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A decision-making tool for restoring lowland grasslands in Europe

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ABSTRACT

Species-rich grasslands suffer from significant loss and degradation all over the world. In particular in lowland Europe, the vast majority of these habitats are in an unfavourable conservation status which requires urgent restoration measures. A significant amount of information on the results of previous restorations exists thanks to the implementation of numerous projects and the publication of action plans, technical notes and scientific articles. This information is however very scattered, which does not facilitate the work of practitioners. We therefore propose here a decision support tool using a step-wise framework informed by the successes and failures obtained in two large-scale restoration projects supplemented by scientific and grey literature. This decision tree addresses different restoration techniques depending on the local context, e.g. the intensity of habitat degradation, the richness of soil nutrients, and the presence in the vicinity of a habitat in a good conservation status. Depending on the type of grassland, our tool then suggests various recurrent management techniques to be applied after restoration. This synthetic work is presented step by step according to a dichotomous key which is intended to help practitioners make the right choices in their restoration process.

1. Introduction

European grasslands can be categorised in seven main habitats (EUNIS, 2012): dry grasslands, mesic grasslands, seasonally wet and wet grasslands, alpine and subalpine grasslands, woodland fringes and clearings and tall forbs stands, inland salt steppes and sparsely wooded grasslands. Grasslands are valuable habitats that provide multiple functions such as a positive influence on the recharge of water tables and a protection effect for water quality (Peeters, 2009). Grasslands also store in the soil *ca.* 34% of the global stock of carbon in terrestrial ecosystems (Silva et al., 2008). They also support a huge amount of biodiversity that has been accumulated during millennia of low-intensity land use (Habel et al., 2013). They include Europe's most species-rich plant communities. For some plot sizes, temperate grasslands hold world records in the number of vascular plant species (Wilson et al., 2012), sometimes exceeding 60 species/1m^2 or 133 species/100 m^2 for calcareous grasslands (Merunková et al., 2012).

Throughout Europe, however, grasslands suffer from multiple threats such as intensification, conversion into forage maize and cereal crops, eutrophication, afforestation and land abandonment (Habel et al., 2013; Peeters, 2009, 2012). Nowadays, grasslands are among Europe's most threatened ecosystems (Janssen, Rodwell, García Criado, Gubbay, & Haynes, 2016; Silva et al., 2008). In the European Union (EU), grasslands have one of the highest proportion of habitats with an unfavourable and deteriorating conservation status (European Commission, 2015, 2020). Some of these habitats (e.g. calcareous grasslands) are even degraded in all European biogeographical regions, and according to assessments of future prospects, it is expected they will continue deteriorating (Olmeda, Šefferova, Underwood, Millan, Gil, & Naumann, 2019).

In Europe, most grassland habitats originated from centuries of grazing, mowing or burning. As these management regimes have currently fallen into disuse in a large part of the continent, the restoration of species-rich grasslands should focus on the reintroduction of these ancestral practices (Blakesley & Buckley, 2016). However, depending on the severity of habitat degradation, the effects resulting from the application of these techniques are not always visible in the short term, and there is not always time to wait. It even appears that they rarely succeed in restoring highly degraded habitats (Resch et al., 2021). During recent decades, more interventionist techniques have been sucessfully tried out, such as topsoil translocation, hay transfer, or seed mixture sowing (e.g. Buisson, Jaunatre, Römermann, Bulot, & Dutoit,

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2018; Kiehl, Kirmer, Donath, Rasran, & Hölzel, 2010; Lepš, Dolezal, Bezemer, Brown, & Hedlund, 2007; Török et al., 2012). Today, there is ample evidence that these approaches are necessary (e.g. Jacquemyn, Van Mechelen, Brys, & Honnay, 2011; Ödman, Schnoor, Ripa, & Olsson, 2012; Tóth & Hüse, 2014; Godefroid, Le Pajolec, Hechelski, & Van Rossum, 2018; Török et al., 2018; Řehounková, Jongepierová, Šebelíková, Vítovcová, & Prach, 2021; Wagner et al., 2021a, 2021b). Barely 17% of the plant species of Northwest Europe have a seed bank subsisting for more than 5 years in the soil (Thompson, Bakker, & Bekker, 1997). Among the characteristic species of dry grasslands, this percentage is even smaller, and the seed bank of these grasslands is mainly represented by ruderal species (e.g. Schmiede, Donath, & Otte, 2009; Kiehl et al., 2010; Godefroid et al., 2018). Another obstacle preventing target species from recovering spontaneously is that for many grassland species, unassisted dispersal of diaspores is limited to a few meters at best (Thomson, Moles, Auld, & Kingsford, 2011). For some plant communities, it can be estimated that the recovery of a typical community under the effect of spontaneous recolonization is therefore impossible on a time scale compatible with the objectives of nature conservation (>50 years) (Öster, Ask, Cousins, & Eriksson, 2009). Only an artificial intervention is effective if one does not/cannot wait several decades (Walker, Stevens, et al., 2004).

A great deal of uncertainty as to the effectiveness of the measures applied is however frequently associated with restoration decisions, which hinders the identification of a strategy that maximises the probability of achieving the desired objectives (Moore & Runge, 2012). Given the dispersion of information in numerous publications and in the grey literature resulting from the outcome of European LIFE projects, it has become essential to synthesize existing knowledge in order to better integrate research and practice and make the best use of the funds available. This is all the more important as each EU Member State has the obligation to restore those habitats present on its territory in such a way that their conservation status becomes favourable. The European Commission's database lists 539 LIFE Nature projects being financed between 1996 and 2020 targeting directly or indirectly the restoration of natural and semi-natural grasslands (http://ec.europa.eu/environment/life/project/Projects/index.cfm), representing billions of euros of investment (Johnson et al., 2020).

When restoring habitats, deciding which techniques to implement is not an easy matter: species recovery trajectories are sometimes difficult to predict, budgets are often limited while restoration is expensive. Practitioners should therefore improve the cost-efficiency of their strategies. When it comes to restoring grasslands such as those defined for the European Union (see European Commission, 2013), a wealth of previous restoration outcome information exists thanks to the completion of numerous projects and the publication of technical notes, action plans and other scientific papers. If the amount of information is high, it is however very scattered. Some sources of information may also provide approximate indications as to the habitat targeted or the environmental conditions under which restoration has taken place. This does not always make it possible to know whether, in a particular case, it is relevant to apply a technique recommended in other (unknown) contexts. Many challenges can also arise during the different stages of a restoration project. In the preparatory phase, it is important to have a clear idea of the objectives, to manage conflicts of interest, to verify the feasibility, risks and sustainability of the project, and to ensure adequate funding. Then comes the choice of techniques to be used depending on the habitat targeted, its conservation status and the local context. A tool that integrates all these aspects for European grasslands is sorely lacking. Decision trees are a good, more practical alternative to dispersed documents. This kind of tool forces the user to consider all possible outcomes of a decision by visually presenting all alternatives allowing direct comparisons in an easy-to-use format. It can therefore be of great help for practitioners to objectively decide between different options and increase the efficiency of their restoration approach.

In this paper, we present a knowledge and literature-based decision tree to facilitate the adoption of the most appropriate restoration measures. We reviewed the different steps necessary to identify the best decision-making choices depending on the type of grassland, addressing the 'how' and the 'what' of implementation. The proposed tool is intended to be a practical guide to assist managers from the moment an idea is conceived until the end of the restoration process and the recurrent management of the restored habitats.

We consider here grasslands in the broad sense (including also meadows), as all these habitats in Europe are officially included in the broad category of "natural and semi-natural grassland formations" (European Commission, 2013).

2. Material & methods

2.1. Contextual framework

Our decision tree is based on a synthesis of the literature combined with own experience accumulated in the context of two large scale eight-year projects that took place in the south of Belgium between 2012 and 2020 (projects no. LIFE11NAT/BE/001059 and LIFE11NAT/BE/001060). These projects aimed at restoring grasslands belonging to 6 habitats of community importance in the European Union:

- Xeric sand calcareous grasslands (EU code: 6120)
- Semi-natural dry grasslands and scrubland facies on calcareous substrates (6210)
- Species-rich *Nardus* grasslands, on siliceous substrates (6230)
- *Molinia* meadows on calcareous, peaty or clayey-silt-laden soils (6410)
- Hydrophilous tall herb fringe communities (6430)
- Lowland hay meadows (6510)

2.2. Literature review

The first step leading to the development of the tool was an analysis of the literature on the management and restoration of grasslands in Europe. We do not claim to have constituted a complete bibliography of the works published on this topic, but we believe, however, to have gathered a relevant number of publications allowing us to make an appropriate synthesis in the form of a decision tree. To carry out this work, we explored data from 227 documents (articles, books, websites, manuals, MSc and PhD theses; see supplementary material). Our research covers a large period of time (1985–2021) allowing to have a good overview of the different approaches used over the decades. Three quarters of the documents reviewed were published in the last two decades, which also allows a fairly comprehensive review of the most recently tested techniques. We also searched the grey literature (in English, French, Dutch and German) as we suspected that a great amount of information would be hidden in these documents (e.g. action plans, regional reports, management team reports, final project reports, minutes of (field) meetings and workshops). We are therefore confident that the work proposed here represents a significant contribution to a synthesis of current knowledge. We also believe that it is timely since this kind of synthesis on grassland restoration techniques is currently recognized as urgently needed (e.g. Dudley et al., 2020; Török, Brudvig, Kollmann, Price, & Tóthmérész, 2021).

2.3. Development of the decision tree

The decision tree and the logic behind it were first gradually developed as the literature was being analysed. This in order to: (1) facilitate the decision-making of managers, conservationists, or future LIFE project teams who generally do not have the time to read all these documents, and (2) share appropriate, cost-effective and state-of-the-art techniques as imposed by the European Commission in the framework of LIFE projects. To do this, we have adopted three main criteria:

- Ecological requirement criteria and the definition of a good conservation status: What is a grassland? What objective to aim for? What do we need?
- Legal, ethical/philosophical and technical/scientific criteria relating to interventionism (e.g. risks of deviating from established standards or risks of genetic pollution): What can or cannot be done to achieve an objective?
- Practical and temporal criteria relating to known technical operations: How to proceed? In which order? What best techniques to choose in each situation?

We then gradually put the pieces of the puzzle together in a step-by-step approach and logical order based on common sense. We proceeded by trial and error, by applying to this decision tree a large number of scenarios encountered during our projects (>850 ha restored and having been monitored before, during and after restoration; Ribod, 2016; Dellicour, 2019 and several unpublished reports). This was carried out until all possible cases were represented in the decision tree and could be resolved as quickly and as efficiently as possible using the tool developed.

The constraint of time and limited budget, the obligation of results and "best practices", and the need to communicate and transfer these so that they are replicated, were ultimately our catalyst, and our framework, in the development of this tool.

In short, the guidelines were initially drafted thanks to the scientific and grey literature, our initial knowledge and that of the group of experts who advised us, but also thanks to the tests set up in 2012 with some preliminary results already in 2014. Then, at the end of both projects (2020), the decision tree was adjusted following the final outcome of the tests (with several years of hindsight) and obviously the restorations as a whole.

2.4. Geographic scope of the tool

The tool can be used in a large part of Europe as it deals with habitats that are present in most biogeographic regions of the continent. The grassland types that are taken into account in the decision tree are best represented in the Continental, Atlantic and Alpine regions, but are also present in more peripheral areas such as the Boreal, Mediterranean and Pannonian regions (https://eunis.eea.europa.eu/habitats). Although this tool was developed in the context of southern Belgium, it can be applied in all regions of Europe having similar exceedance of critical loads for eutrophication, which represents a large part of the continent (see maps in European Environment Agency, 2015). In order to allow the tool to be used in regions of Europe with a significantly different climate, we have also avoided giving precise dates for seeding, mowing, etc. Instead, we suggest time intervals that are long enough for the measures to be relevant for the greatest number of practitioners.

3. Decision-making framework

3.1. Conditions before restoration

Starting point: an idea is launched, a project is proposed in terms of restoration by reintroducing plant species or a reinforcement of plant population on a given target site. A donor site for providing propagules is also known.

Question 1 - Philosophical acceptance (e.g. Fischer, Riechers, Loos, Martin-Lopez, & Temperton, 2021): Do site managers accept the principle of human intervention from a philosophical or ethical point of view? Is it considered acceptable that human beings intervene on other species for conservation purposes?

- Yes: Go to Question 2 - State of play
- No: No need to go further, or start with reflection, documentation and awareness

Question 2 - State of play: Has a complete preliminary assessment (i.e. a preliminary study leading to the drafting of a technical data sheet or identity card of the site) been carried out? This assessment should ideally include the following information:

1. Basic data
   - Administrative data (name, toponymy, geographical coordinates, cadastral parcels, cantonment, owner / manager of the site, purchase documents, Natura 2000 Site, …)
   - Historical data (old maps from 19th and 20th century, former owners, description)
   - Physical data (geology, soil, pH, soil P, natural region, phytogeographical area)
2. Initial state (at the time of management)
   - Vegetation (EUNIS)
   - Conservation status (Natura 2000 Habitat)
   - Plantations (tree species, density, year of planting)
   - Disturbances
   - Species: remarkable fauna / flora (typical, rare …) and population status
   - Other
3. Objectives
   - Objective (restoration objective)
   - Justification
   - Mode of management envisaged
   - Landscape impact
   - Target in terms of species (conservation objective)
   - Access to the public
   - Old goals (if change)
4. Proposed restoration / works, proposed technical itinerary, cost analysis, reintroduction / reinforcement of typical species
5. Recurrent management measures / planned works
6. Planned scientific monitoring
7. Preparing communication to the public
8. Appendices (maps, photos …)

- Yes: Go to Question 3 - Project Objective
- No: Make this assessment before going further

Question 3 – Project aim: What is the aim of the project?

- A habitat-based approach: Increase the overall biodiversity on the site by improving, creating or recreating a specific biotope / natural habitat (if several habitats are targeted, continue the analysis separately site by site depending on the habitats targeted): Go to Question 3bis - Habitat of Community Interest
- A species-based approach: To reintroduce or reinforce one or several species that have disappeared or are threatened on the site: Go to Question 5 - Status of the target species' populations

Question 3bis - Habitat of Community Interest:: Is the study site currently hosting a habitat of community interest (a natural habitat type in Annex I of the EU Habitats Directive)?

- Yes: Go to Question 4 - Conservation status (CS) of the habitat
- No: Go to Question 6 - Targeted Habitat

Question 4 - Conservation status (CS) of the habitat: In what CS is the habitat targeted, and should we intervene?

- Favourable CS (A): No need for intervention in terms of population strengthening. Appropriate management measures to plan: Go to Question 17 - Site Management. If, nevertheless, certain species are absent from the habitat and it is considered important to reintroduce them, aim for a species-based approach: Go to Question 5 – Status of the target species' populations.

- Unfavourable - inadequate CS (B): Possible population reinforcement intervention if the CS has not evolved despite adapted management for several years and if the competent management committee agrees. If no intervention: Go to Question 17 - Site Management. If intervention: Go to Question 6 - Targeted Habitat.
- Unfavourable - bad CS (C) or non-existent target habitat (bare soil, embankments, other habitat of lesser interest …): Go to Question 6 - Targeted habitat.

Question 5 - Status of the target species' populations: Does the target species suffer a severe decline or a threat of extinction at the level of the phytogeographical region or the Natura 2000 site?

- Yes: Go to Question 7 - Need for reintroductions or reinforcements (in general).
- No: Non-priority intervention. Appropriate management measures to plan: Go to Question 17 - Site Management. Possibly aim for a habitat-based approach: Go to Question 3 - Project aim.

Question 6 - Targeted habitat: which habitat do we want to restore or create?

- Humid meadows (6410), mesophile grasslands (6510, 6520) or dry grasslands (6120, 6210, 6230): Go to Question 8 - Need for reintroductions or reinforcements on meadow or grassland
- Other: Go to Question 7 - Need for reintroductions or reinforcements (in general).

Question 7 - Need for reintroductions or reinforcements (in general): Refer to existing literature or experts' advice to answer the question (e.g. Gann et al., 2019). Are the species likely to reappear spontaneously via the soil seed bank or seed dispersion from a source site (wind, animals, waterways…)?

- Yes: No need for intervention in terms of population reinforcements. Appropriate management measures to plan: Go to Question 17 - Site management.
- No: Go to Question 11 - Threat mitigation.

Question 8 - Need for reintroductions or reinforcements in a meadow or grassland, considering a potential soil seed bank: Should we intervene for these habitats?

- If the habitat has an unfavourable - bad (C) CS
  i. The habitat had a favourable (A) or unfavourable - inadequate (B) CS 5 years ago at most: possibility of a soil seed bank or seed rain if the same habitat in a favourable CS is adjacent to the plot to be restored. No need for immediate intervention in terms of population reinforcements. Adapted management measures to provide for at least 3 years before considering population reinforcement (see below): Go to Question 17 - Site management.
  ii. The habitat had an unfavourable - bad (C) CS 5 years ago at most and there is no adjacent habitat in favourable CS: need for intervention: Go to Question 9 - Soil nutrient richness.
- If the habitat has an unfavourable - inadequate (B) CS. The seed bank is non-existent given the absence of evolution of the site despite the application of adapted management for several years (see Question 4): possible intervention: Go to Question 9 – Soil nutrient richness.

Question 9 - Soil nutrient richness: Is it a phosphorus-poor soil (less than 5 mg of available phosphorus per 100 g dry soil; Janssens et al., 1998)?

- Yes: Go to Question 11 - Threat mitigation
- No: Go to Question 10 - Soil depletion

Question 10 - Soil depletion: Can the soil be depleted?

- Yes: After attempts, return to Question 9 - Soil nutrient richness
- No: Abandonment of the project, possibility of other developments (orchard, pond, hedge, afforestation …)

Question 11 - Threat mitigation: Have direct threats to target species or habitat been adequately identified and removed or sufficiently reduced (intensive agricultural practices, habitat destruction, urbanization, eutrophication, pollution, predation, flood …) at the target site?

- Yes: Go to Question 12 - Origin of plant material
- No: Meet the conditions before going further

Question 12 - Origin of plant material: Where are we going to collect plant material? The geographical location of the donor site has to be known precisely. Are all the following conditions fulfilled?

1. No invasive or exotic species are known or have been observed at the donor site.
2. The geographical distance between the donor and the target site is minimal, and in any case is part of the same phytogeographical region.
3. In case of a habitat-based approach, the donor site corresponds to the habitat in a favourable CS. The area of the habitat has to be large and the habitat stable and not isolated.
4. In the case of a species-based approach, the donor site hosts a population that is large (greater than 500 individuals), stable and not isolated (e.g. Godefroid, Piazza, Rossi, Buord, & Stevens, 2011).
5. The soil and water conditions of the donor site are similar to those of the target site.
6. The number of generations during possible ex situ propagation cannot be greater than five (risk of genetic drift, Walker, Hodder, Bullock, & Pywell, 2004, Prasse, Kunzmann, & Schröder, 2010). This rule is also valid for cultivation (nurseries) outside the phytogeographical region or outside soil and water conditions similar to the target site.

No seed was collected on the source site the year preceding the planned seed collection.

- Yes: Go to Question 13 - Final verifications in terms of feasibility, risks and sustainability
- No: Meet the conditions before going further

Question 13 - Final verifications in terms of feasibility, risks and sustainability: Are the necessary resources available for the project? Are all the technical conditions and methods necessary for the smooth running of the intervention and its sustainability known, controlled and applicable? Are the ecological, economic and social risks of the intervention known and limited? Is the checklist below complete?

	Current feasibility
Ecological	The ecological, edaphic and hydrological conditions of the donor and target sites are similar and adequate
	Threats to the donor site (related to the intervention) and the target site are known and limited
Economical	The financial means are sufficient
	Local economic impact is positive or limited
Social	Human resources are sufficient
	Site managers and the general public accept or are likely to accept the project
	Communication and awareness are sufficient or possible
Technical	The techniques and stages of intervention are known and controlled: collection, possible multiplication, transport, preparation of the land, dissemination …
	Sustainability

(*continued on next page*)

(*continued*)

	Current feasibility
Ecological	Donor and target species and habitats are and will be conserved and managed effectively
Economical	Financial resources will remain available for site management
Social	The site benefits from land control or a strong protection status Human resources are sufficient in the future Site managers and the general public are likely to accept the project in the future as well
Technical	Site management techniques are known and will be mastered in the future

- Yes: Go to Question 14 - Restoration technique
- No: Meet the conditions before going further

3.2. *Technical itinerary in case of restoration*

At this point, the initial idea became clear, it eventually evolved or has been adjusted. The project can be ethically and ecologically implemented if it follows the first guidelines above (questions 1–13). It remains to define how to use the donor site to improve the target site.

Question 14 – Restoration technique: Which technique to use to propagate the target species? The methods can be varied, in particular according to the approach (species or habitat-based). In all cases, special attention will be paid to avoid threatening the populations of the donor site. We recommend to keep a minimum area of 50% of the donor site unharvested. A minimum area of the target site (e.g. strips covering 50% of the plot) will also be maintained in order to serve as a control area and allow any interesting species to propagate naturally.

- **Green hay** (habitat-based approach only). If there is a possibility to combine over the same period of time and at a lower cost the mowing of a site rich in species typical of the targeted habitat and the transfer of green hay on the target site, this technique can be privileged. If both sites are close to each other (a few km), the cost of this type of restoration will be even lower. In order to transfer the highest number of typical species, mowing and harvesting the hay in the donor site on strips at several times in the growing season (e.g. between late-May and September depending on the target vegetation) can be considered, although laborious to implement. In the event that only one mowing is possible, hay should be harvested at the time when the maximum number of habitat indicator species is mature without seeds being on the ground.
  Plan green hay transfer with a donor/target area ratio of 1:1 to 3:1 (Kiehl, Thormann, & Pfadenhauer, 2006; Klimkowska, van Diggelen, Bakker, & Grootjans, 2007). Examples of amounts recommended in the literature are 3–15 cm thick hay or 180–1500 g/m^2 (Kiehl et al., 2010; Manchester, McNally, Treweek, Sparks, & Mountford, 1999). Hay should not be tedded and spread as quickly as possible on the site to be restored where the soil will ideally be prepared (harrowing, milling or crushing). The hay then remains a few weeks (1 month maximum) on the target site, and subsequently tedded before being evacuated if the ratio was higher than 2:1. It is also possible to graze the site with the double advantage of removing the hay and put the seeds in contact with the ground (trampling).
  It is also possible to successfully spread raking residues (lichens, mosses and low vascular plants) or the product of litter scraping on recently abandoned grasslands. Working with a brush cutter (equipped with a circular saw blade) will make it possible to scrape the soil very superficially. Ideal germination conditions are thus created on the donor site and, in principle, all species are brought to the target site. The surface worked this way on the donor site should however be limited in view of the induced soil disturbance and the impact on part of the fauna. This method has the advantage of being able to be implemented in autumn/winter.
- **Plantation of clumps, grafts or rhizomes**. In the hypothesis of a donor site whose habitat would be destroyed (urbanization …) or that is anyway the subject of sod cutting, target species (in case of species-based approach) can be uprooted, some clumps may be fragmented, or sods (in case of habitat-based approach) may be harvested and replanted. If the donor site will be destroyed, 30–50 cm thick sods are recommended (Kiehl et al., 2010).
- **Sowing of harvested seeds**. If it is not possible to mow the donor site, if the harvest period is incompatible with that of land preparation, or if transfers are too expensive: seed harvesting can be considered (manually, semi-manually or mechanically).
  In meadows, the recommended seed mixture density is around 30 kg/ha for sowing on bare soil and between 15 and 25 kg/ha for overseeding (Kiehl et al., 2010), although the latter is less recommended, the results being less good. In grasslands, due to the lack of seeds, these values were divided with success by 10 or even 100 (Walker, Stevens, et al., 2004). The aim of sowing seeds harvested in grasslands is, depending on the species, to recreate a loose frame which will become denser thanks to an appropriate management or to restore patches of grasslands likely to recolonize the site afterwards.
  On arable soils, seeding can also be accompanied by nurse crops (e.g. *Lolium multiflorum)* in order to occupy the ground, impoverish the soil and improve the establishment of target species (Walker, Stevens, et al., 2004).
- **Seeding *Rhinanthus minor* (grass hemiparasite).** This can be useful in habitat restoration where indicator and characteristic species are present but scarce. Seeding *R. minor* in mixture with harvested seeds is also possible. It will reduce the competition of social grasses and allow the germination and the development of the forbs by increasing the amount of light reaching the soil (Pywell et al., 2004; Westbury & Dunnett, 2007). The long-term maintenance of *R. minor* can only be ensured by a summer mowing (late ripening and very short longevity of seeds).
- **Planting plug plants and sowing seeds from ex situ propagation**. This technique can be useful for propagating species with little or too early fruiting (which are therefore absent from harvest) or that need special conditions to germinate. This method is expensive but the success rate can be high (e.g. Wallin, Svensson, & Lönn, 2009). The number of ex situ generations should be limited to a maximum of five (Prasse et al., 2010; Walker, Hodder, et al., 2004).
  In the case of meadows with overseeding of propagated seeds: if the seed mixture consists of grasses and forbs with a proportion between 70/30 and 90/10, the density will be around 30 kg/ha for sowing on bare soil and between 15 and 25 kg/ha for overseeding in meadows after soil preparation. On the other hand, if the mixture consists only of forbs, the overseeding density can be adapted between 2 and 10 kg/ha.
- **Use of native plant cultivars**. This technique is to be avoided because of the risks that the introduced genotypes have a higher fitness or are in greater number compared to the local genotypes, with the consequence of a replacement of the local genotypes (dilution of native gene-pools) and a decrease in the fitness of hybrid populations (Dyer et al., 2016; Bucharova et al., 2019).

Go to Question 15 - Preparation of the target site

Question 15 - Preparation of the target site: What kind of soil tillage needs to be done before considering reintroduction or reinforcement? In all cases, the soil should be prepared.

- **The soil is bare**, i.e. an embankment soil, an old cultivated field, a clear cut cleaned from stumps and wood debris, without vegetation: a superficial soil preparation needs be considered to refine the soil structure by harrowing followed by rolling before or after sowing, depending on the case. Using a roller before sowing prevents the seeds from being buried too deeply in the soil, which would impede their germination. If the soil is dry at the time of sowing, using the roller after sowing promotes a better contact between the seeds and the soil.

- **The soil is covered by herbaceous vegetation** but none or very few indicator species from the target habitat are present, and competitive grasses dominate (standing biomass in the meadow well above 5 tons dry matter/ha.year; Schaffers, 2002). In meadows: consider exposing the soil in strips 10 to 20 m wide over 50% of the surface of the target site, in order to optimize the recolonization by the target species (low dispersal capacity). In case of high P content, plowing can be considered, followed by harrowing, sowing and rolling before or after, depending on the case. In grasslands: consider mowing as short as possible followed by a parsimonious manual spreading as well as grazing (bringing seeds into contact with the ground and creating gaps in the soil).
- **Some indicator species from the target habitat are present,** and competitive grasses do not fully dominate (standing biomass of the meadow close to 5 tons dry matter/ha. year; Schaffers, 2002): do not destroy cover and consider overseeding or spreading hay on the existing vegetation. The vegetation on the ground should then be kept very short, either by the effect of previous grazing or low mowing height. Thinning of existing vegetation may also be necessary using a harrow or an overseeder.
- **The soil is covered by woody vegetation** (e.g. broadleaved shrubs, conifer seedlings or saplings): remove and export all woody material. Depending on the management aim (mowing or not, see Question 2 - State of play), consider grinding tree stumps, followed in some cases by superficial sod cutting, and exporting or windrowing woody material.

Go to Question 16 - Sowing Period

Question 16 - Sowing Period: At what time of year should we intervene? This period depends on the preparation of the soil, but also on the availability of seeds (ripe and viable) or green hay.

- **Sowing** should ideally be done during the best germination time (good humidity and temperature), i.e. at the end of the summer (ideally between August 15th and September 30th) or in early spring between April 1st and May 15th. Late summer should be preferred, as it generally precedes periods without drought compared to spring. Sowing before a rain period is recommended.
- **Overseeding** should be done when vegetation is low (after mowing or intensive grazing) between July 1st and September 30 or between April 1 and May 15.

Go to Question 17 - Site Management

Question 17 - Site Management: How to manage the site to improve or maintain the conservation status (CS) of the habitat or of the population of the target species?

- In the case of a habitat-based approach:
- If the habitat is a meadow (6510, 6520, 6410) whose CS has to be improved: Go to Question 18 - Management of a meadow the year of the intervention
- If the habitat is a meadow (6510, 6520, 6410) with favourable CS: Go to Question 20 - Recurrent meadow management
- If the habitat is a tall herb fringe community (6430): Go to Question 21 - Recurrent management of a tall herb fringe community
- For other habitats: possible management are grazing, mowing, prescribed burning, sod-cutting,…
- In the case of a species-based approach: refer to the literature concerning this species and to the advice of experts.

Question 18 - Management of a meadow the year of the intervention: What is the ideal management of a meadow after sowing, overseeding, or simply to improve the floristic richness by relying on the existence of a soil seed bank or natural reseeding from an adjacent meadow?

- **If there is potentially a soil seed bank** (no sowing), a compromise between the two limiting factors should be found: light on the ground allowing seed germination and forb development, and late mowing allowing seed setting of forbs.

Harrowing can be carried out on the meadow to promote light at ground level and facilitate germination of the seed bank. This work should be done when the vegetation is short (after mowing or intensive grazing) between August 15th and September 30th or between April 1st and May 15th. Mowing or grazing should then follow according to the abovementioned scheme.

If the meadow is already in a good CS and the management is identical for at least 5 years: continue with the same management. If the management is not the same for at least 5 years: follow the evolution of the vegetation in order to define the appropriate management according to the objective.

Go to Question 19 - Management of a meadow in the years following the intervention

- **After sowing**, sufficient mowing is essential to allow seeded plants to germinate and grow to cope with the competition from weeds and grasses.
- **If sowing in the spring**, if annual weeds are not too abundant, cutting plant heads within 10 weeks following sowing should be done (Critchley, Burke, & Stevens, 2003; Walker, Stevens, et al., 2004). At least one mowing will be carried out between August 1st and November 30th. If this mowing takes place before September 1st, it will ideally be repeated again in October or November as needed (depending on the plant dynamics at the end of the season). If annual weeds are scarce, it is strongly recommended to mow once before winter (ideally once between July 15th and September 1st and, if necessary, a second time in October or November).
- **In the event of autumn sowing**, an early mowing will be necessary in the next spring (between April 15th and June 1st), followed by a late mowing (between July 15th and the 1st September) and grazing between September and November.

Go to Question 19 - Management of a meadow in the years following the intervention

- **After overseeding**, sufficient mowing and/or grazing is essential to allow overseeded plants to germinate and grow to cope with canopy competition.
- **If overseeding occurs between July 1st and September 30th**, it is recommended that mowing or grazing be done between September 1st and November 30th. Grazing will be more effective because it will create more gaps and bring the seeds into contact with the soil by trampling as a roller would do during sowing. If mowing or grazing is done before September 30th, it will be essential to make a first mowing the following spring, between April 1st and May 1st, followed by a summer mowing (after July 15th) and ideally a fall management by mowing or grazing between September and November.
- **If overseeding occurs between April 1st and May 15** (ideally after a spring mowing) it is recommended to make a first mowing (after July 1st). At least one mowing or grazing will subsequently be done between August 15th and November 30th. If this mowing or grazing takes place before September 30th, it will ideally be necessary to mow or graze again in October/November or the following spring.

Go to Question 19 - Management of a meadow in the years following the intervention

Question 19 - Grassland management in the years following the

intervention: What is the ideal management for a hay meadow in the early years of its restoration phase? The year following sowing (N + 1), restoration actions will continue with a minimum of two mowings, the first of which should be as early as possible. If the state of the vegetation requires it, an additional mowing may even be inserted between the first mowing and the last mowing. The last mowing can also be replaced by a late season grazing. It actually depends on the site fertility: if 5 tons of dry matter/ha.year of standing biomass is exceeded (Schaffers, 2002), mowing should be carried out as soon as this biomass is reached. In the subsequent year (N + 2), restoration actions will ideally follow those described in the next point.

- A mowing or late grazing is done in the previous fall. In this case, the vegetation is sufficiently short in the following spring to allow germination, and the first mowing will be late (around mid-summer). At least one mowing or grazing will be done between August 15th and November 30th. If this mowing or grazing takes place in the late summer, it will be necessary, according to the vegetation dynamics, to mow or graze again in October/November or in the following early spring .
- An early spring mowing is strongly recommended, if no management is performed in the fall of the previous year. This cut is followed by a late summer mowing and ideally a management in the fall by mowing or grazing between September and November. If this mowing or grazing takes place in late summer, it will be necessary, according to the vegetation dynamics, to mow or graze again in October/November or in the following spring.

Go to Question 20 - Recurrent management of a meadow

Question 20 - Recurrent management of a meadow: Once the meadow has a good CS, a mid-summer mowing allowing seed production should be maintained. If necessary, the second crop will be mown or grazed in the fall to eliminate summer production in case it is abundant. If the meadow has already a good CS and the management is identical for at least 5 years: continue with the same management. If the management is not the same for at least 5 years: follow the evolution of the vegetation in order to define the appropriate management according to the objectives. In any case, keeping some areas unmown every year (rotational mowing) will be useful for some animal and plant species.

Learn about the existing literature for more details (early mowing in rotation with late or very late mowing, maintaining refuge strips, grazing …). In all cases, an export of the hay is necessary, and fertilizers are to be avoided.

Question 21 - Recurrent management of a tall herb fringe community: The main reason for a bad to medium CS of this habitat is the lack of management or its abandonment. It is recommended to mow once or twice (or intensively graze for a short time, which has the same effect as mowing) every 5 years (Rouxhet, Halford, Goret, Walot, Le Roi, Thirion, & Mulders, 2008). Given the soil moisture in this habitat type, it is advisable to mow during a dry period regardless of the date (with precautions for nesting species). Although the environment makes the task complicated, removal of the mowing product or stockpiling is necessary. It is useful not to mow the entire surface in the same year but to rotate in two or three times depending on the surface of the habitat (refuge areas).

4. Discussion

We proposed here a decision-making tool using a step-wise framework informed by a review of scientific and grey literature, supplemented by successes and failures obtained in two large-scale restoration projects implemented on 850 ha spread over more than 100 different sites. After 8 years of implementation of restoration techniques, we had enough hindsight to propose a synthesis easily usable by practitioners that can help them make the best choices according to their specific situation. The decision tree starts with an analysis of the situation before restoration, which includes aspects to be considered in general in any habitat restoration, such as philosophical acceptance, preliminary assessment, project aim, its feasibility, risks and sustainability. Different restoration techniques are then approached depending on the soil nutrient richness, the intensity of habitat degradation, the presence of the habitat in good conservation status nearby, and recurrent management to apply after restoration, depending on the type of grassland.

4.1. A wide range of techniques adapted to different contexts

The decision-making framework presented here integrates different possible techniques for the restoration of European grasslands. These were tested in our restoration projects and have borne fruit in less than 8 years after their implementation (Dellicour, 2019; Godefroid, Le Pajolec, & Van Rossum, 2016; Goret, Kints, Lighezzolo, Sevrin, & Huysecom, 2020; Janssens, Godefroid, Baltus, Verté, & Mairesse, 2020). Hay transfer is successfully applied in different situations (Kiehl & Wagner, 2006; Török et al., 2012). A considerable amount of seeds can hereby be transported. For *Molinia* meadows, Rasran et al. (2006) reported that between 41 and 71% of the species found in the mown area were present as seeds in the hay. If high diversity hay sources are available, this technique may even be a cost-effective alternative to the more expensive high-density sowing (Török et al., 2012). During our projects, we observed that the effectiveness of this measure may increase if applied after soil disturbance to reduce competition from pre-existing vegetation, which has also been confirmed by other studies (e.g. Bischoff, Hoboy, Winter, & Warthemann, 2018). In our restorations, the most easily established species were *Centaurea jacea, Leucanthemum vulgare* and *Rhinanthus minor*.

Unlike hay transfer, which must absolutely be carried out in the hours following hay mowing (otherwise the hay can rot or lose its seeds if it is dried), the harvest of seeds followed by their drying allows storage while preparing the land for sowing. Sometimes we even stored the harvested seeds for several months in air-conditioned rooms. This flexibility is essential in a context of large surfaces to be restored in a short period of time, as was the case in our LIFE projects. Inoculating hemiparasitic plants (e.g. *Rhinanthus minor*) has been shown to be effective for increasing grassland diversity by significantly reducing grass biomass (e.g. Hellström et al., 2011). A sowing rate of at least 0.5–2.5 kg per hectare has been recommended to facilitate the establishment of desired forbs and accelerate their colonization, knowing that it takes about 3 years for *R. minor* to reach significant densities to facilitate the persistence of sown species (Pywell et al., 2004). On the other hand, according to Westbury and Dunnett (2007), sowing it at a density of 1000 seeds/m^2 would be necessary to have a significant impact on grass biomass. Knowing that 1000 seeds of *Rhinanthus minor* weigh 2.56 g on average (Royal Botanic Gardens Kew, 2021), this corresponds to spreading 25.6 kg per hectare. In our restorations, we have successfully used a quantity of *Rhinanthus* seeds intermediate between the values reported by these studies, namely 5 kg/ha.

Introducing container-grown young plants (plug planting) is also implemented successfully in the restoration of different types of grassland (Walker, Stevens, et al., 2004; Wallin et al., 2009; Young & Veblen, 2015). In our projects, it has been used only for a small number of red-listed species that are not or very little present in seed mixtures. For example, plug planting of 700 individuals of *Arnica montana* to contribute to the restoration of European habitat 6230 (species-rich *Nardus* grasslands) gave 6 years later 10,169 new seedlings established in the vegetation. The technique is however time-consuming and expensive because, given the scarcity of these species in the source sites, they must be collected manually and, because of the limited numbers of seeds available, their ex situ propagation is necessary.

4.2. Seed-sourcing strategies

During our restoration projects, we also experimented that diaspore supplementation makes it easier to orient the restoration trajectory in the desired direction thanks to the priority effects (Torrez, Mergeay, De Meester, Honnay, & Helsen, 2017; Weidlich et al., 2021; Young, Stuble, Balachowski, & Werner, 2016), giving introduced species a temporal competitive advantage over weeds which otherwise can emerge from the seed bank or be brought in by the seed rain. Sowing seed mixtures was therefore presented here as one of the possible methods of grassland restoration. It is being implemented on increasingly large scales worldwide (e.g. Pedrini & Dixon, 2020; Shaw et al., 2020). However, it is not always easy to know which seed sources are best suited for each situation. It is important to keep in mind that maintaining genetic diversity in restored areas is essential and even more critical given the predicted impacts of climate change (Erickson & Halford, 2020). The "local is best" sourcing practice might therefore need some adjustments to account for future global changes (Volis, 2019). Material originating from multiple populations is suggested to increase restoration success (Vergeer, van den Berg, Roelofs, & Ouborg, 2005).

When following the proposed decision tree, one may need to use multiple source populations which, in certain circumstances, could lead to outbreeding depression (Edmands, 2007). However, there is strong evidence that outbreeding depression plays little role in restoration success when populations originate from similar environments separated by distances of up to a few hundred km (Fenster & Galloway, 2000; Frankham et al., 2011). In our tool, we propose to use resources from neighbouring habitats so that outbreeding depression does not become a problem for restorations implemented in this way. Also, in order to reduce the risks, some regions have developed seed transfer zones, i.e. geographically delineated areas of relative climatic similarity within which seeds can be collected, propagated and used in restoration while minimizing maladaptations (Bower, St. Clair, & Erickson, 2014; De Vitis et al., 2017; Durka et al., 2017; Erickson & Halford, 2020; Hamann, Gylander, & Chen, 2011).

Since the surfaces to be restored are often large, huge quantities of seeds are therefore necessary. Currently, seed banks cannot meet these large-scale restoration demands (Merritt & Dixon, 2011), nor can wild harvesting which can also lead to depletion of native seed resources due to overexploitation (Pedrini et al., 2020). Multiplication of native species in seed orchards might then be considered to try to replace or supplement seed collection in natural populations (e.g. Vander Mijnsbrugge, Bischoff, & Smith, 2010). During our restoration projects, we had to use this option for several species because of insufficient quantities of seeds harvested in relation to the areas to be sown. Native seed farming is an activity that is starting to emerge in Europe (De Vitis et al., 2017), but we advise to be careful when producing seeds in order to avoid genetic drift (Nagel, Durka, Bossdorf, & Bucharova, 2019) or any form of (un)intentional selection that would increase the frequency of traits that are typical for seed production environments but maladaptive in the wild, such as synchronized phenology, low dormancy, poor competitive ability or drought tolerance (Ensslin, Van de Vyver, Vanderborght, & Godefroid, 2018; Basey, Fant, & Kramer, 2015; Ensslin et al., 2011, 2015; Espeland et al., 2017; Pizza, Espeland, & Etterson, 2021). In the proposed tool, we leave the door open to native seed farming, provided that the number of generations does not exceed four in herbaceous perennial species and five in annual and biennial species (Prasse et al., 2010). From a legal standpoint, the European Commission tolerates up to five generations for use within the framework of the preservation of the natural environment (European directive 2010/60/EU). Native plant cultivars are an extreme case of selection occurring in seed production environments as they have often been developed for their aboveground biomass accumulation or their suitability for mechanized harvesting (Chivers, Jones, Broadhurst, Mott, & Larson, 2016), traits that may prove to be unsuitable in the context of habitat restoration (Leger & Baughman, 2015). Our decision tree therefore strongly advises against using native plant cultivars.

4.3. Weaknesses of the tool and possible improvements

The guidelines presented here are based on the observed development of plant communities in response to different restoration techniques. Even though plant community composition is the most widely used criterion to assess the success of restoration measures (Resch et al., 2021), others could also be taken into account, such as for example insect communities, even if it must be recognized that much less work has been done in this area. The most recent research carried out in Switzerland on herbivorous insect communities 22 years after the establishment of different restoration techniques in grasslands has shown a positive effect on their taxonomic and functional diversity (Neff et al., 2020). Another study on North American grasslands also suggests greater pollination services provided at restored sites (Luong, Turner, Phillipson, & Seltmann, 2019). These are promising results, but there is a need for a larger number of studies examining the effects of various grassland restoration techniques on insect communities.

Likewise, we have not integrated the composition of the underground communities into our tool. It appears that this ecosystem component has rarely been considered in restoration projects (Farrell, Léger, Breed, & Gornish, 2020; Resch et al., 2019). In our tool, a certain degree of soil preparation (e.g. superficial sod cutting) was recommended for severely degraded systems. This kind of disturbance can however be detrimental for soil microbial communities and even lead to the failure of some grassland restorations (Koziol & Bever, 2017). Recent evidence suggests that successful restoration may require inoculation of soil microbes to steer plant community development (Wubs, van der Putten, Bosch, & Bezemer, 2016). Even if we have relatively little information on these aspects compared to the data available for plant communities, it would nevertheless be desirable to develop a similar decision tool in the future that also integrates soil fauna.

4.4. Cost-effectiveness of grassland restoration

Nature conservation has to deliver results. It is in our own interest, but it is also a question of credibility with regard to the financial and human resources invested by society. In the EU LIFE program alone, billions of euros have already been invested to restore degraded ecosystems (Johnson et al., 2020). It has contributed to the restoration of considerable areas of grassland on the European continent (Silva et al., 2008). However, the task is immense and the means implemented are generally not sufficient to achieve the objectives. The present tool proposes restoration measures which can be expensive (e.g. top soil removal, propagule addition). A recent study carried out in grasslands in Switzerland confirms that high levels of intervention make it possible to restore the targeted habitats while a lower intervention does not (Resch et al., 2021). However, at equivalent cost, there can also be substantial differences in the success of a restoration as the cost-effectiveness will depend on the target habitat and on the environmental variables that influence the assembly of plant communities (Kimball et al., 2015). De Groot et al. (2013) reviewed the costs and benefits of ecosystem restoration projects in over 200 studies. Among the 10 biomes analysed, they demonstrated that grassland restoration has the highest return on investment, with an internal rate of return between 35 and 59% and a benefit to cost ratio up to 35. In addition to biological outcomes, grassland restoration also provides benefits in terms of ecosystem services. Based on estimates from the Millennium Ecosystem Assessment (2005), the 574 ha of grasslands that we restored in the framework of our LIFE Herbages project should yield on average each year in terms of monetary benefits for our society: € 40,000 in pollination, € 50,000 in water purification, € 100,000 in flood protection, € 180,000 in carbon storage, € 260,000 in better quality food for livestock, and € 400,000 in educational and recreational values, which means more than 1 million euros per year (Janssens et al., 2020).

Research can help optimize investment in ecological restoration (Kimball et al., 2015), but improving the sharing of experiences, the dissemination of scientific data, the communication of project results and exchanges between researchers and practitioners are at least as important. The present work tries to contribute to this, and we hope that the tool provided here can usefully assist practitioners in making their restoration work a success. We believe this contribution is timely in the context of the upcoming UN Decade on Ecosystem Restoration that will run from 2021 through 2030 (Dudley et al., 2020; UNEP & FAO, 2020) and given the continuous and widespread degradation of these habitats across much of Europe.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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