adjust the surface of offset area. This ratio is the result of a negotiation on a case by case basis
A ratio is used to adjust the surface of offset area. This ratio is based on scientific literature or in existing data base which provide scientific feedback on previous restoration actions
Some indicators include this consideration directly (e.g. contribution to a site value)

10-Does the method allow "like for unlike" offsets?
Please choose one answer

No, It only allows "like for like" offsets (e.g. offsets targets the species impacted)
Yes, it allows "like for unlike" offsets (e.g. one species impacted can be offset with another species with the same value)
When using the method, it can be adapted to compute "like for like" offsets, or "like for unlike" offsets when "like for like" offsets are not relevant

If you have any remark(s), comment(s) or suggestion(s), you are welcome to write them here:

Would you like to fill in the form for another method? *
To fill in the form for another method, please click on “Send" and then "Send another answer".

- <u>Comments about experts’ answers to the questionnaire</u>

[1] Only one “other” EAM was filled in (Biobanking in Australia), but it has the same principles as Land Clearing Evaluation since this EAM constituted the base for the development of Biobanking in the New South Wales, Australia. Experts were solicited specifically for their experience in the EAMs suggested in the list, which explains why we did not obtain a lot of “other” answers.

Experts’ contribution was the most important for questions 3, 4, 5, 6, 7 and 9 because the answers required more than a bibliographic study of EAM to be filled in. Notably, to answer questions 3 to 5, expert needs to have tested EAM in practice. Questions 6, 7 and 9 required precision about how EAMs were designed, which is not always explicitly said in theoretical guidelines.
Divergences between published documents analysis and experts answers, and between different experts answers when several answers where obtained for the same EAM, concerned particularly questions 8 and 9. Indeed, we found out after dialogue with expert that there is certain flexibility for spatial considerations and uncertainties as they are often treated in case by case, even if they are not included in the main EAM guideline.

144 **Details about expert answers to the questionnaire**

EAMs	Number of answers	Name and function of expert whose answer has been chosen
Habitat Hectare	1	Expert wish for not to be cited
Pilot method in UK	3	**Joseph William Bull**, Director of Wild Business Ltd
BBOP pilot method	1	Expert wish for not to be cited
Resource Equivalency Analysis	0	
Habitat Equivalency Analysis	1	Expert wish for not to be cited
Landscape Equivalency Analysis	1	**Frank Lupi**, Management Support, Research & Outreach
Habitat Evaluation Procedure	1	**Akira Tanaka**, Chair Professor, Department of Restoration Ecology and Built Environment, School of Environment Tokyo City University
Somerset Habitat Evaluation Procedure	1	Expert wish for not to be cited
Uniform Mitigation Assessment Method	4	**Constance Bersok**, Environmental Administrator Florida Department of Environmental Protection
Californian Rapid Assessment Method	2	**Cara Clark**, member of CRAM workshop
German Ökokonto	3	**Christian Küpfer**, Professor, University of Nürtingen, Germany
Land Clearing Evaluation	1	Expert wish for not to be cited
Canadian method Fish Habitat	1	**Dr Charles K Minns**, Scientist Emeritus, Canadian Department of Fisheries and Oceans, Burlington, Ontario

<u>Appendix D</u>: EAMs' modalities used for the Principal Component Analysis

EAM name and code	Operationality				Scientific Basis				Comprehensiveness			
	IndSetup	**DataAv**	**Exchg**	**ImpRp**	**BiodivInd**	**BiodivIndMc**	**SpCd**	**UnCd**	**EqCd**	**BiodivCp**	**DataTp**	**NbInd**
Habitat Evaluation Procedure	IndSetup1	DataAv1	EqTp3	ImpRp1	BiodivInd1	BiodivIndMc4	SpCd1*	UnCd1*	EqCd2	BiodivCp1*	DataTp3	NbInd2
Resource Equivalency Analysis	IndSetup1	DataAv1	EqTp2	ImpRp2	BiodivInd1	BiodivIndMc4	SpCd1	UnCd1	EqCd2	BiodivCp1	DataTp3	NbInd 2
Habitat Equivalency Analysis	IndSetup1	DataAv1	EqTp2	ImpRp2	BiodivInd1	BiodivIndMc4	SpCd1	UnCd1	EqCd2	BiodivCp3	DataTp3	NbInd 3
Canadian method Fish Habitat	IndSetup3	DataAv2	EqTp2	ImpRp3	BiodivInd2	BiodivIndMc1	SpCd1	UnCd4	EqCd3	BiodivCp3	DataTp3	NbInd 1
Habitat Hectare	IndSetup3	DataAv3	EqTp2	ImpRp4	BiodivInd2	BiodivIndMc2	SpCd3	UnCd1	EqCd2*	BiodivCp1	DataTp2	NbInd 1
Uniform Mitigation Assessment Method	IndSetup3	DataAv3	EqTp2	ImpRp4	BiodivInd2	BiodivIndMc1	SpCd3	UnCd2	EqCd4	BiodivCp1	DataTp1	NbInd 1
Landscape Equivalency Analysis	IndSetup1	DataAv1	EqTp1	ImpRp1	BiodivInd1	BiodivIndMc3	SpCd3	UnCd1	EqCd3	BiodivCp3	DataTp3	NbInd 1
BBOP pilot method	IndSetup1	DataAv1	EqTp2	ImpRp1	BiodivInd1	BiodivIndMc4	SpCd3	UnCd2	EqCd3*	BiodivCp3	DataTp3	NbInd 2
Land Clearing Evaluation	IndSetup3	DataAv2	EqTp1	ImpRp3	BiodivInd3	BiodivIndMc3	SpCd3*	UnCd1	EqCd2	BiodivCp2	DataTp3	NbInd 3
German Ökokonto	IndSetup3	DataAv4	EqTp2*	ImpRp2	BiodivInd2	BiodivIndMc2	SpCd1*	UnCd3	EqCd2 *	BiodivCp3	DataTp2	NbInd 3
Pilot method in UK	IndSetup3	DataAv4	EqTp2*	ImpRp3	BiodivInd2	BiodivIndMc1	SpCd2	UnCd2	EqCd4	BiodivCp2	DataTp2	NbInd 2
Californian Rapid Assessment Method	IndSetup3	DataAv3	EqTp1	ImpRp4	BiodivInd2	BiodivIndMc2	SpCd3	UnCd1	EqCd2	BiodivCp1*	DataTp1	NbInd 2
Somerset Habitat Evaluation Procedure	IndSetup3	DataAv4	EqTp2	ImpRp2	BiodivInd2*	BiodivIndMc1	SpCd1	UnCd2	EqCd3*	BiodivCp1	DataTp3	NbInd 3

* Answers which were subject to dialogue with expert. The main aspects for which we needed to ask precisions to experts concern the "Equivalence Considerations", and as consequence the "Spatial and uncertainty Considerations". Indeed, in practice, it is usual that ratios taking into account delay or risks are used to adjust the offset area, but in is done as an adaptation in case by case (in addition to the EAM baseline).
(1) We did not have an answer for this EAM, because it is almost the same as HEA except for all that concern biodiversity targeted and indicator used. We used only the theoretical guideline to attribute modalities to this EAM.

<u>Appendix E</u>: EAMs challenges average scores and EAMs final scores, expressed as a percentage of challenge achievement.

EAMs	Score Op (%)	Score ScBs (%)	Score Comp (%)	Final Score (%)
Habitat Evaluation Procedure	57.14	53.85	85.711	65,57
Resource Equivalency Analysis	50	76.92	85.71	70,88
Habitat Equivalency Analysis	71.43	92.31	35.71	66,48
Canadian method Fish Habitat	50	53.87	42.86	48,90
Habitat Hectare	50	69.23	42.86	54,03
Uniform Mitigation Assessment Method	57.14	76.92	28.57	54,21
Landscape Equivalency Analysis	50	53.85	42.86	48,90
BBOP pilot method	42.86	69.23	78.57	63,55
Land Clearing Evaluation	57.14	69.23	85.71	70,70
German Ökokonto	57.14	53.87	78.57	63,19
Pilot method in UK	57.14	69.23	78.57	68,32
Californian Rapid Assessment Method	71.433	69.23	64.29	68,32
Somerset Habitat Evaluation Procedure	57.14	92.31	78.57	76,01

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