UNIVERSITY OF PAVIA
Department of Earth and Environmental Science

Using current regulations and practices to develop a certification scheme for native seed production in Europe

Holly Abbandonato

Academic Supervisor: Graziano Rossi (UNIPV)

Tutors: Hugh W. Pritchard (Royal Botanic Gardens, Kew, UK)

Co-Tutors: Giles Laverack (Scotia Seeds, UK), and Francesco Rovero (MUSE, Trento)

Coordinator: Prof. Roberto Sacchi
Academic Year 2016-2017

The NAtive Seed Science, TEchnology and Conservation Initial Training Network

UNIVERSITY OF PAVIA

Department of Earth and Environmental Science

Doctor of Research in Earth and Environmental Sciences
CYCLE XXX – Curriculum NASSTEC (2014-2017)

Using current regulations and practices to develop a certification scheme for native seed production in Europe

Holly Abbandonato

Academic Supervisor: Graziano Rossi (UNIPV)

Tutor: Hugh W. Pritchard (Royal Botanic Gardens, Kew, UK)

Co-Tutors: Giles Laverack (Scotia Seeds, UK), and Francesco Rovero (MUSE, Trento)

Coordinator: Prof. Roberto Sacchi
Academic Year 2016-2017

CERTIFICATION

I, Holly Abbandonato, declare that this thesis, submitted in partial fulfilment of the requirements for the award Doctor of Philosophy, in the School of Earth and Environmental Sciences, University of Pavia, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution. This thesis contains work prepared for publication, some of which has been co-authored.

Holly Abbandonato

August 20th & October 31st, 2017

FUNDING

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n°607785. Institutional support was provided by the Royal Botanic Gardens, Kew, which receives grant-in-aid from Defra.

CONTENTS

Cover photograph: *Daucus* sp. growing on the edge of a temperate forest used to symbolically represent native seed policy for ecological restoration. Photo courtesy of H. Abbandonato.

LIST OF PAPERS

Paper 1:

Abbandonato H, Pedrini S, Pritchard HW, De Vitis M, Bonomi C (in press.) Native seed trade of herbaceous species for restoration: a European policy perspective with global implications. Restoration Ecology, DOI:10.1111/rec.12641

Paper 2:

De Vitis M, Abbandonato H (2017) Nature Correspondence. Nature, submitted.

Paper 3:

Abbandonato H, De Vitis M, Pritchard HW (2017) Native seed community preferences for seed quality and certification for ecological restoration. Restoration Ecology*, manuscript.*

Paper 4:

Abbandonato H, Liu U, Squire G, Iannetta PPM, Pritchard HW (2017) Applying Standard PREanalytical Codes to the marketing of herbaceous native seeds for ecological restoration. Plant Biology, special issue: Natural capital from native seeds*, manuscript.*

Paper 5:

De Vitis M, Abbandonato H, Dixon K, Laverack G, Bonomi C, Pedrini S (2017) The European native seed industry - characterization and perspectives in grassland restoration. Sustainability, DOI:10.3390/su9101682

ABSTRACT

To meet the large-scale restoration needs in Europe such as the UN Convention on Biological Diversity, the EU Biodiversity Strategy to 2020, industrial reclamation projects, or to provide seed at a local level for greening or re-vegetation, an increasing quantity of high quality native seed is required. However, growth in the native seed market, supported by further native seed production and improved technology, is needed so that revegetation is possible in an economic and efficient way. Critically, various ecological and socio-economic aspects require additional research and development since successful restoration is multi-disciplinary. For the first time, key practical challenges were investigated holistically within the native seed sector. Current quality standards in European policy, between disciplines and species, were considered and recommendations formulated to advance this sector and improve native seed policy and certification for the future.

The first approach combined environmental policy with seed biology and ecology by reviewing the current state of native seed production regulations in Europe. Current native seed policies were found to be not well-enforced or practically applicable to the regulation of the seed supply for the developing native seed market in the majority of European countries; and the sale of uncertified native seed was identified as potentially undermining restoration practices. Further measures need to be introduced to ensure product quality and transparency while still maintaining genetic diversity. These aspects should improve existing regulations or the use of an *ad hoc* policy should be designed for the marketing of native seed supplemented by an intersectoral strategy to deliver seeds of high quality in Europe (**Paper 1** & **2**).

Due to the variability in global seed quality standards and the intersectoral division in needs, the second analysis examined both the grower's and user's preferences on native seed quality and certification standards using a socio-ecological bottom-up approach. A global survey was sent out to over 1340 native seed users and stakeholders. All user groups selected origin as the most important seed quality measure and that native seeds should be certified nationally/federally by governmental agencies (**Paper 3**).

Whilst certification standards on seed quality have been available for crops for many years, the native seed sector has no internationally accepted standards for germination and storage. Therefore, an examination of certification applicability was designed based on a bio-banking technique, called SPREC (Standard PREanalytical Codes). Using a DEXi multi-attribute decision tree to understand the processes of native seed quality, the new labelling system was applied to five wild widespread and commonly produced native species. The labelling system and quality assessment was created called U-SeeD (User-based, SPREC and DEXi) certification that can be used for both wild and produced species, within a developing and developed market that meets the needs of the native seed community (**Paper 4**).

There is little published information on the native seed market in Europe, and the average cost and weight of seed bought and sold per member state was investigated using publically available data and a survey of the native seed community. This characterization of the herbaceous native seed market revealed an uneven distribution of native producers across Europe and permitted an assessment of production costs (field management before multiplication had the highest costliness) and the frequency of major customers for seed producers (**Paper 5**).

In conclusion, the various market analyses undertaken, in relation to the availability of quality seed, the development and transfer of scientific knowledge, and the suitability of policy and certification standards, all emphasise the importance of future collaboration between a wide range of stakeholders, far beyond current practice.

INTRODUCTION

In the last decade the perception of conservation has evolved into people and nature as separate entities that affect one another and relate, especially with matters of climate change, resiliency and adaptability (Mace 2014). This is well reflected in current initiatives such as the UN's Convention on Biological Diversity Aichi Biodiversity Targets which contain multidimensional goals that integrate society and the environment (Mace 2014). However, these targets are multifaceted and challenging to measure (Aronson & Alexander 2013), and more than half of European countries have not been able to make positive progress on restoration targets since the baseline assessment (CBD 2010). This means that while we are aware of environmental degradation, implementation to meet them is not so straightforward. In the last decade, 10/14 biomes have decreased in productivity, and over 13,000 species of vascular plants have naturalised outside their native range (RBGK 2016). Plant conservation initiatives lag behind animal projects as socially plants and the environment are not well-noticed, resulting in plant blindness (Balding & Williams 2016). Clewell and Aronson (2007) stressed the importance of a multi-value model to successfully carry out restoration which incorporated ecological, socio-economic, cultural and personal values. Yet, restoration values are often underestimated particularly in Europe. In many countries, budgets and legislation for restoration are limited or non-existent, there is a lack of integration between sectors and little demand from the public

(SER 2016). The fear of losing jobs over environmental protection has been documented in one third of the U.S. population; however, this myth is largely unfounded (Goodstein 1994). There are trade-offs when land is protected at a local level, and pollution control policies have increased net employment and this can positively impact jobs in fisheries and tourism sectors for example (Goodstein 1994).

Europe has already committed to the EU Biodiversity Strategy to 2020 which uses the Natura 2000 Network to protect and restore 15% of degraded ecosystems using a control and command or top-down approach; however, rural landowners in many member states were not in agreement of this (Keulartz 2009).

The question arises of how can we meet this restoration demand and prevent the loss of biodiversity and protect ecosystems services. One of the many strategies is to use native seeds. Seeds are the most convenient propagation strategy since they are more affordable, easily carried in large quantities, survive under long storage regimes, and can withstand hostile micro-environments (Veteto & Skarbø 2009). The multi-value approach was not only useful for problem-solving larger policy issues (Bouwma et al. 2010), but it could address some of the native seed production challenges for restoration. In the past century, an intentional increase in seeds has been used to re-establish wild plants for restoration purposes (Bradshaw 1997; Muller et al. 1998) at various scales (small, broad scale) and funding programs (local, governmental, private) (Broadhurst et al. 2016). Seeds even have cultural and social values. Social anthropologists have found cultural memories associated with cultivation and the properties of a seed consist of learned experiences, sensory embodiments, and social learning especially among farmers (Ellen & Platten 2011). Seeds are easily exchanged creating a cultural mechanism for seed dispersal even among growers. However, purchasing herbaceous native seeds for restoration greatly depends on the member state. We know that over one-third of European countries are without a native seed industry, and thus monitoring and quality control is scarce. In contrast, the use and production of agricultural seeds in Europe is highly regulated and strictly monitored. Rules from the European Commission for propagating seeds include everything from labeling, marketing to inspecting seeds for use in agriculture, vegetable, fruit, fodder, forest, and ornamental species. Yet, very few policies exist for the use and production of native herbaceous plant species in Europe outside the fodder directives (EU Commission 1966; EU Commission 2010), especially for restoration purposes.

Furthermore, very little is available in the scientific literature on native seed quality, nor is there a consensus on how to define seed quality for restoration (Hampton and Hill 2011; Baskin & Baskin 2014). Existing certification schemes greatly vary per country and continent, with no current review on efficacy of native seed standards and requirements.

One method used for *ex situ* conservation in mega diverse countries is Biospecimen Science which considers both the quality of a biological sample, but also tracks the processing steps (Harding et al. 2013). Not only are herbaceous species found in biodiverse hotspots (Wilson et al. 2012), but collected and multiplied seeds go through a series of processing steps, e.g., timing of collection, drying, storing, cleaning which can affect both quality and genetic diversity since they do not follow agricultural standards of distinctness, uniformity, and stability. This is one technique that could be used to evaluate seed quality and processing in a simple, transparent and efficient way.

OVERALL OBJECTIVES

This PhD examined the current regulating systems applicable to native seed production in Europe with the aim of supporting and improving certification schemes for restoration programmes requiring high quality and large quantities of herbaceous native seed. Desk-based and experimental studies set the groundwork for developing a certification scheme called U-SeeD in Europe with applications abroad.

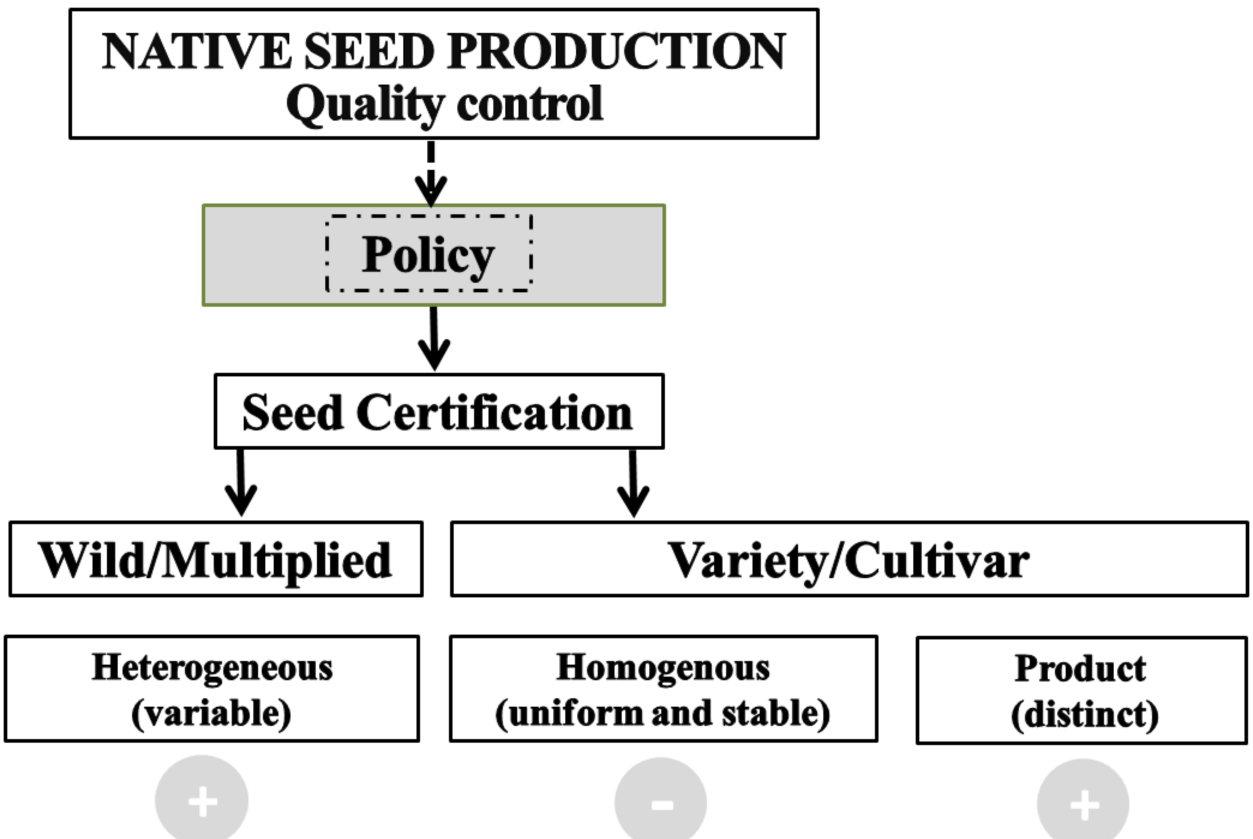

Figure 1. Quality control schematic applied to the marketing of native seeds which can be implemented through policy (legally binding is symbolized by the grey square) rules at a supranational or national level or through direct certification schemes (without policy indicated by the dotted line) which is often participatory or contract-based. *Wild/multiplied*: box ensures that the seed are variable to preserve genetic diversity, usually with a known origin specified.

Variety/Cultivar: box indicates the UPOV Convention's harmonized tests for a variety (DUS Testing: distinctness, uniformity, stability). The + boxes can be suitably applied to native seed, whereas the - box is incongruously applied to native seed.

Legally-binding policies applicable to the marketing of native seeds across Europe were critically reviewed pertaining to the global demand for ecosystem restoration to feature the state of regulations and future developments. Other unique certification schemes (e.g., optional, contract-based, participatory) implemented in more developed countries exist, but with little standardization or agreement on seed quality procedures. A survey of the native seed community set the groundwork for native seed quality and certification for the first time. With applied restoration being a largely interdisciplinary field, quantifying the values of researchers, industry and practitioners enabled the design of an *ad hoc* certification scheme (U-SeeD) that could meet the needs all parties involved (producers, researchers, users). To apply certification efficiently and ensure transparency, a new labelling system was designed using DEXi taking a biomedical and *ex situ* conservation technique: SPREC and agricultural quality labeling standards for eggs (ECE/TRADE/C/WP.7/2009/14). Seed quality and genetic diversity was examined by testing the labelling system on wild seed from the Millenium Seed Bank database (RBG Kew, UK) and on two produced widespread species, *Papaver rhoeas* and *Silene vulgaris* sourced from three native seed producers in Europe.

Within the NASSTEC project, I worked on two co-authored papers: one on the native seed market (De Vitis et al. submitted); and the other on the restoration species pool (Ladouceur et al. 2017). As a contribution to the first co-authored paper, I co-designed a survey on seed quality, certification and quantification of the native seed market. To the second co-authored paper, I contributed the fodder and conservation species data (germination and production availability) currently listed under native seed policies (66/401/EEC and 2010/60/EU) to compare with indicator species. For both papers, I discussed the policy perspectives and contributed to the writing of the manuscripts (see Other Publications and Appendix).

RESULTS AND DISCUSSION

The native seed trade of herbaceous species in Europe is not functioning as well as it could be. To address this, the policy framework applicable to the marketing of native seeds in the EU was reviewed to determine its suitability for ecological restoration (**Paper 1)**.
Although there an urgent need to meet ambitious restoration targets in Europe, to contribute to global targets (Aichi Biodiversity, Global Strategy for Plant Conservation, EU Biodiversity strategy) and human well-being (Sustainable Development Goals), the possibility exists that the native seed sector for the production of herbaceous species is not sufficiently developed to deliver this ambition yet. One possible hindrance is that the policy framework for the trade in native seeds is neither practical nor supportive. In this context it is important to evaluate the current ‘ready-made’ policy frameworks in Europe regarding the native seed supply of herbaceous species. The results of the analysis of current seed policies reveal a generally, unsatisfactory framework for both producers and users. Initially, such policies were designed for species used as animal feed and apply distinctiveness, uniformity, and stability seed rules; traits that do not follow the genetic heterogeneity of native species required for ecological restoration. Until recently, more suitable certification standards were designed to multiply fodder seed for the preservation of the natural environment to facilitate the Natura 2000 network; however, due to

the disparateness of the seed market in Europe this policy is rarely practical and does not encompass all herbaceous native species often resulting in unregulated seed sales. A consequence of these findings is the recommendation that a new or adapted native seed policy should be constructed through a participatory or bottom-up approach. Such a policy could stimulate the native seed trade with concomitant impacts on the speed of improving ecosystems services.

The first key step in bringing about change in this sector is to secure the backing of the policy makers. Only in this way can the likelihood of implementation be increased. Transfer of knowledge from research (desk-based, laboratory-based or field-based) to policy officials requires the use of many means of communication. In short, opinion articles can be very effective. For example, those of Merritt and Dixon (2011) on restoration seed banks, and of Cortina-Segarra et al. (2016) on using biodiversity to speed restoration of EU ecosystems. **Paper 2** (correspondence) took this approach. To meet the ecological restoration activities in the coming years the argument was made that most European countries have few native seed producers. The exceptions being Austria, Germany and France, where there are more companies in operation and where producers and researchers have collaborated to create supportive tools, such as native seed certification standards and seed transfer zones. Even in these countries, meeting the demand for native seeds for restoration remains a challenge because of: (1) the application of restrictive policies and inappropriate standards developed within the agricultural sector; (2) the lack of a European-wide strategy aimed at facilitating and strengthening coordination of production and intersectoral collaboration to deliver native seeds of high quality. The USA has a National Seed Strategy for Rehabilitation and Restoration and a similar approach in Europe should provide coordination between producers and users with the goal of restoring plant communities. But for this to happen in Europe existing policies on collection, production and use of native seeds must be adapted. Any changes in standards should be based on existing scientific knowledge and inputs from the community of users (particularly the native seed industry and local end users) through a consultative participatory approach. This process is necessary to assist the emerging sector of native seed production which can only benefit future restoration and climate change obligations.

Policy developments are only as good as the evidence base used to design them. Such evidence needs to be well-grounded in the needs of native seed community on seed quality and certification for ecological restoration, as without the community will likely not fully comply with the emerging policy. **Paper 3** focuses on this topic. One challenge was how to balance the delivery of habitat restoration using wild-harvested seed as opposed to (or complementary with) using farmed seed. To better understand this challenge, a survey on seed quality and certification was sent out in five languages (English, French, German, Italian, Spanish) to more than 1300 native seed users. The users represented different sectors of the native seed community: land managers, researchers and trade professionals. It was found that all members of the native seed community shared a similar perspectives on the importance of knowing the seed quality of the material used, had a high interest in the clear reporting of seed lot origin, and the need for a compulsory certification system at a national/federal level run by governmental agencies. However, the responses varied among groups; in particularly, land professionals primarily chose origin and provenance, whereas research and trade both chose origin, viability, purity and germination. Whilst the research and trade professionals' views were generally aligned, land professionals were primarily concerned about meeting restoration projects on time with source-identified seed. This study provides the first look at native seed user and stakeholder perspectives that can be used to generate and inform seed production policy bettering current and future seed quality certification systems to come.

To help support the restoration targets in Europe and regulate the native seed sector, we devised a labelling framework for the marketing of native seed for ecological restoration. To understand what defines "quality" for this purpose we consulted the survey on the native seed community and developed a user and full code, and quality assurance rank in **Paper 4** for wild and commonly produced native species: *Daucus carota*, *Hypericum perforatum*, *Lotus corniculatus*, *Papaver rhoeas* and *Silene vulgaris*. Using a DEXi model, a production system on native seed quality was developed for wild and produced species that defined seed quality as maintaining genetic diversity, but also product quality as a result of processing, handling and seed properties. A label was then designed using a Standard PREanalytical Codes (SPREC) commonly applied to biomedicine and *ex situ* conservation to track sample quality and processing. Overall wild seed lots demonstrated high quality under the newly created U-SeeD certification (**Fig. 2**); however, this was primarily due to the vast information available and seeds samples of decent quality in germination, viability and purity. Produced seed lots showed more variation from low to high quality. This was primarily due to the lack of information on genetic diversity, such as date of harvesting, origin, provenance and seed lot on the seed packages. This study provides a simplistic and transparent certification system with seed standards designed for ecological restoration accounting for both genetic diversity and product quality to facilitate a growing herbaceous native seed marketplace.

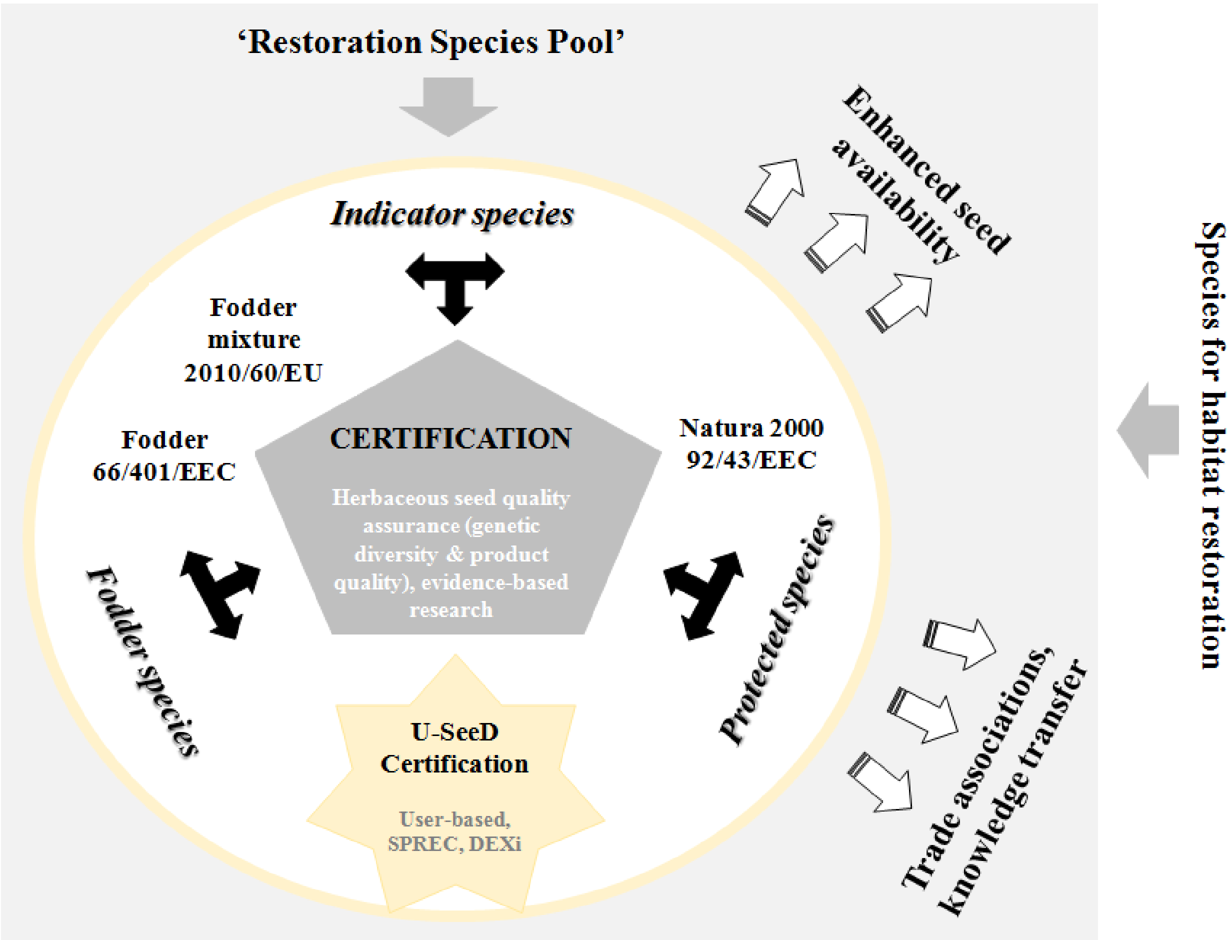

Figure 2. Certification of herbaceous native species requires a seed quality definition and understanding through evidence-based research what the users (researchers, producers and practitioners) need. Current EU directives attempted to regulate both product quality taking an agricultural viewpoint and a genetic resources viewpoint; however, in the end created a mismatched set of directives that are trying to fit the growing herbaceous seed sector. We know that the "Restoration Species Pool" (RSP) includes indicator, fodder and protected species; yet this separation based on policy primarily is not working for regulating purposes and we proposed a new U-Seed (User-based, SPREC and DEXi) certification that is an easy and transparent labelling system that promotes future seed enhancements, the formation of trade associations and knowledge transfer to advance restoration targets using marketed herbaceous native seed.

Understanding the dynamics of the native seed industry sets the groundwork for improvements and new research development. **Paper 5** investigated the European native seed market with emphasis on characterizing the industry, funding schemes for restoration, seed zones, outreach and current seed purchases by cost and weight. The majority of companies were found in countries with greatest decline in species-rich grasslands, such as Great Britain, France and Germany; however, businesses are typically SMEs or family run consisting of 1-9 employees. Furthermore, countries with seed zones and certification system already in place had pre-formed trade associations that are largely responsible for their design. Participants were also in favour in being part of knowledge sharing network. This follows suit with the policy and participatory recommendation. Responses from the survey indicated that on average 3 600 kilograms of herbaceous seeds with an average expenditure of € 17 600 occurred annually in Europe. Species with seed biology data and producer availability are primarily fodder species) rather than indicator or conservation status species; and improving the restoration species pool (Ladouceur et al. 2017) will facilitate market growth and help to meet the restoration demand, protect biodiversity, and ecosystem services.

CONCLUSION

The findings of this PhD research programme demonstrate the complexity of native seed production for restoration in relation to the marketplace, science support, the production environment and policy frameworks. One clear outcome is an understanding that seed quality and certification regulations do profoundly impact on access to and the use of marketed seed. Appreciating this is important as ultimately seed quality affects seed performance and plant establishment for restoration. With the increasing need for high quality native seeds to meet restoration targets, especially herbaceous species, regulations need to be both more practical and beneficial for the users and producers to facilitate restoration practices. A route forward is identified that depends on changes in policy and certification, and the creation of practical solutions taking an interdisciplinary approach, preferably through the establishment of a functioning trade association.

Overall, herbaceous native seed policy for ecological restoration is impractical on the scale needed. New regulations should be implemented at a national level that begins by certifying seed origin, enforced by governmental agencies. In Europe, native seed producers when present are largely private SMEs. As the market develops, other seed quality attributes that directly measures seed quality could be implemented; however, a species registry or handbook providing information on germination, viability, and purity could be beneficial in conjunction. Using bio-analytical coding (e.g. SPREC) with DEXi, it is shown how a simple bar-coding method could be designed to meet these needs to ensure transparency to consumers who require it, while not causing a vulnerability to seed producers in a developing market.

FUTURE WORK

This study is not without its limitations. All in all, the studied topics are original and unprecedented, and thus have some short-comings, such as finding sufficient published scientific material (mainstream and grey literature) and esteemed advice, including from experts that span seed science, production and business practice. In addition, tracking local policy measures of the EU directive 66/401/EEC in member states proved extremely difficult since many reports were unavailable or challenging to locate due to the language barriers. Most of these challenges were overcome to a certain extent. At the experimental level, further research is clearly needed on testing the effect of certified fodder seed and seed mixtures in the lab and field to determine precisely which authorisation requirements could be useful or impractical experimentally.

I decided to explore the field of social sciences to try and find a welcomed solution to native seed policy and certification for restoration that would satisfy and quantify the needs of native seed users (research, production, restoration); however, due to the disparateness of professions and sectors this may have resulted in an underestimation of user preferences. Creating and sustaining a native seed network in Europe would be very promising for similar studies on this topic to better find and access professionals.

Field emergence from 'farm' produced seed of *Papaver rhoeas* and *Silene vulgaris* grown in three countries was omitted from this thesis due to very low germination in the transects. It could be due to a number of confounding factors such as dormancy, competition, and environmental conditions such altitude, temperature, precipitation, and soil type. Germination results in the lab, were challenging to compare due to the variability in seed age, number of generations multiplied, seed size, and storage regime. Future research should compare quality aspects (seed mass variability, germination speed, etc.) of produced seed lots with wild accessions to examine which species and traits may be more vulnerable to inadvertent human selection. Nematodes were present in one *Silene* seed accession and were identified to be two bacterial feeders: *Plectus* sp. and *Panagrolaimus* sp. which are climate sensitive and can influence moss substratum (Barbuto & Zullini 2006). Little is known or required on native seed health or phytosanitation. Work in this field is greatly lacking and could have implications on the native seed trade as well as movement between countries and seed zones.

Lastly, testing the novel bio-specimen code (SPREC) label and weighting system on numerous and families and species could aid in creating a native seed registry on seed biology, but also create modifications and/or limitations for future use of U-SeeD.

ACKNOWLEDGEMENTS

Funding for this project was possible by the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n°607785. I would like to begin by graciously thanking my family and partner for helping me overcome adversity, stay true to myself, and persevere. This experience has made me more interdisciplinary, intersectoral and wise. A tremendous thanks goes to Prof. Hugh Pritchard for his invaluable mentorship and academic supervision throughout these last three years. Thanks also to Giles Laverack for his guidance and for allowing me to visit his company on multiple occasions, where I was able to better understand the inner workings of native seed harvesting, processing, and production. I am grateful for the support I received from my external adviser Dr. Heidi Hauffe and from my supervisor Dr. Rovero, and previous input from Costa Bonomi. I would like to thank the NASSTEC consortium for providing a supportive environment for Early Stage Researchers. Lastly, many thanks to all the other ESRs, my field assistants, Nicola Angeli, and last, but not least to Emma Ladouceur & Angela Ruggiero for your friendship and support.

REFERENCES

Aronson J, Alexander S (2013) Ecosystem restoration is now a global priority: time to roll up our sleeves. Restoration Ecology 21:293–296

Balding M, Williams KJH (2016) Plant blindness and implications for plant conservation. Conservation Biology DOI: 10.1111/cobi.12738

Barbuto M, Zullini A (2006) Moss inhabiting nematodes: influence of the moss substratum and geographical distribution in Europe. Nematology 8:575-582

Baskin CC, Baskin JM (2014) Seeds. Ecology, biogeography, and evolution of dormancy and germination. 2nd Edition. Elsevier Inc. San Diego, California

Bouwma IM, van Apeldoorn R, Kamphorst DA (2010) Current practices in solving multiple use issues of Natura 2000 sites: Conflict management strategies and participatory approaches. Alterra, Wageningen, the Netherlands

Bradshaw A (1997) Restoration of mined lands—using natural processes. Ecol. Eng. 8:255-269

Broadhurst LM, Jones TA, Smith FS, North T, Guja L (2016) Maximising seed resources for restoration in an uncertain future. Bioscience 66:73-79

CBD (Convention on Biological Diversity) (2010) Find National Targets https://www.cbd.int/nbsap/targets/default.shtml (accessed 18 April 2016)

Clewell AF, Aronson J (2007) Ecological restoration principles, values, and structure of an emerging profession. Island Press. Washington, D.C.

Cortina-Segarra J, Decleer K, Kollmann J (2016) Biodiversity: speed restoration of EU ecosystems. Nature 535: 231

Ellen R, Platten S (2011) The social life of seeds: The role of networks of relationships in the dispersal and cultural selection of plant germplasm. Journal of the Royal Anthropological Institute 17:563-584

European Commission (1966) Council Directive 66/401/EEC of 14 June 1966 on the marketing of fodder plant seed. Official Journal of the European Communities 2298:132-142

European Commission (2010) Commission Directive 2010/60/EU of 30 August 2010 providing for certain derogations for marketing of fodder plant seed mixtures intended for use in the preservation of the natural environment. Official Journal of the European Union 228:10-14

Goodstein EB (1994) Jobs and the environment. The myth of a national trade-off. Economic Policy Institute. Washington D.C.

Hampton JG, Hill MJ (2002) Seed quality and New Zealand's native plants: An unexplored relationship? New Zealand Journal of Botany 40:357-364

Harding K, Benson EE, da Costa Nunes E, Kokowicz Pilatti F, Lemos J, Viana AM (2013) Can biospeciman science expedite the *ex situ* conservation of plants in megadiverse countries? A focus on the flora of Brazil. Critical Reviews in Plant Sciences 32:411-444.

Haslgrübler P, Krautzer B, Blaschka A, Graiss W, Pötsch EM (2013) Quality and germination capacity of seed material harvested from an Arrhenatherion meadow. Grass and Forage Science 69:454-461

Keulartz J (2009) European Nature Conservation and Restoration Policy–Problems and Perspectives. Restoration Ecology 17:446–450

Ladouceur E, Jiménez-Alfaro B, Marin M, De Vitis M, Abbandonato H, Iannetta PPM, Bonomi C, Pritchard H (2017) Native seed supply and the ecological restoration species pool. Conservation Letters. DOI:10.1111/conl.12381

Mace GM (2014) Whose Conservation? Science. 345:1558-1560

Merritt DJ, Dixon KW (2011) Restoration seed banks— a matter of scale. Science 332: 424-425

Muller S, Dutoit T, Alard D, Grévilliot F (1998) Restoration and rehabilitation of species-rich grassland ecosystems in France: a review. Restoration Ecology 6:94–101

Royal Botanic Gardens Kew (RBGK) (2016) State of the world's plants. https://stateoftheworldsplants.com/2016/report/sotwp_2016.pdf (accessed 23 January 2017)

SER (Society for Ecological Restoration) 2016. An overview of ecological restoration in Europe Session. Presented at SER Europe Conference, Freising, Germany

UN/ECE (United Nations Economic Commission for Europe) (2009) UNECE STANDARD EGG-1 concerning the marketing and commercial quality control of edible hen eggs-in-shell. https://www.unece.org/fileadmin/DAM/trade/agr/standard/eggs/Recommendations/EGG01_EggsInShell_2009_e.pdf (assessed 15 May 2017)

Veteto JR, Skarbø K (2009) Sowing the seeds: anthropological contributions to agrobiodiversity studies. Culture and Agriculture 31:73–87

Wilson JB, Peet RK, Dengler J, Partel M (2012). Plant species richness: the world records. J. Veg. Sci. 23:796-802

OTHER PUBLICATIONS

The following publications and activities transpired during my enrollment as a Marie-Curie Early Stage Researcher and PhD candidate from October 2014 to September 2017. A manuscript on climate change and plant phenology was submitted in a special issue from my Master's thesis on plant ecology and is now undergoing the re-submission process. I co-authored an article in The Mediterranean Garden Society with Marcello De Vitis. I contributed to six NASSTEC handbook chapters on policy, germination protocols, fit-for-purpose seed, certification, the Mediterranean pilot project, and the state of the native seed industry and restoration species pool. I participated in seven conferences and prepared 10 presentations in the various forms: oral presentation, poster, workshop, and panel. I completed a number of educational outreach events both online, in person and on TV. I was the Early Stage Researcher Representative for NASSTEC from 1/11/2014 to 1/07/2016.

PUBLICATIONS IN PEER-REVIEW JOURNALS

Abbandonato H, Semenchuk PR, Elberling B, Cooper EJ (2016) Snowmelt timing and soil temperature as important drivers for autumn senescence in High Arctic Svalbard. Submitted to Environmental Research Letters (29/07/2016).

Ladouceur L, Jimenez-Alfaro B, Marin M, De Vitis M, **Abbandonato H**, Iannetta PPM, Bonomi C, Pritchard HW (2017) Native seed supply and the restoration species pool. Conservation Letters DOI: 10.1111/conl.12381 (see Appendix)

BOOK CHAPTERS

Abbandonato H (2017) The EU regulatory framework for ecological restoration and the use of native seeds. In: NASSTEC Handbook. Unpublished.

Abbandonato H (2017) Protocols for germination, cultivation, propagation: *Papaver rhoeas*. In: NASSTEC Handbook. Unpublished.

Abbandonato H, Fiegener R (2017) How to evaluate the fit-for-purpose seed. In: NASSTEC Handbook. Unpublished.

De Vitis M, **Abbandonato H**, Marin M, Pedrini S (2017) Native seed certification cases. In: NASSTEC Handbook. Unpublished

Frischie S, **Abbandonato H**, Hernández González M, Galvez C (2017) Mediterranean pilot project. In: NASSTEC Handbook. Unpublished.

Ladouceur E, **Abbandonato H**, De Vitis M (2017) The state of the native seed industry in Europe and the Restoration Species Pool (RSP). In: NASSTEC Handbook. Unpublished.

De Vitis M, **Abbandonato H** (2016) The NASSTEC Project: Promoting the Use of Native Seeds to Preserve Local Biodiversity. In: The Mediterranean Garden Society. No. 85 July 2016. Pgs 62-65.

CONFERENCE PRESENTATIONS

Abbandonato H, Pritchard HW (2017) A bottom-up approach to native seed quality and certification: Is EU policy fit-for-purpose. *Natural capital from native seeds NASSTEC conference at Kew Gardens. Richmond, U.K.*

De Vitis M, **Abbandonato H**, Bonomi C, Pedrini S (2017) The role of networks connecting native seed stakeholders and improving success in ecological restoration. *Oral presentation at the 7th World Conference on Ecological Restoration, Iguassu, Brazil.*

Abbandonato H, Pedrini S, De Vitis M, Bonomi C, Pritchard HW (2017) A bottom-up approach to seed quality and certification: a survey of the native seed community. *Oral presentation at the National Native Seed Conference, Washington DC, U.S.A.*

Abbandonato H, Bonomi C, Pritchard H, Laverack G, Pedrini S (2016) Ecological restoration policy and a native seed solution: can we seed the future of Europe? *Oral presentation at the Society for Ecological Restoration Conference, Freising, Germany.*

De Vitis M, Laverack G, **Abbandonato H**, Bonomi C (2016) A European tool to facilitate knowledge transfer among native seed producers, researchers and users. *Poster presentation at the Society for Ecological Restoration Conference, Freising, Germany.*

Bonomi C, Laverack G, Marin M, **Abbandonato H**, Dello Jacovo E, Blandino C, Hernández González M, Lopez del Egido L (2015) The current status, challenges, and opportunities in seed production and use for grassland restoration – a global perspective. *Workshop at the 6th World Conference on Ecological Restoration, Manchester, U.K.*

Abbandonato H, Laverack G, Pritchard H, Bonomi C (2015) Policy and certification for native seed restoration in Europe. *Poster presentation at the 27th International Congress for Conservation Biology, Montpellier, France.*

Abbandonato H, Frischie S (2015) Reaching out to society: explaining the importance of native seeds. *Poster presentation at the 27th International Congress for Conservation Biology, Montpellier, France.*

Abbandonato H, Laverack G, Pritchard H, Bonomi C (2015) Bridging the gap between academia and industry: using current regulations and practices to develop a certification scheme for native plant species in Europe. *Oral presentation at the National Native Seed Conference, Santa Fe, NM, U.S.A.*

Bonomi C, Gálvez Ramírez C, Dixon K, **Abbandonato H**, Frischie S, Lopez del Egido L (2015) Global networking to benefit seed production: exchanging experiences and production models. *Panel at the National Native Seed Conference, Santa Fe, NM, U.S.A.*

OUTREACH AND PUBLIC ENGAGEMENT

Written article for the International Network for Seed-Based Restoration, SER chapter on: *Taking a holistic approach to ecosystem restoration using native seeds* (29/04/2017);

NASSTEC display at Europe Day (14/05/2016);

NASSTEC display at Researcher's Night (25/09/2016);

NASSTEC display at Ecsite Annual Conference (12/05/2015);

NASSTEC display at engres Marie Sklodowska Curie Conference (18/11/2014); and,

NASSTEC interview by Trentino TV - Mille Nature Ambiente Trentino (8/12/2014).

Paper 1:

Abbandonato H, Pedrini S, Pritchard HW, De Vitis M, Bonomi C (in press.) Native seed trade of herbaceous species for restoration: a European policy perspective with global implications. Restoration Ecology, DOI:10.1111/rec.12641

Native seed trade of herbaceous species for restoration: a European policy perspective with global implications

Running Head: Herbaceous native seed policies for restoration

Holly Abbandonato[1, 2, 3], Simone Pedrini[4, 5], Hugh W. Pritchard[6], Marcello De Vitis[7], and Costantino Bonomi[1]

[1]MUSE – Science Museum, Corso del Lavoro e della Scienza, 3, 38122, Trento, Italy

[2]University of Pavia, Corso Strada Nuova, 65, 27100, Pavia, Italy

[3]Address correspondence to H. Abbandonato, email h.abbandonato@gmail.com

[4]Curtin University, Kent Street, Bentley, Perth, Western Australia, 6102

[5]Kings Park and Botanic Garden, Fraser Avenue, Kings Park, Western Australia, 6005

[6]Royal Botanic Gardens, Kew, Wellcome Trust Millennium Building, Wakehurst Place, Ardingly, West Sussex, RH17 6TN, UK

[7]Scotia Seeds, Mavisbank, Brechin, DD9 6TR, UK

Type: Policy Article

Author contributions:

HA, CB conceived the purpose of the study reported; HA was the lead writer and designer; HA, MDV designed the figures and tables; and manuscript revision was given by SP, HWP, MDV, CB.

Abstract

With the need to meet ambitious restoration targets, an improved native seed sector for the production of herbaceous species with a practical and supportive policy framework is recognized. We evaluated the current 'ready made' policy frameworks in Europe regarding the native seed supply of herbaceous species and found them to be, generally, unsatisfactory for both producers and users. Initially, such policies were designed for fodder seed and relate to distinctness, uniformity, and stability; traits that do not reflect the genetic heterogeneity of native species required for ecological restoration. Until recently, more suitable certification standards were designed to multiply fodder seed for preservation of the natural environment; however, due to the disparateness of the seed market in Europe this policy is rarely practical and fails to encompass all herbaceous native species often resulting in unregulated seed sales. We recommend a new or adapted native seed policy constructed through a participatory or bottom-up approach and supported through the formation of widely-based trade associations. Such a policy could stimulate the native seed trade with concomitant impacts on the speed of improving ecosystems services.

Key words: bottom-up approach, certification, fodder seed, native seed production, seed policy, seed quality.

Implications for Practice

- When multiple stakeholders are involved, a participatory or bottom-up approach should be used to adapt or devise a new native seed policy for restoration.
- Native seed policy should start by being applicable to all species to prevent the sale of seeds of unknown origin and quality.
- Member states can modify regulations based on the development of their seed market.
- Native seed regulations need to focus on protecting genetic integrity by applying certification procedures that are not agriculturally based (distinctness, uniformity, and stability).
- Quantitative restrictions in seed policies limit market expansion and do not facilitate the demand for large quantities of herbaceous native seed for ecological restoration.

Introduction

Policy steps to protect biodiversity ensure ecosystem resilience, and combat environmental change is at the forefront of United Nations and other institutional initiatives. The connection between ecosystem services and society (Target 14), and the restoration of 15% of degraded ecosystems around the world (Target 15) has been emphasized in the UN Convention on Biological Diversity (CBD) Strategic Plan for Biodiversity 2011-2020 (CBD 2015; CBD 2016). However insufficient progress of the targets by European members states has occurred since the mid-term assessment (**Table 1**; CBD 2012), even after implementing the European Union's Biodiversity Strategy to 2020 (EU Commission 2015). Since the baseline assessment, grasslands, croplands and urban ecosystems have continued to decline (EU COM/2015/0478). The Global Strategy for Plant Conservation has ensured protection of c. 10% in situ by area of terrestrial ecosystems, and 66 countries now have seed banks for native plant conservation (CBD 2014);

however, the availability of seed material is limited for restoration efforts (Bekessey et al. 2010). Vast quantities of native seed are required for large-scale restoration and demands cannot be met by relying solely on wild resources (Merritt & Dixon 2014). Seed supply costs vary and can impose financial constraints on restoration practices (Broadhurst et al. 2016), since seed yield and quality (including dormancy) fluctuates with inter and intra-variability in pollen flow, natural disturbances and climate variability (Broadhurst et al. 2016; Merritt & Dixon 2014). Preference towards using a few core species and/or non-native seed mixtures (Broadhurst et al. 2016; Tischew et al. 2011), also increases the risk of hybridization with natural populations inducing changes in genetic diversity (Schröder & Prasse 2013). There is the need to identify 'local' seed production areas (SPA) or seed zones (Durka et al. 2016; Nevill et al. 2016) so that plant material is adapted to the site conditions (Broadhurst et al. 2016; Bischoff et al. 2010; Hufford & Mazer 2012; Tischew et al. 2011), since seeds multiplied in dissimilar environments from the restoration site may not be considered "restoration-ready" (Chivers 2016).

Table 1. International and European targets for ecological restoration to be implemented through national actions and reporting.

Organizer	*Strategy*	*Target*
United Nations Convention on Biological Diversity (CBD)	Strategic Plan for Biodiversity 2011-2020	**Target 14** *"By 2020, ecosystems that provide essential services, including services related to water, and contribute to health, livelihoods and well-being, are restored and safeguarded, taking into account the needs of women, indigenous and local communities, and the poor and vulnerable."* **Target 15** *"By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced, through conservation and restoration, including restoration of at least 15 per cent of degraded*

		ecosystems, thereby contributing to climate change mitigation and adaptation and to combating desertification."
United Nations Convention on Biological Diversity (CBD)	Global Strategy for Plant Conservation (GSPC)	**Target 4** *"At least 15 per cent of each ecological region or vegetation type secured through effective management and/or restoration."* **Target 8** *"At least 75 per cent of threatened plant species in ex situ collections, preferably in the country of origin, and at least 20 per cent available for recovery and restoration programmes."*
EU Commission	EU Biodiversity Strategy to 2020	**Target 2** *"By 2020, ecosystems and their services are maintained and enhanced by establishing green infrastructure and restoring at least 15 % of degraded ecosystems."*

However, much of the native seed market in Europe regarding herbaceous species is unregulated and poor seed quality is a common occurrence (Haslgrübler et al. 2013; Laverack et al. 2007; Marin et al. 2017; Ryan et al. 2008). In the UK, the native seed market is estimated to grow to 120-140 tons and be worth £ 9-17 million by 2019/2020 (UK Native Seed Hub 2011).

Whilst the projected need globally to restore 150 million hectares of disturbed or degraded land by 2020 requires U.S. $18 billion investment per year, the benefit to the global economy would be c. U.S. $84 billion (Menz et al. 2013). An analysis of more than 200 studies indicates that the cost-benefit ratio of ecological restoration is as high as 35:1 for grasslands (De Groot et al. 2013). Whilst the economic case to intervene and restore native vegetation is strong, the current policy environment in Europe appears insufficient to stimulate the expansion of native seed production of herbaceous species.

Our aim in this commentary has been to: 1) evaluate existing policies regulating the trade of native herbaceous seeds; 2) examine alternative seed directives; and 3) suggest how policy can evolve to better enable the native seed trade to adequately support internationally agreed ecological restoration targets.

Herbaceous Native Seed Policy in Europe

Historically, seed quality assurance policies were designed around the "truth in labeling" concept to protect the farmer from negative externalities (Copeland & McDonald 2001). These focus on the commercialization of a product, but can be influenced by international agreements on Intellectual Property, biosafety, and business regulations (Louwaars 2008). In Europe, seed policies in the agricultural sector (i.e., varieties) are based on the certification of minimum standards. Legislation that affects native seed in Europe includes the protection of habitats and species (EU Commission 1992) and fodder (EU Commission 1966; EU Commission 2010) with no specialized or comprehensive inclusion of native seed for restoration (**Fig. 1**).

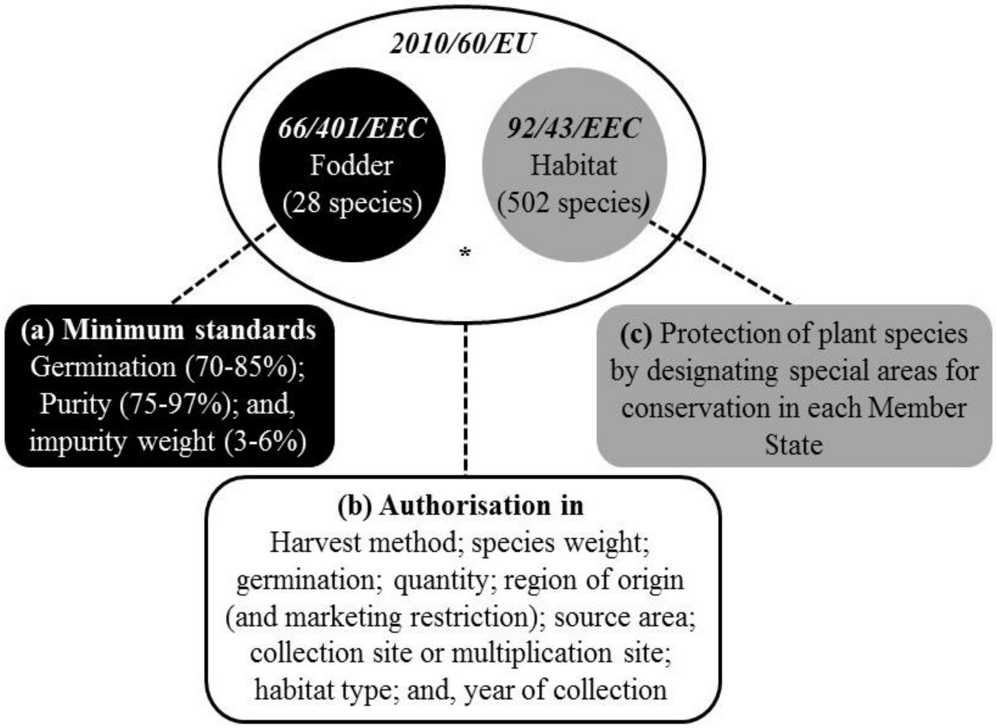

Figure 1. Seed quality policy requirements applicable to the marketing of native species in Europe. (a) Corresponds to the directive 66/401/EEC for fodder plant species certified as commercial seed (the lowest certification) using the minimum standards; (b) corresponds to the directive 2010/60/EU requiring authorisation in fodder seed mixtures to preserve the natural environment; and, (c) corresponds to the directive 92/43/EEC designating specific protected areas for at risk species.

*Species not listed, but can be certified as commercial seeds in 66/401/EEC include conservation varieties from 2008/62/EC and other species under comparable source areas rules.

The EU Directive on the conservation of habitats and species (92/43/EEC) covers 502 species of vascular plants with conservation status (**Table 2**; EU Commission 1992). These species are prioritized for action under the Natura 2000 European ecological network implementing the goals of the EU Biodiversity Strategy and ultimately the CBDs Aichi Biodiversity Targets to restore 15% of degraded land. But in the EU, insufficient seeds of these species are commercially available, and germination data is not freely accessible in comparison to indicator and fodder species (Ladouceur et al. 2017). This may be due to economic reasons (hard to produce) and access (e.g. need for collection permits). Nonetheless, this convergence of factors has resulted in four times more restoration outside than within the Natura 2000 network (Dickie 2016).

The EU directive on the marketing of fodder plant seed (66/401/EEC) is the primary EU regulation applicable to native seeds (Table 2; EU Commission 1966). It covers 24 species and four genera (*Agrostis*, *Lolium*, *Poa*, *Vicia*) of grasses and legumes and requires minimum standards of seed germination (<75 - 85%), seed purity (<75 - 97%), and restrictions on the presence of weed seed. Of the species listed, 48% are native to European grasslands (Ladouceur et al. 2017), provide important ecosystem services, and occur in extremely biodiverse habitats (Bischoff et al. 2006). The directive impacts the native seed industry even though it was designed for fodder quality assurance. Unlike crop varieties, the seeds of native species rarely reach minimum seed standards for germination and purity, due to their natural heterogeneity (Broadhurst et al. 2016; Lesica & Allendorf 1999) and do not easily conform to the agricultural sector requirements of distinctiveness, uniformity and stability (DUS). Although no standardized definition of seed quality for native seeds exists, there is agreement that seed for restoration purposes should be sourced locally to maintain genetic integrity (**Fig. 2**).

Table 2. European directives applicable to the marketing of native seed.

Legislation	*Organizer*	*Number*	*Title*	*Website*
Directive	European Economic Community (EEC)(EEC)	66/401/EEC	Council Directive of 14 June 1966 on the marketing of fodder plant seed	http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:31966L0401
Directive	European Economic Community (EEC)	92/43/EEC	Council Directive of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora	http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31992L0043
Directive	European Union (EU)	2010/60/EU	Commission Directive of 30 August 2010 providing certain derogations for marketing of fodder plant seed mixtures intended for use in the preservation of the natural environment	http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32010L0060

The EU directive on fodder plant seed mixtures (2010/60/EU) for the “conservation of genetic resources” is the first regulatory attempt to harmonize agricultural production and conservation/restoration needs (**Table 2**; EU Commission 2010). It includes fodder species listed under Directive (66/401/EEC), species with special habitat concerns (92/43/EEC), conservation varieties (2008/62/EC) and other species required for preservation of natural and semi-natural habitats (**Fig. 1**). Seed used must be from “source areas” listed in the Natura 2000 network or areas under comparable rules. A quantitative restriction limits the total yearly production of seed for preservation mixtures to not exceed 5% of the total weight of fodder seed certified from

Council Directive 66/401/EEC per member state. This ceiling, originally set to protect the fodder variety industry from unfair competition, could severely limit the growth of the native seed market. This directive is not actively used in many European countries as most native species are not categorized as fodder or sourced exclusively from Natura 2000 areas. This directive does provide unique labeling requirements and, for the first time, labeling specifications of origin and provenance (**Fig. 1**). However, further labeling obligations that enable comparison with agricultural seed lots are often too demanding for a nascent industry, as knowledge of native seed quality (germination, dormancy breaking treatments, viability, purity), particularly of the most threatened species, may be lacking in many countries (Ladouceur et al. 2017; Wade et al. 2016). Today, one-third of Europe is without an herbaceous native seed industry. In more developed markets, independent native seed certification schemes exist, such as those operated in Austria, France, and Germany. However, the strict enforcement of regulations of native seed lots in less developed markets could stimulate unregulated seed sales of non-certified seeds.

Alternative Seed Policies with a Lighter Touch

With the European Union's demonstrable interest in protecting genetic resources and biodiversity, it is recommendable to develop policies that support the sustainable trade of herbaceous native seeds for large-scale restoration. Certification and labeling requirements must be simple when a policy has an EU-wide application (**Fig. 2**), taking into account relevant economic, political and technological factors in each member state (Tripp 2002).

Closest in essence to the market needs for native seed supply and demand, are the forestry and landraces directives which have specialized procedures relating to the reproduction of plant material while still protecting biodiversity. For example, the EU Directive on the marketing of forest reproductive material (1999/105/EC) stresses the importance of genetic and phenotypic suitability, and external quality standards of reproductive material (EU Commission 1999). Source identified tree seeds must be from a single region of provenance and identity must be labeled on the certificate. A national register for basic material is required by each member state and a supplier's label must also include purity, germination or viability, seed weight and live seed. The OECD (2016) forest seed and plant scheme uses similar minimum requirements with approval on origin, population size, and adaptation and resistance for source-identified seed.

Conservation varieties or landraces (2008/62/EC) are considered to be plant genetic resources and biodiversity for varieties of agricultural species (EU Commission 2008). Member states have the flexibility to decide DUS to be used for in situ conservation based on Directive 2003/90/EC and are exempt from official certification. This basic and limited form of regulation enables member states to decide species-specific quality criteria.

Even more liberal is the legislation for the marketing of ornamental plants (98/56/EC), requiring only the tracking of processes and materials, i.e. an audit trail. However, these species may end up being used in restoration if other seeds are not available and, as evidenced recently, can contribute the spread of diseases, e.g., ash die back in the UK (Thomas 2016). In contrast, the

International Seed Testing Association uses accredited laboratories to issue certificates of quality for agricultural, flower and tree seed lots in the trade based on purity and viability (ISTA 2009).

Herbaceous native seeds should also be considered as genetic resources, and be assigned similar protection, particularly as temperate grasslands in Continental Europe are considered conservation hotspots due to their high species richness (Wilson et al. 2012). The need for a lighter legislative framework is illustrated by Germany's ambition, under the Nature Protection and Landscape Conservation Act, to exclusively use native plant material for all restoration projects (§40 (4) Nr.51 vom 06.08.2008) by March 2020. The German native seed market is expecting a ten-fold growth and will likely exceed the 5% fodder quota (http://ser-insr.org/webinars/2016/11/17/native-seed-production-in-germany).

Closing the Gap between Users and Producers

Our review of the policy arena suggests that a more pragmatic policy for native seed quality assurance is needed that does not follow the DUS principles, but accounts for the genetic diversity while still ensuring basic product quality to prevent negative externalities, such as disease or the loss of genetic biodiversity (**Fig. 2**). We see this to some degree in the United States, as the Federal Seed Act demands that all seed batches sold present a purity and germination label (Jones & Young 2005) and wild collected native seeds can be certified as source-identified (i.e., with origin on the label) (Young et al. 2003). Furthermore, the Bureau of Land Management's National Seed Strategy for Rehabilitation and Restoration is currently characterizing federal policies, tools and storage facilities aiming to "put the right seed in the right place at the right time" (Oldfield & Olwell 2015; PCA 2015). As noted, the (re)establishment of the plant community is critical to initiating ecosystem change towards the desired trajectory (SER 2004). Such an initiative falls squarely behind the new, 2015 sustainable development goals (http://www.sustainabledevelopment2015.org/), including actions to protect the planet. There is an urgent need for Europe to follow this lead.

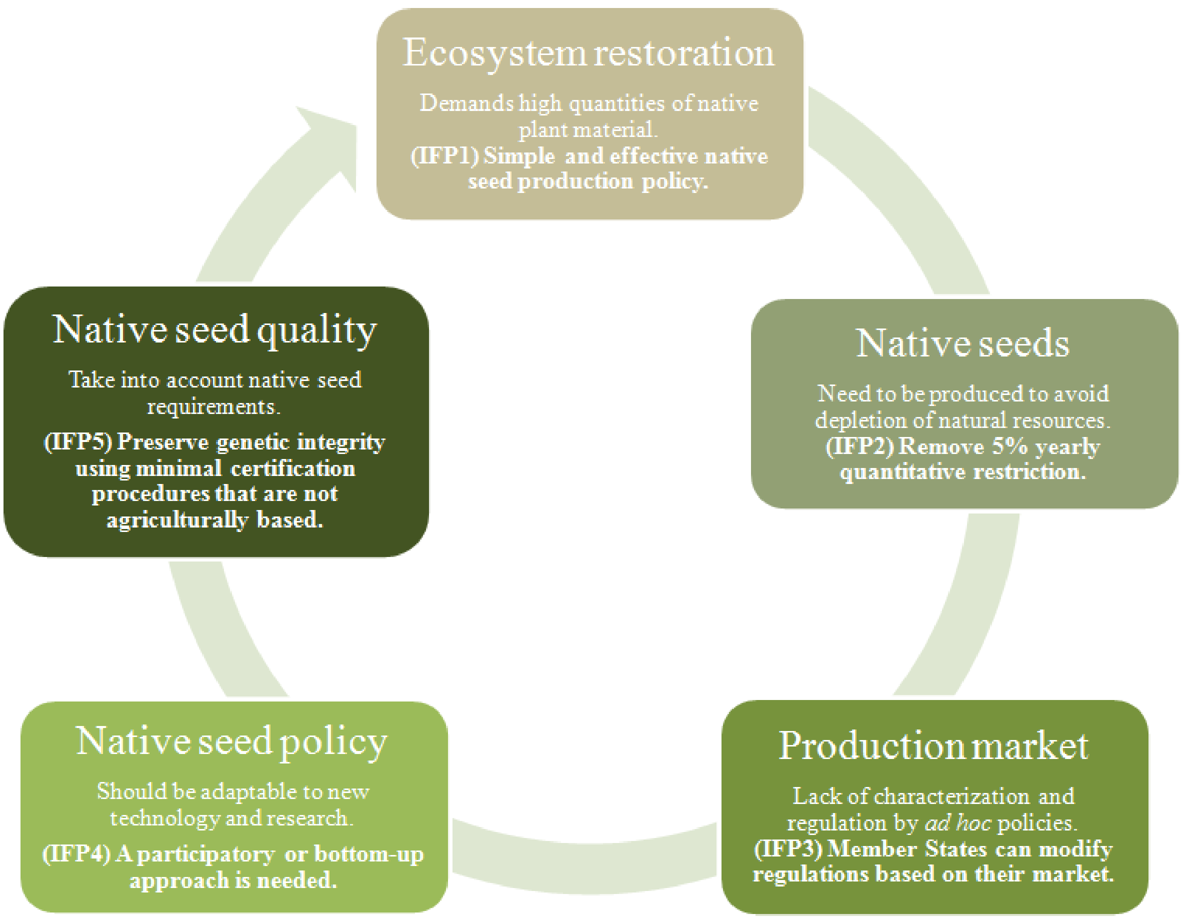

Figure 2. Implications for practice (IFP) at-a-glance. (1) **Ecosystem restoration.** The need for a well-developed native seed industry stems from the urgent need to restore ecosystems on a large-scale to protect ecosystem services and maintain biodiversity. (2) **Native seeds**. The need to use and multiply native herbaceous seeds to preserve genetic integrity, and maintain ecosystem resilience over the long-term. (3) **Production market.** Is dynamic and unique in each member

state; however, using a one-size fits all policy to regulate native seeds is not satisfactory while the market is still under developed in many member states. (4) **Native seed policy**. Top-down policies that exclude users and follow agriculturally based standards (DUS) are problematic for the native seed industry. A revised or new flexible policy that considers the needs of the users and producers would be beneficial. (5) **Native seed quality.** To protect the buyer and seller, a simple product quality scheme needs to be determined for native seeds that is not agriculturally based and takes a user approach.

Action can be taken at a number of levels, as current restoration activity supports about 10,000 jobs, although the potential is 25,000 jobs to meet the Natura 2000 15% target of restored land; however, this activity is not well documented (Dickie 2016). The Common Agricultural Policy (CAP) is offering farmers additional payments conditional on landscape greening improvements (2013/1307/EU), an initiative that could greatly benefit from an expanded herbaceous native seed industry. However, the full potential of these economic and environmental opportunities, including job creation will only be realized through improved intersectoral efforts.

Policy development involving diverse stakeholder groups using a participatory approach helped the implementation process of Natura 2000 after a top-down approach was originally taken (Keulartz 2009). The European Commission is now looking to solve multiple land use concerns from the Natura 2000 sites by building a toolkit using member state experiences (Bouwma et al. 2010). More widely, recent successes in restoration planning and implementation have combined ecological, economic, and cultural considerations, including FAOs' Great Green Wall of Africa, the Satoyama initiative, and the Ecological Restoration Alliance of Botanic Gardens (IPSI 2016; Sacande & Berrahmouni 2016; Sharrock et al. 2014).

Finally, to improve or create a new policy that takes into account genetic diversity and product quality, there is a need to define herbaceous seed quality among users and determine what type and level of regulation is favoured in this growing marketplace (**Fig. 2**). To provide ample policy support, the identification of key issues in supply and demand, linking communities, stakeholders, practitioners, and researchers is needed (Jalonen et al. 2014) and could be determined using a participatory or bottom-up approach. Most likely, this could be facilitated by the establishment of a native seed trade association that unites producers in Europe, commissions research, embraces public engagement, promotes education and collectively negotiates legislations that address the needs of the native seed market. Emphasis on regulatory frameworks that includes both landscape restoration and seed production goals will only be pertinent and effective if they are devised and implemented by both producers (farmers, retailers, etc.) and users (NGOs, government bodies, charities, researchers, etc.).

Conclusion

This commentary examined how EU-wide policies regulate the herbaceous native seed trade in Europe, primarily by considering herbaceous species for restoration as animal feed (fodder). While the recent fodder mixture directive (2010/60/EU) does consider the preservation of genetic resources, it is still not functional for native seed businesses, consequently limiting seed availability and the capability to perform large-scale restoration. To regulate native seeds on an

EU-wide level, a supportive policy is required that maintains genetic integrity and product quality, but does not strictly follow the agricultural model of DUS. We propose that the current policy directive (2010/60/EU) is either modified or replaced by an *ad hoc* policy underpinning the needs of the seed users and producers regarding seed quality and certification to facilitate both local and large-scale ecosystem restoration using herbaceous species in the coming years.

Acknowledgements

This research was funded by the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n°607785. The Royal Botanic Gardens, Kew receives grant-in-aid from Defra. We thank Rob Fiegener for the opportunity to present this topic at the National Native Seed Conference in 2015 and 2017, and for the invaluable feedback from Giles Laverack, Ted Chapman, Graziano Rossi, and Emma Ladouceur.

LITERATURE CITED

Bekessy SA, Wintle BA, Lindenmayer DB, Mccarthy MA, Colyvan M, Burgman MA, Possingham HP (2010) The biodiversity bank cannot be a lending bank. Conservation Letters 3:151-158

Bischoff A, Crémieux L, Smilauerova M, Lawson CS, Mortimer SR, Dolezal J, Lanta V, Edwards AR, Brook AJ, Macel M, Leps J, Steinger T, Müeller-Schärer, H (2006) Detecting local adaptation in widespread grassland species – the importance of scale and local plant community. Journal of Ecology 94:1130-1142

Bischoff A, Steinger T, Müller-Schärer, H (2010) The importance of plant provenance and genotypic diversity of seed material used for ecological restoration. Restoration Ecology DOI 10.1111/j.1526-100X.2008.00454.x

BNatSchG, Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (2010) Act on Nature Conservation and Landscape Management (Federal Nature Conservation Act – BNatSchG) of 29 July 2009. Federal Nature Conservation Act. 1

Bouwma IM, van Apeldoorn R, Kamphorst DA (2010) Current practices in solving multiple use issues of Natura 2000 sites: Conflict management strategies and participatory approaches. Alterra, Wageningen, the Netherlands

Broadhurst LM, Jones TA, Smith FS, North T, Guja L (2016) Maximising seed resources for restoration in an uncertain future. Bioscience 66:73-79

CBD (Convention on Biological Diversity) (2012) Global Biodiversity Outlook 4 https://www.cbd.int/gbo4/ (accessed 13 May 2015)

CBD (Convention on Biological Diversity) (2014) Progress in achieving the targets of the global strategy for plant conservation 2011-2020 (UNEP/CBD/SBSTTA/18/3) https://www.cbd.int/doc/meetings/sbstta/sbstta-18/official/sbstta-18-03-en.pdf (accessed 13 May 2015)

CBD (Convention on Biological Diversity) (2015) History of the convention, introduction https://www.cbd.int/history/ (accessed 5 May 2015)

CBD (Convention on Biological Diversity) (2016) CBD COP13 decision XIII/23 https://www.cbd.int/doc/decisions/cop-13/cop-13-dec-23-en.pdf (accessed 12 October 2017)

Chivers IH, Jones TA, Broadhurst LM, Mott IW, Larson SR (2016) The merits of artificial selection for the development of restoration-ready plant materials of native perennial grasses. Restoration Ecology DOI 10.1111/rec.12323

Copeland LO, McDonald MB (2001) Seed Science and Technology 4th Edition. Kluwer Academic Publishers, Massachusetts

De Groot RS, Blignaut J, Van Der Ploeg S, Aronson J, Elmqvist T, Farley J (2013) Benefits of investing in ecosystem restoration. Conservation Biology 27:1286-1293

Dickie I (2016) Ecosystem Restoration in the EU – Biodiversity Strategy Target 2 Delivery. Presented at SER Europe, Freising, Germany

Durka W, Michalski S, Berendzen KW, Bossdorf O, Bucharova A, Hermann J-M, Holzel N, Kollmann J (2016) Genetic differentiation within multiple common grassland plants supports seed transfer zones for ecological restoration. Journal of Applied Ecology DOI 10.1111/1365-2664.12636

European Commission (1966) Council Directive 66/401/EEC of 14 June 1966 on the marketing of fodder plant seed. Official Journal of the European Communities 2298:132-142

European Commission (1992) Council Directive 92/43/EEC of 21 of May 1992 on the conservation of natural habitats and wild fauna and flora. Official Journal of the European Communities 206:7-50

European Commission (1998) Council Directive 98/56/EC of 20 of July 1998 on the marketing and propagating material of ornamental plants. Official Journal of the European Communities 226:16-23

European Commission (1999) Commission Directive 1999/105/EC of 22 December 1999 on the marketing of forest reproductive material. Official Journal of the European Communities 11:17-40

European Commission (2008) Commission Directive 2008/62/EC of 20 June 2008 providing for certain derogations for acceptance of agricultural landraces and varieties which are naturally adapted to the local and regional conditions and threatened by genetic erosion and for marketing of seed and seed potatoes of those landraces and varieties. Official Journal of the European Union 162:13-19

European Commission (2010) Commission Directive 2010/60/EU of 30 August 2010 providing for certain derogations for marketing of fodder plant seed mixtures intended for use in the preservation of the natural environment. Official Journal of the European Union 228:10-14

European Commission (2013) Regulation (EU) No 1307/2010 of the European Parliament and of the council of 17 December 2013 establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation (EC) No 637/2008 and Council Regulation (EC) No 73/2009. Official Journal of the European Union 347:608-670

European Commission (2015) EU Biodiversity to 2020 – towards implementation. The European Union Parliament adopts resolution on the EU 2020 Biodiversity Strategy http://ec.europa.eu/environment/nature/biodiversity/comm2006/2020.htm (accessed 12 June 2015)

European Commission (COM) 478 of 2 October (2015) report from the commission to the European parliament and of the Council [2015]

Haslgrübler P, Krautzer B, Blaschka A, Graiss W, Pötsch EM (2013) Quality and germination capacity of seed material harvested from an Arrhenatherion meadow. Grass and Forage Science 69:454-461

Hufford KM, Mazer SJ (2012) Local adaptation and the effects of grazing on the performance of *Nassella pulchra*: implications for seed sourcing in restoration. Restoration Ecology 20:688-695

IPSI (The International Partnership for the Satoyama Initiative) (2016) Concept http://satoyama-initiative.org/en/about/ (accessed 22 September 2016)

ISTA (2009) ISTA Handbook on seedling evaluation 3rd edition. The International Seed Testing Association. Bassersdorf, Switzerland

Jalonen R, Thomas E, Cavers S, Bozzano M, Boshier D, Bordacs S, Gallo L, Smith P, Loo J (2014) Analysis of genetic considerations in restoration methods. Pages 245–448 In: Bozzano, M et al. editors. Genetic considerations in ecosystem restoration using native tree species. Food and Agricultural Organization of the United Nations. Rome, Italy

Jones TA, Young S (2005) Native seeds in commerce: More frequently asked questions. Native Plants Journal 6:286-293

Keulartz J (2009) European Nature Conservation and Restoration Policy–Problems and Perspectives. Restoration Ecology 17:446-450

Lammerant J, Peters R, Snethlage M, Delbaere B, Dickie I, Whiteley G (2013) Implementation of 2020 EU Biodiversity Strategy: priorities for the restoration of ecosystems and their services in the EU. Report to the European Commission. ARCADIS (in cooperation with ECNC and EFTEC)

Ladouceur E, Jiménez-Alfaro B, Marin M, De Vitis M, Abbandonato H, Iannetta PPM, Bonomi C, Pritchard HW (2017) Native seed supply and the restoration species pool. Conservation Letters 00:1-9

Laverack G, Matthews S, Powell AA, Hosseini MK (2007) Scottish wildflower seeds: production and use. Botanical Journal of the Linnean Society 58: 49-58

Lesica P, Allendorf FW (1999) Ecological genetics and the restoration of plant communities: Mix or match? Restoration Ecology 7:42-50

Louwaars NP (2008) Seed policy, legislation and law. Widening a narrow focus. Journal of New Seeds 4:1-14

Marin M, Toorop PT, Powell AA, Laverack G (2017) Tetrazolium staining predicts germination of commercial seed lots of European native species differing in seed quality. Seed Science & Technology 45:1-16

Menz MHM, Dixon KW, Hobbs RJ (2013) Hurdles and opportunities for landscape-scale restoration. Science 339:526-527

Merritt DJ, Dixon KW (2014) Seed availability for restoration. Pages 97–104 In: Bozzano, M et al. editors. Genetic considerations in ecosystem restoration using native tree species. Food and Agricultural Organization of the United Nations. Rome, Italy

Nevill PG, Tomlinson S, Elliot CP, Espeland EK, Dixon KW, Merritt DJ (2016) Seed production areas for the global restoration challenge. Ecology and Evolution 1-8

OECD (Organisation for Economic Cooperation and Development Trade and Agriculture Directorate) (2016) OECD scheme for the certification of forest reproductive material moving in international trade http://www.oecd.org/tad/code/oecd-forest-scheme-rules-and-regulations-en.pdf (assessed 3 July 2017)

Oldfield S, Olwell P (2015) The Right Seed in the Right Place at the Right Time. Bioscience 65:955-956

PCA (Plant Conservation Alliance) (2015) National seed strategy for rehabilitation and restoration 2015-2020 https://www.blm.gov/sites/blm.gov/files/program_natural%20resources_seed%20strategy_quick%20link_seed%20stregy.pdf (assessed 20 August 2016)

Ryan N, Laverack G, Powell A (2008) Establishing quality control in UK wildflower seed production. Seed Testing International 135: 49-53

Sacande M, Berrahmouni N (2016) Community participation and ecological criteria for selecting species and restoring natural capital with native species in the Sahel. Restoration Ecology 24:479-488

Schröder R, Prasse R (2013) Cultivation and hybridization alter the germination behavior of native plants used in revegetation and restoration. Restoration Ecology 21: 793–800

Sharrock S, Jones M (2009) Conserving Europe's threatened plants. Progress towards target 8 of the Global Strategy for Plant Conservation Botanic Gardens Conservation International, Richmond, UK

Society for Ecological Restoration International Science & Policy Working Group (2004) The SER International Primer on Ecological Restoration. www.ser.org & Tucson: Society for Ecological Restoration International

Thomas PA (2016) Biological flora of the British Isles: *Fraxinus excelsior*. Journal of Ecology DOI 10.1111/1365-2745.12566

Tischew S, Youtie B, Kirmer A, Shaw N (2011) Farming for restoration: building bridges for native seeds. Ecological Restoration 29:219-222

Tripp R (2002) Seed regulatory reform: an overview. Pages 103–115 In: N.P. Louwaars N, editor. Seed policy, legislation and law. Widening a narrow focus. Food Products Press, New York

UK Native Seed Hub (2011) 10 year business plan. Chris Blandford Associates http://www.kew.org/sites/default/files/UK%20Native%20Seed%20Hub%2010%20Year%20Business%20Plan.pdf (accessed 5 May 2015)

Wade EM, Nadarajan J, Yang X, Ballesteros D, Sun W, Pritchard HW (2016) Plant species with extremely small populations (PSESP) in China: A seed and spore biology perspective. Plant Diversity 38:209-220

Wilson JB, Peet RK, Dengler J, Partel M (2012). Plant species richness: the world records. J. Veg. Sci. 23:796-802

Young S, Schrumpf B, Amberson E (2003) The AOSCA Native Plant Connection. AOSCA

Paper 2:

De Vitis M, Abbandonato H (2017) Nature Correspondence. Nature, submitted.

Nature – Correspondence

Authors:
Marcello De Vitis
Affiliation/postal address: Scotia Seeds, Brechin, DD96TR, UK
Email address: marcellodevitis@scotiaseeds.co.uk
Telephone contact number: 00447549505676

Holly Abbandonato
Affiliation/postal address:
(1) MUSE - Science Museum, Corso del Lavoro e della Scienza, 3, 38122, Trento, Italy
(2) University of Pavia, Corso Strada Nuova, 65, 27100, Pavia, Italy
Email address: holly.abbandonato@muse.it
Telephone contact number: 00393664386177

Native seed production in Europe is predicted to play a pivotal role in the coming years to enable the acceleration of ecological restoration activities so that the 15% restoration target of the European Union's Biodiversity Strategy 2020 is delivered (*Nature* **535**, 231; 2016). However, in most European countries, the native seed production sector has few, if any, producers. Exceptions are, for example, in Austria, Germany and France, where more companies have been established and where producers and researchers have collaborated to create supportive tools, such as native seed certification standards and seed transfer zones. Even in these countries, meeting the demand for native seeds for restoration remains a challenge. Two issues largely contribute to this: (1) the application of restrictive policies and inappropriate standards developed within the agricultural sector, and (2) the lack of a European-wide strategy aimed at facilitating and strengthening coordination of production and intersectoral collaboration to deliver native seeds of high quality. In the USA, a National Seed Strategy for Rehabilitation and Restoration was designed to provide coordination between producers and users with the goal of restoring plant communities. In Europe, the need for a similar strategy for the seed sector is urgent and must incorporate revision of existing policies covering collection, production and use of native seeds. We believe that these standards should be based on existing scientific knowledge and inputs from the community of users (particularly the native seed industry and local end users) through a consultative participatory approach. This process is necessary to assist this emerging sector of native seed production which is essential to meet future restoration and climate change obligations.

Reference

Cortina-Segarra J., Decleer K. & Kollmann J. (2016) Biodiversity: Speed restoration of EU ecosystems. *Nature* **535**, 231; url: http://www.nature.com/nature/journal/v535/n7611/full/535231d.html

Paper 3:

Abbandonato H, De Vitis M, Pritchard HW (2017) Native seed community preferences for seed quality and certification for ecological restoration. Restoration Ecology, *manuscript.*

Native seed community preferences for seed quality and certification for ecological restoration

Running head: Native seed quality and certification

Holly Abbandonato[1, 2, 3], Marcello De Vitis[4], and Hugh W. Pritchard[5]

[1]MUSE – Science Museum, Corso del Lavoro e della Scienza, 3, 38122, Trento, Italy

[2]University of Pavia, Corso Strada Nuova, 65, 27100, Pavia, Italy

[3]Address correspondence to H. Abbandonato, email h.abbandonato@gmail.com

[4]Scotia Seeds, Mavisbank, Brechin, DD9 6TR, UK

[5]Royal Botanic Gardens, Kew, Wellcome Trust Millennium Building, Wakehurst Place, Ardingly, West Sussex, RH17 6TN, UK

Type: Research Article

Author contributions:

HA conceived the purpose of the study reported; HA, MDV created and circulated the survey; all authors discussed the findings; and HA drafted the manuscript with inputs from HWP and MDV.

Abstract

To meet the global and European restoration targets, native seed production is essential since we cannot rely solely on wild collected native seed. To better understand the challenges associated with the use of native seed produced for restoration, a survey on seed quality and certification was sent out in five languages (English, French, German, Italian, Spanish) to approx. 1340 native seed users to investigate the needs of the native seed community (land, research, trade professionals) on a global scale. We found that the native seed community shared similar perspectives on the importance of knowing the seed quality of the material used, a high interest in the clear reporting of seed lot origin, and finally the need for a compulsory certification system at a national/federal level run by governmental agencies. However, the responses varied among groups; in particularly, land professionals primarily chose origin and provenance, whereas research and trade both chose origin, viability, purity and germination. Whilst the research and trade professionals' views were generally aligned, land professionals were primarily concerned about meeting restoration projects on time with source-identified seed. This study provides the first look at native seed user and stakeholder perspectives that can be used to create and inform seed production policy improving current and future seed quality certification systems to come.

Key words: land, native seed stakeholders, native seed users, research, seed origin, seed testing, trade.

Implications for Practice

- Ecological restoration is a multidisciplinary field and quantifying the needs of users and stakeholders groups can aid in informing policy and regulation decisions in a developing market.

- User and stakeholder groups agree that traded native seeds should always contain a certified label of origin when used for ecological restoration.

- Native seed certification should consider other selected seed quality attributes, such as viability, germination, and purity as more research becomes available on applied native seed biology.

Introduction

The perception of conservation has been shifting over the last 50 years, from species to ecosystems; to “people and nature” as separate entities (Mace 2014) that work together to create sustainable alternatives that are resilient, adaptable and integrative. Evidence of this is present in the UN’s Convention on Biological Diversity which delineated 20 Aichi biodiversity targets which includes both social and ecological requirements (Mace 2014; CBD 2010; Tolvanen et al. 2011; Cortina et al. 2016); and among them targets 14 and 15 specifically on ecosystem restoration. With the increasing global demand to restore degraded habitats and ecosystems, caused by intensive agricultural, mining natural resources, natural disasters, etc. (Neville et al. 2016; Tischew et al. 2011; PCA 2015), the restoration of natural or semi-natural habitats is often required to conserve ecosystem services and protect biodiversity for future generations (CBD 2010; SER 2014). However, restoration practices are not meeting the demand in the majority of European ecosystems, such as grasslands, croplands, heathlands and urban ecosystems (EU COM/2015/0478). There is an urgent need for a reinvigorated native seed industry to provide multiplied wild seed for restoration purposes, since wild populations cannot support this demand alone (Merritt & Dixon 2011; Nevill et al. 2016). The use of fresh seeds for restoration is often impractical and thus artificial storage (Silveira et al. 2014) and/or multiplication is necessary (Tischew et al. 2011; Ladouceur et al. 2017).

Current policies for the marketing of native seed in Europe are either too restrictive, based on varietal standards or is lacking in many countries (Abbandonato et al. unpublished); and that a revised or *ad hoc* policy is recommendable for herbaceous native seed. Awareness of product quality control is extremely valuable for the marketing of seeds (Louwaars 2008; Copeland & McDonald 2001; Young et al. 2013) to prevent the buyers and sellers from negative externalities, e.g. mislabelled seed, poor performing seed, presence of weed seed, etc. For centuries, humans have been moving plants outside of their natural range with over 13, 168 naturalised vascular species often resulting in the spread of invasive species ultimately resulting in the loss of biodiversity (Kew 2016).

Native seed quality is not frequently or consistently defined in the scientific literature and has various meanings; from purity, to species and end use, to genotype and pre-storage environment (Haslgrüber et al. 2013; Hampton & Hill 2002; Baskin & Baskin 2014). High variability in the quality of germination and purity was found in nine wildflower species seeds sold online in the UK (Ryan et al. 2008). However, low germination may not necessarily represent poor quality seeds, but seeds that require a dormancy breaking stimulus (Laverack et al. 2007; Marin et al. 2016); and high germinating seeds may have lost dormancy due to human selection after numerous multiplied generations (Chivers 2016; Qu et al. 2005) or changes in dormancy post-harvest handling of the seed lot. This complexity in germination alone highlights the urgent need to increase the characterization of wild species' seed biology across a range of families for restoration purposes. The use of high quality native seeds is critical for field emergence, but it requires accurate seed testing (Elias et al. 2006). Recently, the ISTA/AOSA Native/Wild Species Working Group has been created to compile existing seed testing information and to write a handbook on native/wild species.

Although native seed quality control can be costly and time consuming generally (Tilley et al. 2011), new techniques are being developed in the USA to meet the USDA's Federal Seed Act's (FSA) germination and purity requirements, such as the pop test (Tilley et al. 2011) or in Europe the conductivity test (Marin et al. 2016). Native seed certification varies and has been used on multiple scales (primarily supra-nationally by the European Commission); however these regulations do not function well for herbaceous seeds, as varietal agricultural standards of distinctness, uniformity and stability are applied or the labelling requirements are too revealing in a relatively young market (Abbandonato et al. unpublished). In contrast, forest reproductive material legislation is more flexible allowing a local approach to be taken per species throughout the countries in the European Union (EU Commission 1999). Nonetheless, national, provincial and local certification schemes for native herbaceous seeds have been implemented in some countries, such as the U.S.A. (AOSCA, FSA), Australia (ASF, RIAWA), Austria (G-Zert, REWISA, RGF), Germany (RegioZert, VWW-Regiosaaten), France (Végétal local), Italy (Flora Autoctona), and Switzerland (CPS).

What is also needed is an understanding of the demands of researchers, industry, and restoration practitioners regarding certification and labelling standards. User and stakeholder groups greatly vary between sector and profession; however, the native seed community largely shares similar goals to protect biodiversity and ecosystem services by restoring, rehabilitating, reclaiming or greening landscapes, habitats or ecosystems. To date, little agreement exists on how the native seed market should be regulated, and there is an ongoing debate between countries and stakeholder groups, especially for native herbaceous species (Abbandonato et al. unpublished; SALVERE 2012; Tischew et al. 2011). We aim to contribute to the debate by providing evidence of how various stakeholder and user groups perceive native seed quality and certification through a wide consultation with a range of professionals in different sectors of the industry. Such an approach helps to limit conflict between stakeholders and to inform native seed policy (Keulartz 2009; Abbandonato et al. unpublished). We determined if seed quality and certification was important to all stakeholder groups and their preferences for how to use and enforce certification for native seeds on a global scale.

Methods

To evaluate seed quality and certification needs for native seeds, we designed and administered a web-based survey to native seed users. The request for participation was made globally. To formulate and define the survey questions, the current literature on native seed quality and certification was reviewed in scientific articles, reports, policy documents, and books. Four native seed producers and one plant material center were visited in Italy, the United Kingdom, Spain, Germany, and the USA to identify production challenges in native seed quality and certification.

The online survey was distributed using SurveyMonkey (https://www.surveymonkey.com) and consisted of three sections and thirteen questions on participant details (n=5), seed quality (n=3), and certification (n=5) (S1). The survey was written in English and then translated into four other languages (Italian, Spanish, French and German). All questions administered were worded neutrally and concisely. Nominal answer choices were randomized, and all questions in the seed quality and certification sections contained a “Don’t know” option to prevent false positives or skipping questions. The survey was circulated to approx. 1340 native seed users by email containing a hyperlink to the survey platform in each language and was circulated in August and October 2016. The survey was left open for 6 months and was then closed at the end of January 2017.

Response options on native seed quality measures were defined to prevent misinterpretation (**Fig. S1**). Seed quality attributes were reviewed in certification schemes applied under various levels and enforcement in numerous countries including the European Union and the USA (**Table 12**). A list of 27 attributes was compiled and then narrowed down to 18 that were measurable and directly related to seed quality (**Table S1**). To define these attributes, existing certification schemes, books and seed quality publications were used (AOSA 2002; Baskin & Baskin 2014; Bewley et al. 2013; Copeland & McDonald 2001; EU Commission 2010; Hanson 1985; ISTA 2009; NRCS 2009). When appropriate, these definitions were simplified to be easily comprehensible by all participants (**Fig. S1**).

A pool of end-users were identified through a web-based inquiry using the keywords “native” and “seed” separately and together, and were translated into 15 other languages (Bulgarian, Croatian, Czech, Danish, Dutch, French, Finnish, German, Greek, Hungarian, Italian, Portuguese, Romanian, Slovenian, Spanish), and by contacting researchers in the field of native seed science and restoration (for further details, see De Vitis et al. unpublished). The following international groups and networks agreed to forward the survey at a global scale: Kew's UK Native Seed Hub (https://www.kew.org/science/data-and-resources/seeds/kews-uk-native-seed-hub), International Network for Seed Based Restoration section of the Society for Ecological Restoration (http://ser-insr.org/), International Seed Testing Association (ISTA)/Association of Official Seed Analysts (AOSA) Native/wild species working group, NAtive Seed Science, TEchnology, and Conservation (NASSTEC) network (https://nasstec.eu/home), and the Native Seed Network (http://nativeseednetwork.org).

Data Analysis

In total 263 responses were received; however, two types of responses: 1) from users who indicated that they did not work with native seeds (n=21); and from users that did not presently, but planned to in the future (n=15) were removed. Of the resulting 227 responses, data was excluded from respondents that only completed 39% (5/13 questions – participant details only) of the survey and left the remaining blank (n=32) and responses from 195 participants were analyzed. All survey questions allowed a single response, except for the type of species used (**Table 4**), seed quality attributes (**Fig. 2**), and pre-existing certification schemes which were multi-response (**Table 12**).

All analyses were performed in *R Statistical Computing Language and Platform* version 3.3.3 (R Core Development Team 2016). A Likelihood ratio test was used for the three-way contingency tables to determine associations between profession and sector for nominal categorical response variables (certification type, certification level, certification enforcement), and ordinal response variables (seed quality and certification importance). A log-linear model was chosen due to the smaller sample size and a joint independence model [AB][C] (~response + profession | sector) fit best to all nominal and ordinal response variables (Friendly 2000; Kuruppumullage & Sooriyaracchi 2011). Three-way log-linear mosaic plots of joint independence and the *logit* (log odds) and summary statistics were created using the package *vcd*.

A multiple marginal independence (MMI) test using a Bonferroni post hoc was used to determine the associations between the single response categorical variable (profession) with the multiple response categorical variable (seed quality attributes). This was used to prevent false positives when testing multiple comparisons (Bilder & Loughin 2004). The package *MRCV* was used to create marginal positive response plots, summary statistics, and a marginal table including positive response frequencies and counts.

Results

Participant details

The majority of respondents were from the private (43%) and public (40%) sectors followed by NGOs (17%) (**Table 1**). Respondents were pre-dominantly from the European Union (80%) since the majority of stakeholder contacts collected were from Europe (**Table 2**). Due to the small sample size in any one country, all country data was pooled together. The three categories of professions consisted of "land" (28%), "trade" (26%), and "research" (46%) (**Table 3**). For profession and sector, respondents who chose "Other, please specify" were investigated using the additional comments section and the institutional email (if provided) to see which profession (n=19) or sector (n=13) the participant belonged to (**Fig. S2**). Respondents who stated they worked in more than one sector or profession (n=4) were randomly assigned to one of their given sectors or professions (**Fig. S2**). Participants (i.e. most professions) worked primarily with herbaceous seeds (54%), followed by native trees and shrubs (34%), and agricultural varieties/cultivars (12%) (**Table 4**).

Table 1. Number of participants by sector surveyed from July 26th to January 31st, 2017.

Sector	*Number of participants*
Nongovernmental organization/non-profit	34
Public	78
Private	83
Total	195

Table 2. Number of participants by country surveyed from July 26th to January 31st, 2017. European Union and non-European Union sub-totals are 155 and 40 countries

Countries	*Number of participants*
Austria	3
Belgium	9
Bulgaria	1
Denmark	1
Estonia	2
Finland	2
France	27
Germany	22
Greece	2
Italy	19
Netherlands	2
Portugal	7
Romania	1
Slovakia	1
Spain	17
Sweden	2
United Kingdom	37
Australia	4
Canada	1
Ireland	3
Lebanon	2
New Zealand	1
South Africa	1
Switzerland	1
Tunisia	2
United States of America	25
Total	195

Table 3. Number of participants by category and profession surveyed from July 26^{th} to January 31^{st}, 2017.

Categories	*Profession*	*Number of participants*
Land (n=54)	Consultant	8
	Land manager	4
	Landscape contractor	4
	Restoration/conservation practitioner	32
	Technician/fieldworker	6
Trade (n=50)	Farmer	4
	Nursery	16
	Seed producer	28
	Seed retailer	2
Research (n=89)	Botanic Garden	1
	Researcher	65
	Seed analyst	17
	Student	6
Total		195

Table 4. Type of native seed used by participants per category (land, trade, research) (n=195).

Profession	*Agricultural**	*Native Herbaceous*	*Native Trees and Shrubs*	*Total*
Land	8	47	33	88
Trade	5	38	26	69
Research	23	80	46	149
Total	36	165	105	306

*cultivars/varieties

Seed quality

The majority of participants from the private sector and trade professions were significantly more likely to select seed quality to be “yes, always” important ($L = -4.14$, $P < 0.01$). This was also true in the public sector and research professions ($L = -3.59$, $P < 0.001$) (**Table 5**). Moderate associations between “yes, always” with private/trade and public/research were apparent; “never” was chosen by NGO/trade professional; and “in most cases” by NGO/land using a likelihood ratio test corresponding to the shaded positive residuals ($P < 0.001$) (**Fig. 1**). Participants from private/research were under represented as shown by a strong shaded negative residual (**Fig. 1**).

All three groups of professions (land, research, trade) positively chose the seed quality attribute “origin” with a marginal frequency of 96%, 87%, and 86% respectively (**Table 6**); however “viability” ($P = 0.001$) and “none” ($P < 0.001$) were significantly associated with profession under the multiple marginal independence test using a Bonferroni adjusted p-value (**Table 7**). Trade (82%) and research (80%) professions selected “viability” after “origin”, whereas land (50%) chose it in one fifth of cases. Land (48%) also chose “none” whereas trade (6%) and research (13%) rarely selected it. Almost half of all land professionals (48%) still chose “origin” (96%) while selecting “none”. Overall, origin, viability, germination, purity and provenance were successively chosen the most frequently by all professions (**Fig. 2**).

Table 5. Log-linear model (log odds) testing the association between seed quality importance (Yes, always – Yes, In most cases – Most, In few cases – Few, Never – NV, Don't know – DK) between profession and sector.

	Land			*Research*			*Trade*		
NGO	*L*	Std. Error	*P*	*L*	Std. Error	*P*	*L*	Std. Error	*P*
DK:FW	0.00	1.16	1.0000	0.00	2.00	1.0000	0.00	2.00	1.0000
FW:Most	-1.47	0.91	0.1050	-1.61	1.55	0.2989	0.00	2.00	1.0000
Most:NV	2.57	1.47	0.0805	1.61	1.55	0.2989	-1.61	1.55	0.2989
NV:Yes	-2.94	1.45	0.0420	-2.83	1.46	0.0515	-0.79	0.76	0.3013
Public									
DK:FW	0.00	2.00	1.0000	-1.10	1.63	0.5011	0.00	2.00	1.0000
FW:Most	-1.61	1.55	0.2989	-2.20	0.86	0.0107	-1.10	1.63	0.5011
Most:NV	1.61	1.55	0.2989	2.20	0.86	0.0107	1.10	1.63	0.5011
NV:Yes	-3.37	1.44	0.0192	-3.59	0.83	0.0000	-2.20	1.49	0.1405
Private									
DK:FW	1.10	1.63	0.5011	1.10	1.63	0.5011	0.00	2.00	1.0000
FW:Most	-1.95	1.51	0.1981	-1.10	1.63	0.5011	-2.71	1.46	0.0637
Most:NV	1.95	1.51	0.1981	-0.51	1.03	0.6209	2.71	1.46	0.0637
NV:Yes	-3.56	1.43	0.0132	-1.22	0.72	0.0890	-4.14	1.43	0.0037

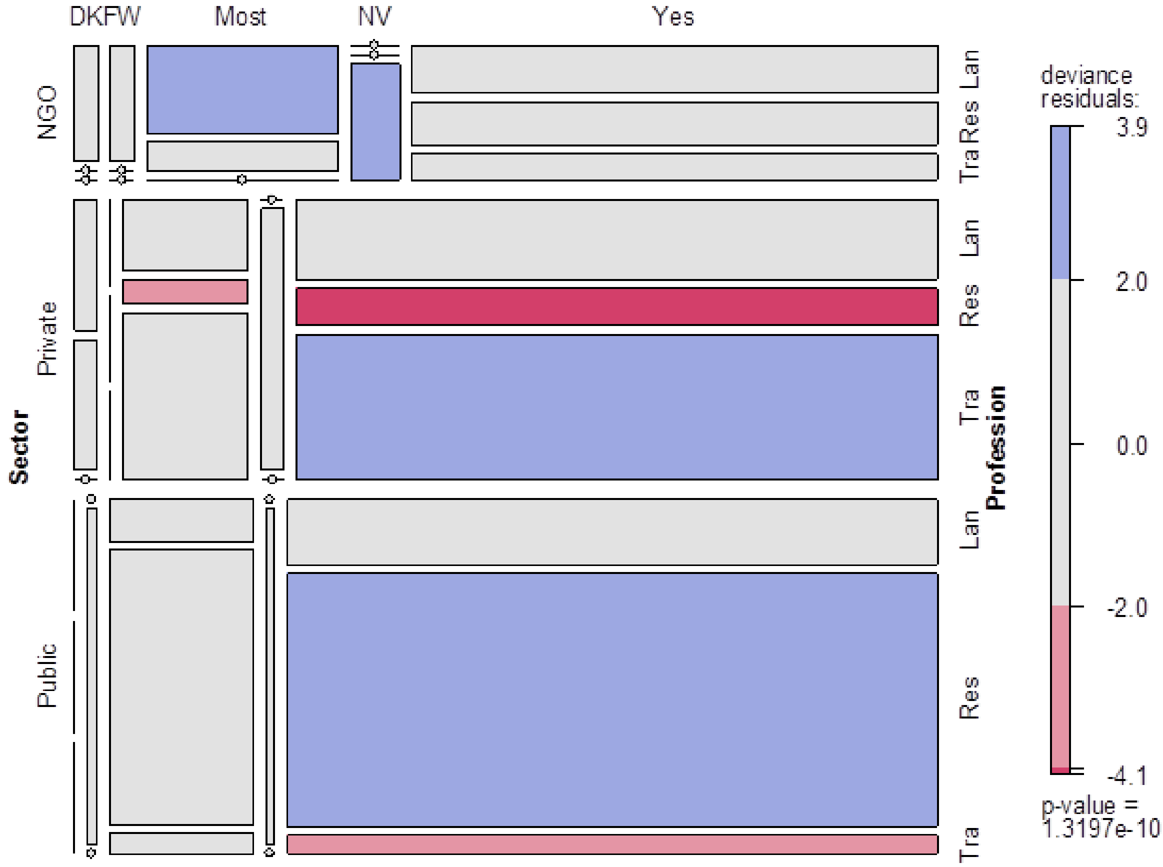

Figure 1. Log-linear joint independence mosaic display of certification importance (Yes, always – Yes, In most cases – Most, In few cases – Few, Never – NV, Don't know – DK), profession (Trade – Tra, Research – Res, Land – Lan) and sector using a likelihood ratio test.

Table 6. Marginal table of positive responses between profession and seed quality attributes [*n* (%)]. Subscripts indicate attributes by order chosen by more than 60% for each profession.

Profession	*Seed quality attributes*					
	Collection date		*Harvest date*		*Origin*	
Land (n=54)	30	(56)	20	(37)	52	(96)[1]
Research (n=91)	49	(54)	41	(45)	79	(87)[1]
Trade (n=50)	32	(64)[6]	28	(56)	43	(86)[1]
	Provenance		*Generations Multiplied*		*Seed lot*	
Land	35	(65)[2]	16	(30)	26	(48)
Research	52	(57)	41	(45)	46	(51)
Trade	29	(58)	20	(40)	32	(64)[5]
	Purity		*Storage*		*Moisture Content*	
Land	24	(44)	23	(43)	15	(28)
Research	66	(73)[4]	45	(50)	23	(25)
Trade	36	(72)[3]	31	(62)[6]	19	(38)
	Viability		*Seed health*		*Germination*	
Land	27	(50)	20	(37)	29	(54)
Research	74	(81)[2]	40	(43)	70	(77)[3]
Trade	41	(82)[2]	27	(54)	35	(70)[4]
	Germination rate		*Pure live seed*		*Dormancy*	
Land	17	(32)	9	(17)	16	(30)
Research	31	(34)	28	(31)	45	(50)
Trade	13	(26)	12	(24)	22	(44)
	Dormancy type		*Seed vigour*		*Seed pre-treatment*	
Land	18	(33)	9	(35)	15	(28)
Research	35	(39)	26	(29)	32	(35)
Trade	16	(32)	11	(22)	15	(30)
	None					
Land	26	(48)				
Research	12	(13)				
Trade	3	(6)				

Table 7. Marginal multiple independence (MMI) test statistics of seed quality attributes chosen by profession (n=195).

Attribute	X^2_S	$X^2_{S,I,J}$	C^2_M
Collection date		1.41	1.000
Harvest date	115.8	3.79	1.000
Origin		3.90	1.000
Provenance		0.89	1.000
Generations multiplied		3.38	1.000
Seed lot		3.15	1.000
Purity		13.29	0.026
Storage		4.03	1.000
Moisture		2.60	1.000
Viability		19.66	0.001
Seed health		3.05	1.000
Germination		8.55	0.264
Germination rate		0.98	1.000
Pure live seed		3.63	1.000
Dormancy		5.50	1.000
Dormancy type		0.73	1.000
Seed vigour		2.21	1.000
Pre-treatment		0.95	1.000
None		34.09	0.000

X^2_S: The modified Pearson statistic

$X^2_{S,I,J}$: A matrix containing the individual Pearson statistics

C^2_M: Bonferroni adjusted p-value

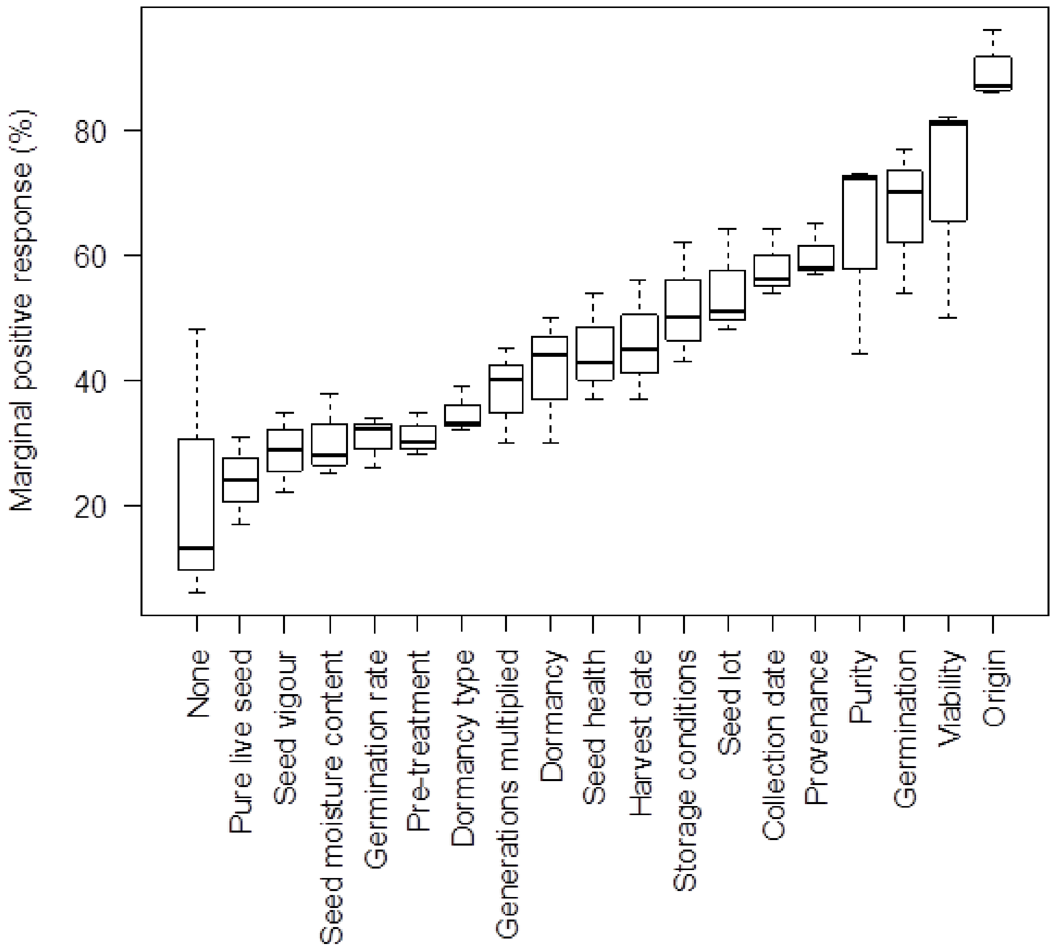

Figure 2. Overall percent frequency of marginal positive responses for seed quality attributes including all professions (n=195).

Certification

Similar to responses on seed quality importance, the majority of participants from the private sector and trade profession were significantly more likely to choose a preference for certification to be “yes, always” important ($L = -2.00$, $P < 0.01$). This was also true in the public sector and research profession ($L = -4.40$, $P < 0.01$), but public/research also largely selected “in most cases” ($L = -2.05$, $P < 0.01$) (**Table 8**). Moderate associations were found between “yes, always” and NGO/land professionals, private/trade, and public/research; “never” with private/trade; “in most cases” with public/research; and, “in few cases” with NGO/land, private/trade, and public/research corresponding to the positive shaded residuals ($P < 0.001$) (**Fig. 3**).

Participants from the public sector and research profession were significantly more likely to chose “compulsory” certification ($L = 1.23$, $P < 0.001$) (**Table 9**). In addition, moderate associations between compulsory certification and NGO/land, private/trade, and public/research existed, but also between participatory certification and private/trade; and between “don’t know” and public/research corresponding to the positive shaded residuals ($P < 0.001$) (**Fig. 3**).

Participants from the private/research profession were under represented as shown by a strong negative shaded residual (**Fig. 4**).

Participants from the private/trade and public/research professions were significantly more likely to chose “national/federal” certification level ($L = -2.64$, and $L = -2.69$ respectively, $P < 0.01$) (**Table 10**). Moderate associations corresponding to the positive shaded residuals were found between “supranational” certification and private/trade and public/research; followed by “provincial/state” and NGO/research; “private” with private/trade, “national/federal” with NGO/land, private/trade, and public/res and lastly “don’t know” with public/res ($P < 0.001$) (**Fig. 5**).

Table 8. Log-linear model (log odds) testing the association between certification importance (Yes, always – Yes, In most cases – Most, In few cases – Few, Never – NV, Don't know – DK) between profession and sector.

	Land			*Research*			*Trade*		
NGO	*L*	Std. Error	*P*	*L*	Std. Error	*P*	*L*	Std. Error	*P*
DK:FW	-2.20	1.49	0.1405	-0.51	1.03	0.6209	1.10	1.63	0.5011
FW:Most	0.59	0.79	0.4562	-0.79	0.76	0.3013	-1.10	1.63	0.5011
Most:NV	1.61	1.55	0.2989	2.40	1.48	0.1045	0.00	1.15	1.0000
NV:Yes	-3.14	1.44	0.0300	-1.61	1.55	0.2989	-1.10	0.94	0.2439
Public									
DK:FW	0.51	1.03	0.6209	1.22	0.72	0.0890	0.00	2.00	1.0000
FW:Most	-0.85	0.98	0.3853	-2.05	0.67	0.0022	-1.61	1.55	0.2989
Most:NV	1.95	1.51	0.1981	3.66	1.43	0.0105	1.61	1.55	0.2989
NV:Yes	-3.04	1.45	0.0354	-4.39	1.42	0.0020	-1.95	1.51	0.1981
				1.22	0.72	0.0890	0.00	2.00	1.0000
Private									
DK:FW	-0.34	0.83	0.6845	-0.59	0.79	0.4562	-0.37	0.61	0.5487
FW:Most	-0.62	0.66	0.3505	0.59	0.79	0.4562	-0.27	0.52	0.6067
Most:NV	2.56	1.47	0.0805	1.61	1.55	0.2989	1.22	0.72	0.0890
NV:Yes	-3.04	1.45	0.0354	-2.20	1.49	0.1405	-2.00	0.67	0.0030

Table 9. Log-linear model (log odds) testing the association between certification type (Compulsory – CP, Contract-based – CT, Don't know – DK, None – N, No response – NR, Other – O, Participatory – P) between profession and sector.

	Land			*Research*			*Trade*		
NGO	*L*	Std. Error	*P*	*L*	Std. Error	*P*	*L*	Std. Error	*P*
CP:CT	0.75	0.57	0.1916	0.00	0.89	1.0000	1.95	1.51	0.1981
CT:DK	2.20	1.49	0.1405	-0.34	0.83	0.6845	0.00	2.00	1.0000
DK:N	0.00	2.00	1.0000	1.95	1.51	0.1981	-1.10	1.63	0.5011
N:NR	0.00	2.00	1.0000	0.00	2.00	1.0000	0.00	1.15	1.0000
NR:O	-1.10	1.63	0.5011	-1.10	1.63	0.5011	1.10	1.63	0.5011
O:P	-0.85	0.98	0.3853	-0.51	1.03	0.6209	-1.61	1.55	0.2989
Public									
CP:CT	1.85	0.88	0.0357	1.22	0.35	0.0005	0.00	0.89	1.0000
CT:DK	0.00	1.15	1.0000	-0.09	0.43	0.8312	1.61	1.55	0.2989
DK:N	1.10	1.63	0.5011	3.14	1.44	0.0300	0.00	2.00	1.0000
N:NR	-1.10	1.63	0.5011	-2.20	1.49	0.1405	-1.10	1.63	0.5011
NR:O	0.00	1.15	1.0000	1.10	0.94	0.2439	1.10	1.63	0.5011
O:P	-0.85	0.98	0.3853	-1.73	0.89	0.0502	0.00	2.00	1.0000
Private									
CP:CT	1.00	0.63	0.1103	-1.95	1.51	0.1981	0.97	0.50	0.0529
CT:DK	0.34	0.83	0.6845	-0.45	0.68	0.5086	0.79	0.76	0.3013
DK:N	1.61	1.55	0.2989	1.30	0.92	0.1584	0.00	0.89	1.0000
N:NR	-1.10	1.63	0.5011	1.10	1.63	0.5011	0.00	0.89	1.0000
NR:O	-0.51	1.03	0.6209	0.00	2.00	1.0000	0.51	1.03	0.6209
O:P	-0.59	0.79	0.4562	-1.95	1.51	0.1981	-2.12	0.86	0.0141

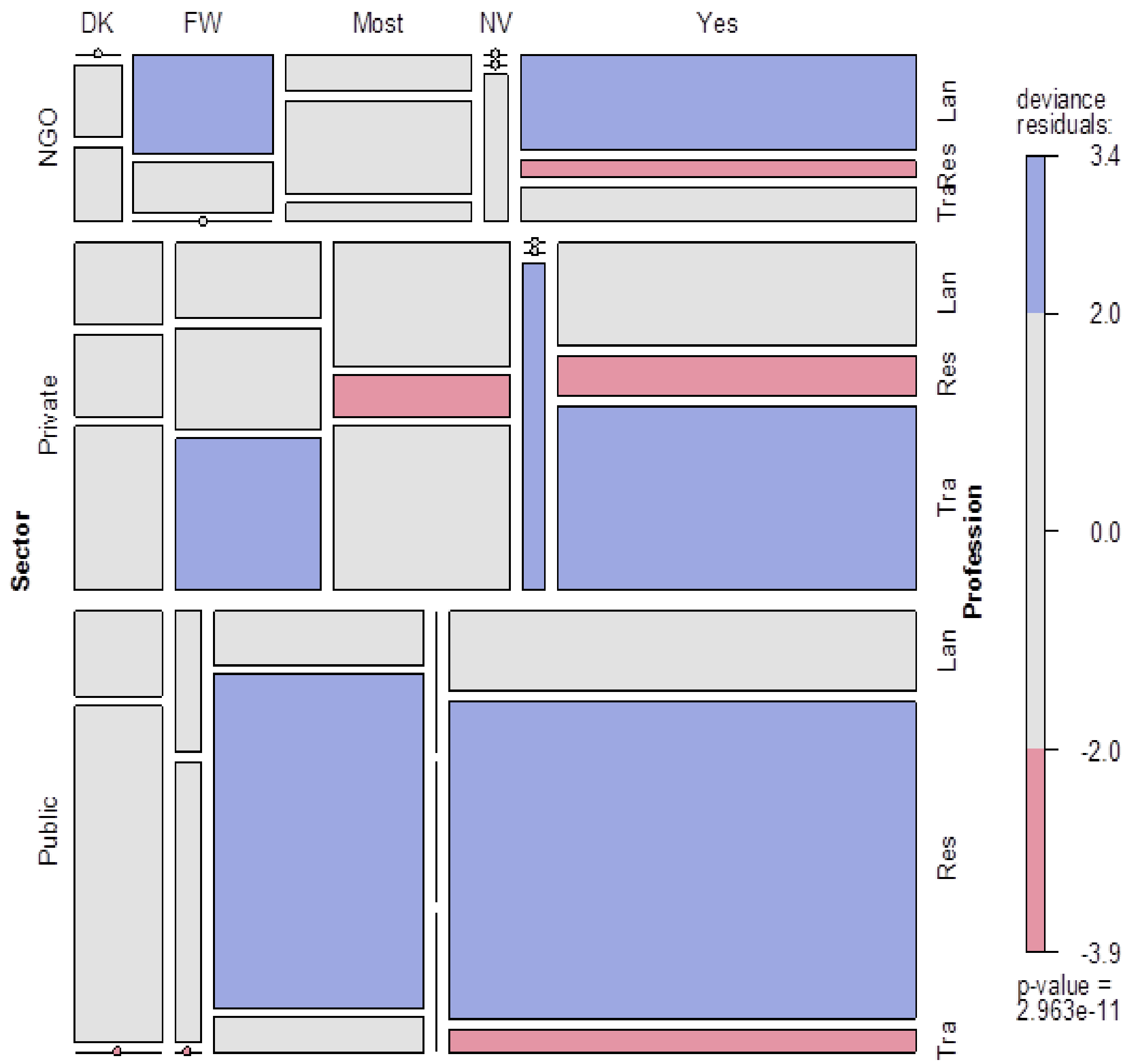

Figure 3. Log-linear joint independence mosaic display of certification importance (Yes, always – Yes, In most cases – Most, In few cases – Few, Never – NV, Don't know – DK), profession (Trade – Tra, Research – Res, Land – Lan) and sector using a likelihood ratio test.

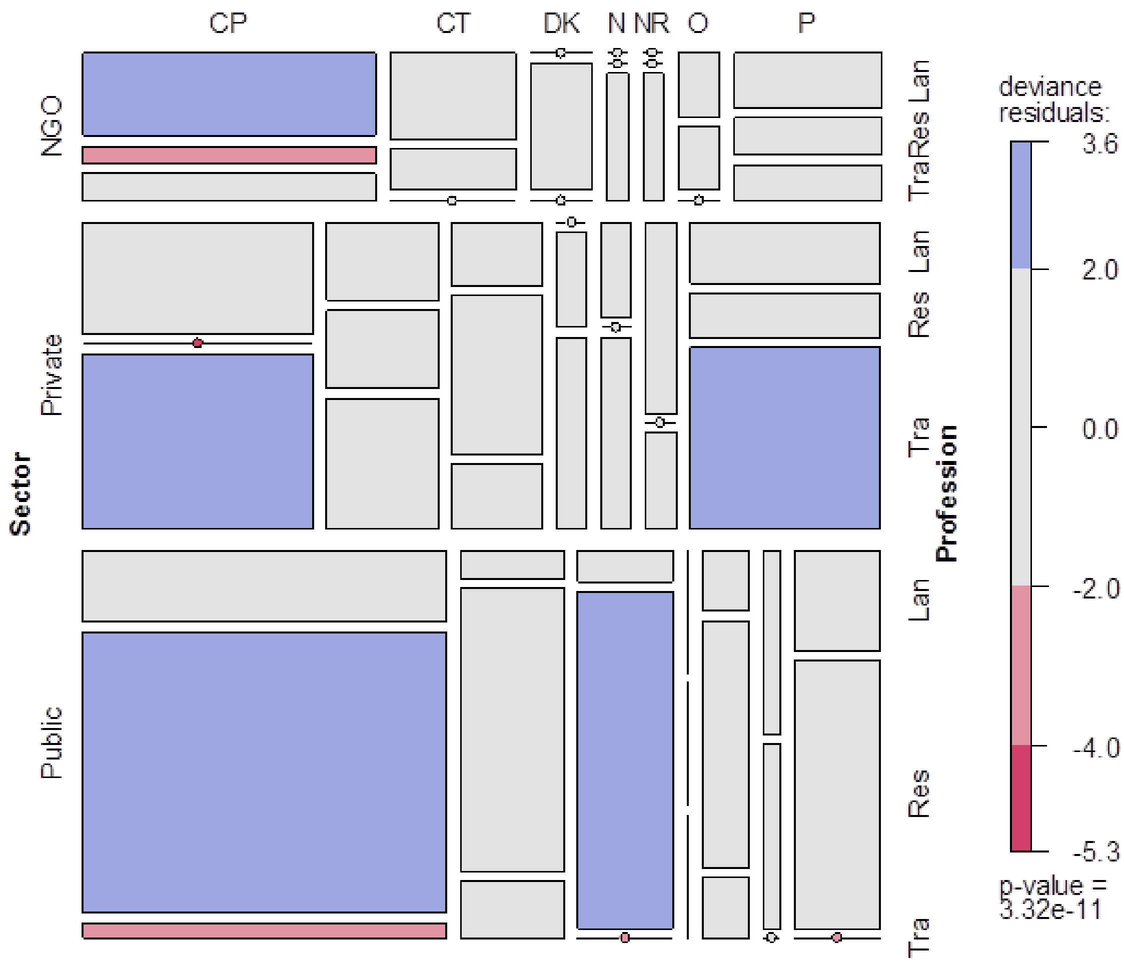

Figure 4. Log-linear joint independence mosaic display of certification type (Compulsory – CP, Contract-based – CT, Don’t know – DK, None – N, No response – NR, Other – O, Participatory – P), profession (Trade – Tra, Research – Res, Land – Lan), and sector using a likelihood ratio test.

Table 10. Log-linear model (log odds) testing the association between certification level (Don't know – DK Supranational – EU, Federation/Assocation/NGO – Fed., Municipal – MN, National/Federal – N/F, None, No response – NR, Provincial/state – P/S, Private – PR, Regional - RG) between profession and sector.

	Land			*Research*			*Trade*		
NGO	*L*	Std. Error	*P*	*L*	Std. Error	*P*	*L*	Std. Error	*P*
DK:EU	-2.20	1.49	0.1405	1.10	1.63	0.5011	-1.10	1.63	0.5011
EU:Fed.	0.59	0.79	0.4562	0.00	2.00	1.0000	0.00	1.15	1.0000
Fed.:MN	1.61	1.55	0.2989	-1.10	1.63	0.5011	1.10	1.63	0.5011
MN:N/F	-3.14	1.44	0.0300	0.00	1.15	1.0000	-1.95	1.51	0.1981
N/F:None	3.14	1.44	0.0300	1.10	1.63	0.5011	0.85	0.98	0.3853
None:NR	0.00	2.00	1.0000	0.00	2.00	1.0000	0.00	1.15	1.0000
NR:P/S	0.00	2.00	1.0000	-2.56	1.47	0.0805	1.10	1.63	0.5011
P/S:NR	0.00	2.00	1.0000	1.47	0.91	0.1055	0.00	2.00	1.0000
PR:RG	0.00	2.00	1.0000	1.10	1.63	0.5011	0.00	2.00	1.0000
Public									
DK:EU	0.00	0.76	1.0000	-1.36	0.53	0.0102	-1.95	1.51	0.1981
EU:Fed.	1.95	1.51	0.1981	2.46	0.85	0.0039	0.85	0.98	0.3853
Fed.:MN	0.00	2.00	1.0000	1.10	1.63	0.5011	1.10	1.63	0.5011
MN:N/F	-1.95	1.51	0.1981	-3.85	1.43	0.0071	-1.10	1.63	0.5011
N/F:None	1.95	1.51	0.1981	3.85	1.43	0.0071	1.10	1.63	0.5011
None:NR	-1.10	1.63	0.5011	-2.71	1.46	0.0637	0.00	2.00	1.0000
NR:P/S	0.00	1.15	1.0000	0.14	0.54	0.7894	0.00	2.00	1.0000
P/S:NR	1.10	1.63	0.5011	0.96	0.74	0.1992	0.00	2.00	1.0000
PR:RG	-2.40	1.48	0.1045	-1.34	0.71	0.0604	0.00	2.00	1.0000
Private									

DK:EU	-0.96	0.74	0.1992	0.34	0.83	0.6845	-3.04	1.45	0.0354
EU:Fed.	2.56	1.47	0.0805	0.51	1.03	0.6209	1.10	0.62	0.0751
Fed.:MN	0.00	2.00	1.0000	1.10	1.63	0.5011	0.85	0.98	0.3853
MN:N/F	-2.83	1.46	0.0515	-1.10	1.63	0.5011	-2.27	0.86	0.0082
N/F:None	2.83	1.46	0.0515	0.00	1.15	1.0000	1.76	0.68	0.0103
None:NR	-1.10	1.63	0.5011	1.10	1.63	0.5011	0.00	0.89	1.0000
NR:P/S	1.10	1.63	0.5011	-1.95	1.51	0.1981	0.51	1.03	0.6209
P/S:NR	0.00	2.00	1.0000	1.95	1.51	0.1981	-0.85	0.98	0.3853
PR:RG	-2.20	1.49	0.1405	-1.10	1.63	0.5011	0.34	0.83	0.6845

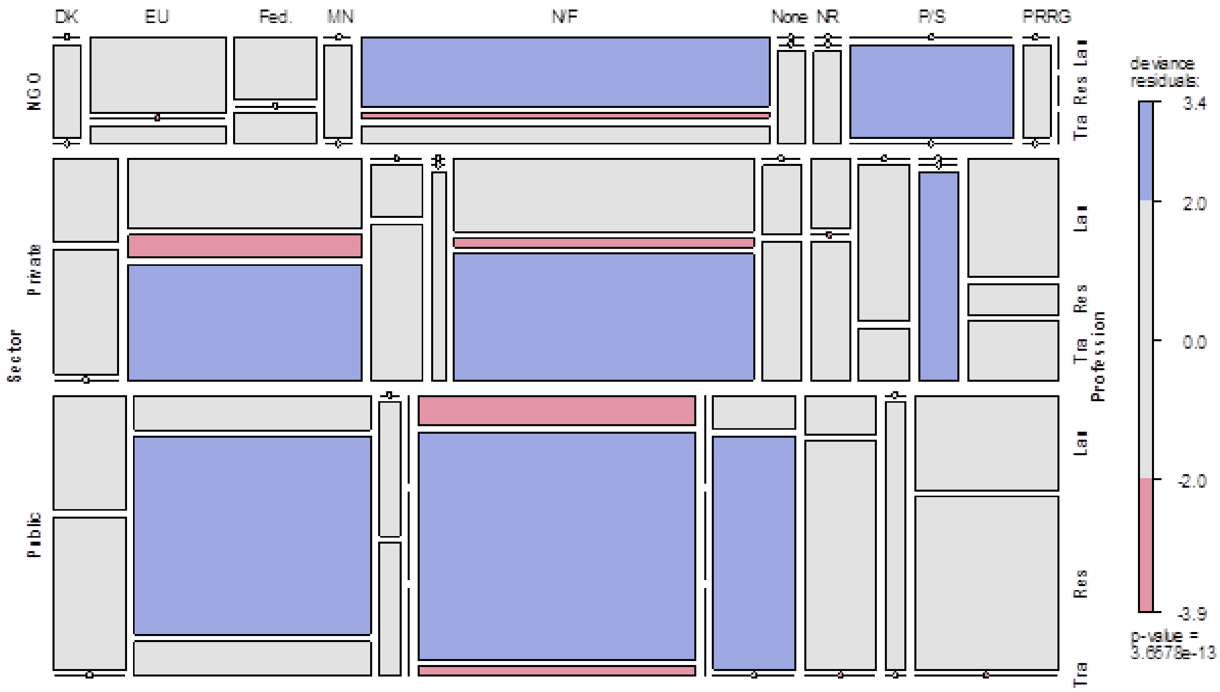

Figure 5. Log-linear joint independence mosaic display of certification level (Don't know – DK Supranational – EU, Federation/Assocation/NGO – Fed., Municipal – M, National/Federal – N/F, None, No response – NR, Provincial/state – P/S, Private – PR, Regional - RG), profession (Trade – Tra, Research – Res, Land – Lan) and sector using a likelihood ratio test.

Participants from the public sector and research profession were significantly more likely to chose "governmental agency" for certification enforcement ($L = -1.84$, $P < 0.001$) and it was chosen the most frequently in all three sectors (**Table 11**). Moderate associations between NGO/land and public/research and "governmental agency" were found; followed by "germplasm bank" for public/research; and lastly "private companies" with private/trade corresponding to the positive shaded residuals ($P < 0.001$) (**Fig. 6**). For pre-existing certification schemes, "not applicable" was chosen by one third of participants (37%), especially by the land (25%) and research (68%) professions. The certification scheme selected most often was the EU directive (99/105/EC) for source-identified forest reproductive material (18%), mostly chosen by trade professionals (70%). However, responses were minimal and greatly varied among certification schemes (**Table 12**).

Table 11. Log-linear model (log odds) testing the association between certification enforcement (Botanic Garden – BG, Governmental Agency – GA, Germplasm banks – GB, No response – NR, Other – O, Private companies – PC, Trade associations – TA, Universities – U) between profession and sector.

	Land			*Research*			*Trade*		
NGO	*L*	Std. Error	*P*	*L*	Std. Error	*P*	*L*	Std. Error	*P*
BG:GA	-1.34	0.71	0.0603	0.00	0.89	1.0000	-1.61	1.55	0.2989
GA:GB	1.85	0.88	0.0357	1.61	1.55	0.2989	1.61	1.55	0.2989
GB:NR	1.10	1.63	0.5011	0.00	2.00	1.0000	-1.10	1.63	0.5011
NR:O	-1.95	1.51	0.1981	-2.40	1.48	0.1045	-0.51	1.03	0.6209
O:PC	0.84	0.98	0.3853	2.40	1.48	0.1045	0.00	0.89	1.0000
PC:TA	1.10	1.63	0.5011	0.00	2.00	1.0000	1.61	1.55	0.2989
TA:U	-1.10	1.63	0.5011	-1.10	1.63	0.5011	0.00	2.00	1.0000
Public									
BG:GA	-0.96	0.74	0.1992	-1.84	0.46	0.0000	-1.61	1.55	0.2989
GA:GB	2.57	1.47	0.0805	1.40	0.38	0.0002	0.51	1.03	0.6209
GB:NR	-1.61	1.55	0.2989	0.13	0.50	0.8027	0.00	1.15	1.0000
NR:O	0.00	0.89	1.0000	0.14	0.54	0.7894	1.10	1.63	0.5011
O:PC	0.00	0.89	1.0000	0.17	0.58	0.7731	0.00	2.00	1.0000
PC:TA	0.51	1.03	0.6209	0.79	0.76	0.3013	-1.10	1.63	0.5011
TA:U	0.00	1.15	1.0000	0.00	0.89	1.0000	1.10	1.63	0.5011
Private									
BG:GA	-1.61	0.69	0.0202	-2.40	1.48	0.1045	-1.76	0.69	0.0102
GA:GB	3.22	1.44	0.0256	0.45	0.68	0.5086	1.76	0.69	0.0102
GB:NR	-1.10	1.63	0.5011	1.95	1.51	0.1981	0.00	0.89	1.0000
NR:O	-0.51	1.03	0.6209	-1.95	1.51	0.1981	-0.96	0.74	0.1991
O:PC	0.51	1.03	0.6209	0.85	0.98	0.3852	-0.14	0.54	0.7894
PC:TA	0.00	1.16	1.0000	1.10	1.63	0.5011	0.76	0.65	0.2391
TA:U	-0.51	1.03	0.6209	0.00	2.00	1.0000	0.34	0.83	0.6845

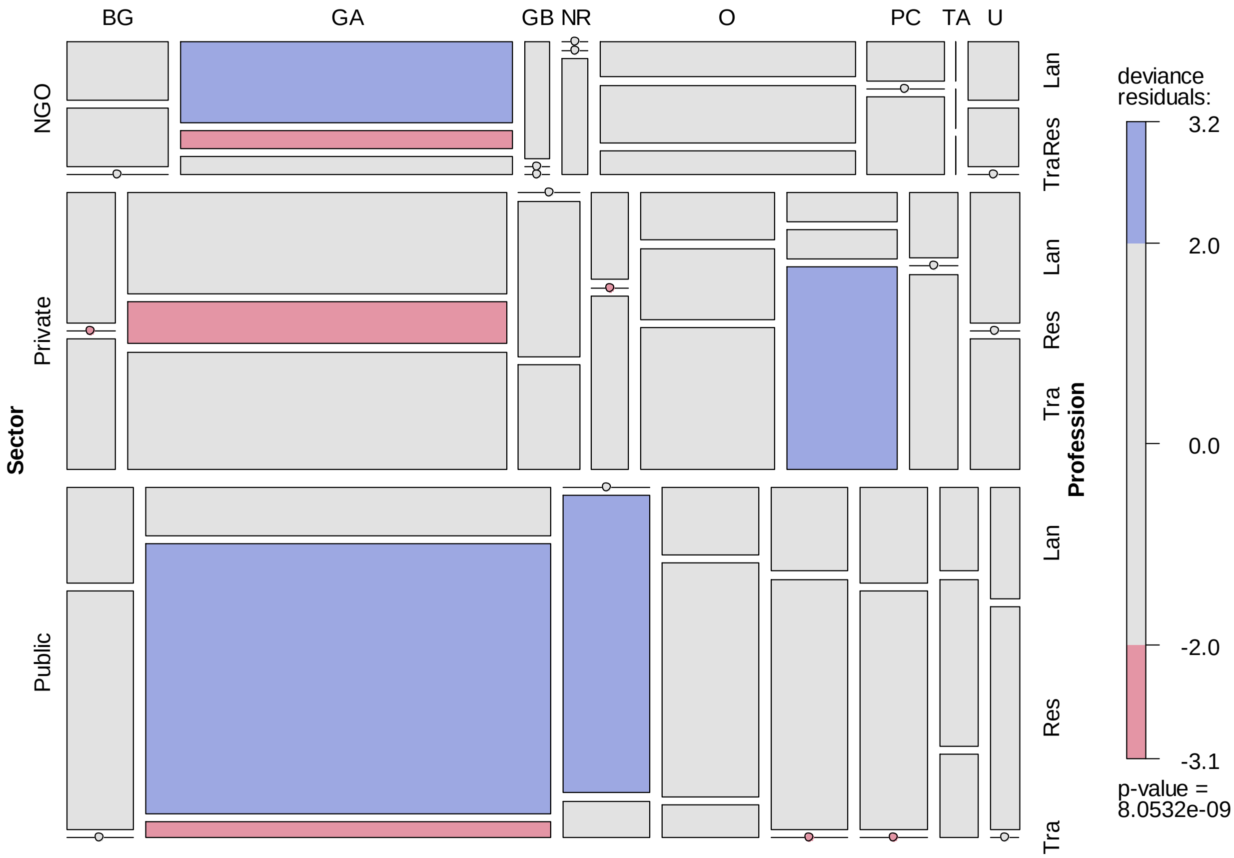

Figure 6. Log-linear joint independence mosaic display of certification enforcement (Botanic Garden – BG, Governmental Agency – GA, Germplasm banks – GB, No response – NR, Other – O, Private companies – PC, Trade associations – TA, Universities – U), profession (Trade – Tra, Research – Res, Land – Lan) and sector using a likelihood ratio test

Table 12. Pre-existing native seed certification schemes in Europe and the United States used (produced, bought, or sold) by participants from each category (land, trade, research) (n=195).

Profession	*ABCert*	*AOSCA (Association of Official Seed Certifying Agencies) Source-identified seed (yellow label)*	*AOSCA (Association of Official Seed Certifying Agencies) Source-identified seed (green label)*	*AOSCA (Association of Official Seed Certifying Agencies) Source-identified seed (blue label)*	*Bio-Suisse*	*Bioverita*	*DAFM (Department of Agriculture, Food and the Marine)*	*Demeter*	*European Directive 66/401/EEC Basic, commercial or certified fodder seed*	*European Directive 99/105/EC Source-identified forest reproductive material (yellow label)*	*European Directive 2010/60/EU Preservation mixtures*	*Flora Locale*	*OECD (Organisation for Economic Co-operation and Development) Seed Scheme*	*REWISA (Regionale Wildpflanzen & Samen)*	*VWW Regio-saaten/ RegioZert*	*Not applicable*	**Total**
Land	3	1	1	1	0	0	0	1	6	5	7	9	0	1	2	18	55
Trade	3	5	5	5	1	0	1	2	9	16	4	5	0	0	2	5	63
Research	1	7	4	3	0	2	0	1	4	2	6	2	1	0	0	48	81
Total	7	13	10	9	1	2	1	4	19	23	17	16	1	1	4	71	199

Discussion

Overall, native seed users and producers had very similar perspectives on seed quality and certification for all questions in terms of frequency of response. Even though the sectors and countries varied, all participants agreed that native seed quality and certification was always important (**Fig. 1** & **3**), in particularly regulating the origin of the material being made available (**Fig. 2**); and that certification should be compulsory at the national/federal level and enforced by governmental agencies (**Fig. 4**, **Fig. 5** & **Fig. 6**).

We found significant associations in seed quality and certification needs from participants based in private companies and public research institutions. With the majority of the native seed market uncharacterized in Europe until recently (De Vitis et al. unpublished), we provide a perspective on the variation in the native seed sector for ecological restoration with respect to the profession of users and stakeholder groups.

Research professionals in the public sector had strong opinions shown by the significant associations in seed quality and certification importance, the need for compulsory certification to be implemented at a national/federal level and enforced by governmental agencies. However, more than half of researchers who responded did not use certified native seeds in their work likely since research on produced seeds instead of wild seed is less common, and a quarter of participants selected "don't know" for certification type. Multiplied seeds have been used in restoration-related research (Bischoff et al. 2010; Marin et al. 2017); however, many herbaceous species are not commercially available (Ladouceur et al. 2017), thus using wild collections for research is more common practice. The few that did, have primarily used source-identified seed from the AOSCA or the EU directive (2010/60/EU) on fodder seed mixtures. A moderate association was found among NGOs and provincial/state level certification and among private trade professionals which may be in part due to the need for a regulated system that can still account for biogeographical differences, and that does not limit the species produced or the areas where they can be sourced. Supranational or national/federal level regulations could be too restrictive in countries where the trade or land market is not yet well-developed nor are native seed traits well-studied.

Seed quality attributes chosen by more than 60% of research professionals were origin, viability, germination and purity. In the scientific literature on seed quality, the following aspects are widely measured and reported: germination capacity, seedling growth, storage, soil seed banks, origin, viability and germination (Bischoff et al. 2010; Haslgrübler et al. 2013; Marin et al. 2017; Silveira et al. 2014; Wennström et al. 2002); however, relatively little seed germination data is freely available on herbaceous species of high restoration value, such as protected or indicator species, when it comes to European grasslands of conservation concern (Ladouceur et al. 2017). One review found the purity and viability were the most important seed quality tests to prevent weed seed and poor seedling establishment (Elias et al. 2006).

The highest level of seed quality and certification importance was positively associated with private/trade professionals, similar to the public/research group. However, “never” was moderately associated with NGO/trade on seed quality and private/trade for certification quality. This difference in opinion was due to some participants concern in the cost and time needed to certify seeds that may be impractical for smaller businesses to meet. A nurseryman stated in the additional comments section: “There is too much nonsense and red tape already we don't need more. Thank you”.

Both compulsory and participatory certifications types were associated with private/trade professionals. Although a compulsory certification scheme may be desired, following agricultural minimum standards may be impossible for most species since native seeds do not behave in a uniform or stable manner. Supranational and national/federal levels of certification were favoured, but to be conducted by trade associations. This would enable trade professionals to have a say in how the seeds should be certified and provide them a unified voice for policy is critical for the future success of the market. A greater level of research on native seed quality and production could provide industry with further knowledge for development.

Professionals in the land category were predominantly NGOs and private companies; however the log-odds were only significant for research and trade professionals whereas only moderate associations from the log-linear models were found overall (likely due to the smaller sample size and widespread distribution among sectors) in comparison to the other professions. NGO/land professionals said that seed quality was important "in most cases" since time constraints to meet projects may not facilitate the use of seeds of high quality; however many land professionals did stress the importance of locally sourced seed being paramount in their restoration seed selection decision. This was seen more clearly when land professionals chose "none" as well as additional seed quality attributes, in particular, "origin". Certification was always considered to be important and "in few cases" by NGO/land professionals. Compulsory certification conducted by governmental agencies was largely favoured; however, it was evident from additional comments provided by some land professionals that there is concern that certification process would raise the price of native seeds.

Existing certification schemes for native seed vary widely. The Federal Seed Act (7 U.S.C. 1551-1611) regulates interstate and foreign commerce of agricultural seeds, including grass and forage focused on origin, germination and purity. The AOSCA has developed certification labels for pre-variety germplasm that can be source-identified, selected or tested. This state seed certification program helped to ensure site-adapted native seed and in the early 90s drastically increased the sales of native shrubs in the western USA (Curran et al. 1997). Within Europe, the European Commission regulates the marketing of seed for forestry and fodder that enables member states to implement and enforce on a national level. These directives focus on numerous authorisation and labelling requirements for certification (Abbandonato et al. unpublished), but for trees a registry for each tree species is needed in addition. This registry could be useful in the future for herbaceous species to list the seed biology needs for each species per country. More specialized certification schemes created under the 2010/60/EU fodder mixtures denote seed zones, specific rules and limitations. For example, in Germany, the VWW-Regiosaaten uses 22 regions of origin and concise rules on species, sample retainment for auditing purposes, collection, reproduction (e.g. multiplied generations), documentation, and transfer and trade (VWW 2017). In Austria, REWISA uses similar rules corresponding to seed zones, propagation, processing, storage and distribution, and seed reserves (REWISA 2010).

Our findings suggest that a compulsory and national/federal certification scheme is used to address origin and provenance (the needs of the customers) first; otherwise users (in particularly land professionals) may not be inclined to pay more for certified seeds of higher quality and resort to cheaper alternatives such horticultural or fodder varieties. This need seems to be met for forest species in Europe under the (1999/105/EC), but in countries where native seed certification does not exist, this could be the starting point, especially for herbaceous species. A simple certification scheme verifying origin and provenance would enable fast turnover rates for seed lots and increase jobs in certification enforcement. Further rules on origin could be made, such as distance between donor sites and even the implementation of seed zones. Other attributes selected by trade and research professionals such as viability, purity and germination can be participatory or under provincial/state regulation. Due to the known effects of environment and physiological interactions on seed weight and growth (Wennström et al. 2002), breeding and maturity (ENSCONET 2009), germination and dormancy (Silveira et al. 2014; Hampton & Hill 2002) and more is needed on the seed testing of economically important native species (Curran et al.1997). Having access to data on these attributes may be important for implementation in the future after a working seed certification scheme is in place.

This study consulted widely with native seed industry stakeholders. We found that native seed users and producers shared similar preferences on the importance of seed quality, the awareness of factors that can affect quality such as origin, and finally the need for a compulsory certification system at a national/federal level run by governmental agencies.

Acknowledgements

This research was funded by the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n°607785. The Royal Botanic Gardens, Kew, receives grant-in-aid from Defra. We thank C. Blandino, R. Fiegener, S. Frischie, F. Guest, P.P.M. Iannetta, E. Ladouceur, G. Laverack, M. Marin, and C. Trivedi for reviewing the survey draft. We are grateful for the translations by E. Fernández-Pascual, S. Frischie, Jürgen Schneider, M. Tudela Isanta, and V. Carrier.

References

AOSA (Association of Official Seed Analysts) (2002) Seed Vigor Testing Handbook. contribution no. 32 to the Handbook on seed testing.

Baskin CC, Baskin JM (2014) Seeds. Ecology, biogeography, and evolution of dormancy and germination. 2nd Edition. Elsevier Inc. San Diego, California

Bewley JD, Bradford KJ, Hilhorst HWM, Nonogaki H (2013) Seeds: Physiology of development, germination and dormancy 3rd Edition. Springer-Verlag, New York

Bilder CR, Loughin TM (2004) Testing for marginal independence between two categorical response variables with multiple responses. Biometrics 60:241-248

Bischoff A, Steinger T, Müller-Schärer, H (2010) The importance of plant provenance and genotypic diversity of seed material used for ecological restoration. Restoration Ecology DOI 10.1111/j.1526-100X.2008.00454.x

CBD (Convention on Biological Diversity) (2010) Aichi Biodiversity Targets https://www.cbd.int/sp/targets/ (accessed 5 May 2015)

Chivers IH, Jones TA, Broadhurst LM, Mott IW, Larson SR (2016) The merits of artificial selection for the development of restoration-ready plant materials of native perennial grasses. Restoration Ecology DOI 10.1111/rec.12323

Copeland LO, McDonald MB (2001) Seed Science and Technology 4th Edition. Kluwer Academic Publishers, Massachusetts

Cortina-Segarra J, Decleer K, Kollmann, J (2016) Biodiversity: Speed restoration of EU ecosystems. Nature 535:231

Currans SP, Kitchen SG, Lambert SM (1997) Ensuring identity and quality of native seeds. General Technical Report - US Department of Agriculture, Forest Service. INT-GTR 372:17-20

Elias S, Garay A, Schweitzer L, Hanning S (2006) Seed quality testing of native species. Native Plants Journal 7:15-19

ENSCONET (2009) ENSCONET seed collecting manual for wild species, 1st Edition. European Community's Sixth Framework Programme

European Commission (1999) Commission Directive 1999/105/EC of 22 December 1999 on the marketing of forest reproductive material. Official Journal of the European Communities 11:17-40

European Commission (2010) Commission Directive 2010/60/EU of 30 August 2010 providing for certain derogations for marketing of fodder plant seed mixtures intended for use in the preservation of the natural environment. Official Journal of the European Union 228:10-14

European Commission (COM) 478 of 2 October (2015) report from the commission to the European parliament and of the Council [2015]

Friendly M (2000) Visualizing categorical data. SAS Institute Inc., Cary, NC, USA

Hampton JG, Hill MJ (2002) Seed quality and New Zealand's native plants: An unexplored relationship? New Zealand Journal of Botany 40:357-364

Hanson J (1985) Practical Manuals for Genebanks No. 1. Procedures for Handling Seeds in Genebanks. International Board for Plant Genetic Resources, Rome.

Haslgrübler P, Krautzer B, Blaschka A, Graiss W, Pötsch EM (2013) Quality and germination capacity of seed material harvested from an Arrhenatherion meadow. Grass and Forage Science 69:454-461

ISTA (2009) ISTA Handbook on seedling evaluation 3rd edition. The International Seed Testing Association. Bassersdorf, Switzerland.

Kew (2016) Royal Botanic Gardens Kew State of the world's plants. https://stateoftheworldsplants.com/ (accessed 15 May 2017)

Keulartz J (2009) European Nature Conservation and Restoration Policy–Problems and Perspectives. Restoration Ecology 17:446-450

Kuruppumullage P, Sooriyarachchi R (2011) Log-linear models for ordinal multidimensional categorical data. Journal of the National Science Foundation of Sri Lanka 35:29-40

Ladouceur E, Jiménez-Alfaro B, Marin M, De Vitis M, Abbandonato H, Iannetta PPM, Bonomi C, Pritchard HW (2017) Native seed supply and the restoration species pool. Conservation Letters 00:1-9

Laverack G, Matthews S, Powell AA, Khajeh Hosswini M (2006) Scottish wildflower seeds: production and use. Botanical Journal of Scotland 58:49-58.

Louwaars NP (2008) Seed policy, legislation and law. Widening a narrow focus. Journal of New Seeds 4:1-14

Mace GM (2014) Whose Conservation? Science. 345:1558-1560

Marin M, Toorop PT, Powell AA, Laverack G (2017) Tetrazolium staining predicts germination of commercial seed lots of European native species differing in seed quality. Seed Science & Technology 45:1-16

Merritt DJ, Dixon KW (2011) Restoration seed banks—A matter of scale. Science. 332:424-425

Nevill PG, Tomlinson S, Elliot CP, Espeland EK, Dixon KW, Merritt DJ (2016) Seed production areas for the global restoration challenge. Ecology and Evolution 1-8

NRCS (Natural Resources Conservation Service) (2009) Plant materials technical note no. 10 Understanding seed certification and seed labels. United States Department of Agriculture. https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/lapmctn9030.pdf (accessed 20 April 2016)

PCA (Plant Conservation Alliance) (2015) National seed strategy for rehabilitation and restoration 2015-2020 https://www.blm.gov/sites/blm.gov/files/program_natural%20resources_seed%20strategy_quick%20link_seed%20stregy.pdf (assessed 20 August 2016)

Qu L, Wang X, Chen Y, Scalzo R, Widrlechner MP, Davis JM, Hancock JF (2005) Commercial seed lots exhibit reduced seed dormancy in comparison to wild seed lots of *Echinacea purpurea*. HortScience 40:1843-1845

SALVERE (2012) General conditions for an European native plant certificate. CLEUP, Padova

Silveira FAO, Negreiros D, Ranieri BD, Silva CA, Araújo1 LM, Wilson Fernandes G (2014) Effect of seed storage on germination, seedling growth and survival of *Mimosa foliolosa*

(Fabaceae): implications for seed banks and restoration ecology. Tropical Ecology 55:385-392

Society for Ecological Restoration International Science & Policy Working Group (2004) The SER International Primer on Ecological Restoration. www.ser.org & Tucson: Society for Ecological Restoration International

Tilley DJ, Ogle D, Cornforth B (2011) The pop test: a quick aid to estimate seed quality. Native Plants Journal 12:227-232

Tischew S, Youtie B, Kirmer A, Shaw N (2011) Farming for restoration: building bridges for native seeds. Ecological Restoration 29:219-222

Tolvanen A, Aronson J (2016) Ecological restoration, ecosystem services, and land use: a European perspective. Ecology and Society 21:47

VWW (2017) Regelwerk zur Zertifizierung von „VWW-Regiosaaten®“. http://www.natur-im-vww.de/wp-content/uploads/2015/02/Regelwerk-VWW-Regiosaaten.pdf (accessed 15 May 2017)

Wennström U, Bergsten U, Nilsson J-E (2002) Effects of seed weight and seed type on early seedling growth of *Pinus sylvestris* under harsh and optimal conditions. Scand. J. For. Res. 17:118-130

Young S, Schrumpf B, Amberson E (2003) The AOSCA Native Plant Connection. AOSCA

Table S1. Original list of seed quality measures

Section	*Seed Quality Measure*	*Used/removed*
HARVESTING METHODS		
	Collection date	Used
	Collection site/origin	Used
	GPS coordinates	Removed
	Multiplication site/provenance	Used
	Habitat type	Removed
	Ripening year	Removed
	Multiplied generations	Used
	Seed lot/accession	Used
SEED PROCESSING AND STORAGE		
	Quantity of seeds	Removed
	Seed weight/mass	Removed
	Purity	Used
	Storage conditions	Used
	Seed moisture content	Used
	Seed viability	Used
	Seed longevity	Removed
	Seed health	Removed
RESTORATION OR MULTIPLICATION		
	Germination	Used
	Pure Live Seed	Used
	Presence of dormant seeds	Removed
	Drought tolerance	Removed
	Seed vigour	Used
	Uniformity	Removed
	High seed yield	Removed

Figure S1. Survey questionnaire

The NAtive Seed Science, TEchnology and Conservation Initial Training Network

Investigating native seed quality for ecological restoration: A survey of the native seed community

About Us

Dear participants,

We are two researchers part of the European Union funded **NASSTEC** (**NA**tive **S**eed **S**cience, **TE**chnology and **C**onservation) project. This is a partnership between industrial and academic partners whom aim to find innovative solutions to improve large-scale native seed production and meet the restoration demand. Native seeds are critical for ecological restoration to sustainably maintain local biodiversity and ecosystem resilience, and they are derived from plant species that naturally occur in a particular region, ecosystem, or habitat.

The survey will take you about 15 minutes and your identity will be kept anonymous and treated confidentially*. Your contribution is essential to understand the current standards in native seed quality, market status, and the transfer of knowledge between international and intersectoral stakeholders.

Your responses will be used for research purposes only and you will receive a copy of the published results for your contribution. We encourage you to share this survey with other native seed researchers, producers, practitioners, and users worldwide.

Thank you in advance for your participation.

Sincerely,

Holly Abbandonato and Marcello De Vitis

NASSTEC

The NAtive Seed Science, TEchnology and Conservation Initial Training Network

MARIE CURIE ACTIONS

PEOPLE

Investigating native seed quality for ecological restoration: A survey of the native seed community

Section 1. Participant Information

We would like to know the following information about you for our analyses.

* **1. Which sector are you *working* in?**

- ◯ Non Profit/Non Governmental Organisation (NGO)
- ◯ Private
- ◯ Public
- ◯ Other (please specify)

* 2. Which of the following ***best*** **describes your** **current profession?**

- ◯ Researcher
- ◯ Student
- ◯ Technician/Fieldworker
- ◯ Seed analyst
- ◯ Administration
- ◯ Land manager
- ◯ Consultant
- ◯ Restoration/Conservation practitioner
- ◯ Landscape contractor
- ◯ Farmer
- ◯ Nursery
- ◯ Seed producer
- ◯ Seed retailer
- ◯ Policy-maker
- ◯ Other (please specify)

* **3. In which *country* is your profession or your main affiliation based?**

Section 2. Native Seed Quality Requirements

Native seed quality can be related to a combination of factors including the *genetic make-up* and the *methods* used to collect, store, process, and multiply the seeds (Baskin & Baskin 2014; Probert *et al.* 2006).

We would like to know which aspects of native seed quality are important to you.

*** 4. Do you use native seeds for your work?**

- ◯ Yes
- ◯ No
- ◯ No, but I plan to in the future

*** 5. Which of the following species do you work with? (check all that apply)**

- ☐ Native Trees and Shrubs
- ☐ Native Herbaceous (e.g. wildflowers, grasses)
- ☐ Agricultural (e.g. vegetables, wheat)
- ☐ Other (please specify)

*** 6. Is *seed quality* an important factor to you when using native seeds?**

- ◯ Yes, always
- ◯ In most cases
- ◯ In few cases
- ◯ Never
- ◯ Don't know

*** 7. Which information related to *native seed quality* is important to <u>you</u> (check all that apply)?**

- [ ] **Collection Date** *(date when the seeds were collected from the wild population)*
- [ ] **Harvesting Date** *(date when the seeds were harvested after crop multiplication of the wild population)*
- [ ] **Origin** *(specific location of the collected wild population)*
- [ ] **Provenance** *(location where the seeds were multiplied, if different from the origin)*
- [ ] **Multiplied Generations** *(Number of times a native seed crop has been multiplied since the original collection)*
- [ ] **Seed Lot** *(Traceability of the seed lot to the collector/producer using an alphanumerical code)*
- [ ] **Purity** *(percentage by weight of the target seeds, other seeds and inert matter)*
- [ ] **Storage Conditions** *(the relative humidity and temperature of the dry room during storage)*
- [ ] **Seed Moisture Content** *(represents the percentage of water maintained in a sealed package of seed before distribution)*
- [ ] **Seed Viability** *(is a measure of how many live seeds are in a seed lot including dormant seeds which are seeds that may not germinate immediately, but are still alive)*
- [ ] **Seed Health** *(the presence or absence of disease-causing organisms such as fungi, nematodes, bacteria, viruses and insects in a seed lot)*
- [ ] **Germination** *(percentage of germinated seeds (radicle emergence) at optimal conditions)*
- [ ] **Germination Rate** *(the speed at which seeds germinate at optimal conditions)*
- [ ] **Pure Live Seed** *(A more precise measure of the percentage of live seed within a seed package (purity x viability)/100)*
- [ ] **Presence of Dormancy** *(Seeds controlled by environmental conditions that regulate the timing of germination to optimize seedling survival and plant maturation in their natural environment)*
- [ ] **Type of Dormancy** *(Classification of seed dormancy type, e.g. physiological, physical, morphological)*
- [ ] **Seed Vigour** *(germination performance under unfavourable conditions)*
- [ ] **Seed Pre-treatments** *(enhancement of seed performance, e.g. priming, pelleting, dormancy-breaking)*
- [ ] Don't know
- [ ] Other (please specify)

*** 8. What *seed quality* control activities do <u>you</u> perform? (check all that apply)**

- [ ] Germination
- [ ] Viability (e.g. tetrazolium test, cut test, conductivity test)
- [ ] Purity
- [ ] Seed health
- [ ] None
- [ ] Other (please specify)

9. Additional Comments

Section 3. Native Seed Quality Certification

We would like to know if certification for *native seed quality* is something effective or useful when producing or buying native seeds.

*** 10. Should *native seeds* on the market be certified for their quality?**

- ◯ Yes, always
- ◯ In most cases
- ◯ In few cases
- ◯ Never
- ◯ Don't know

*** 11. What type of *certification* should be applied to native seeds?**

- ◯ Compulsory
- ◯ Participatory
- ◯ Contract-based
- ◯ None
- ◯ Don't know
- ◯ Other (please specify)

*** 12. If so, at what *scale* should <u>native seed certification</u> be regulated?**

- ◯ Supranational (e.g. European Union)
- ◯ National/Federal
- ◯ Regional
- ◯ Provincial/State
- ◯ Municipal
- ◯ Private
- ◯ Federation/Association/NGO
- ◯ Don't know
- ◯ None

*** 13. *Who* should conduct <u>native seed certification</u>?**

- ◯ Governmental Agencies
- ◯ Germplasm Banks
- ◯ Universities
- ◯ Botanic Gardens
- ◯ Trade Associations
- ◯ Private companies
- ◯ Other (please specify)

*** 14. Are you currently *producing*, *selling* or *buying* native seeds with the following seed certification? (check all that apply)**

- [ ] **Basic, commercial or certified fodder seed** *(European Directive 66/401/EEC)*
- [ ] **Source-identified forest reproductive material (yellow label)** *(European Directive 99/105/EC)*
- [ ] **Preservation mixtures** *(European Directive 2010/60/EU)*
- [ ] **Seed Scheme** *(OECD - Organisation for Economic Co-operation and Development)*
- [ ] **REWISA** *(Regionale Wildpflanzen & Samen)*
- [ ] **VWW Regio-saaten/ RegioZert**
- [ ] **DAFM** *(Department of Agriculture, Food and the Marine)*
- [ ] **Flora Locale**
- [ ] **Bio-Suisse**
- [ ] **Bioverita**
- [ ] **Demeter**
- [ ] **ABCert**
- [ ] **Source-identified seed (yellow label)** *(AOSCA - Association of Official Seed Certifying Agencies)*
- [ ] **Selected seed (green label)** *(AOSCA - Association of Official Seed Certifying Agencies)*
- [ ] **Tested seed (blue label)** *(AOSCA - Association of Official Seed Certifying Agencies)*
- [ ] I do not use certified native seeds
- [ ] I do not apply certification to my native seeds
- [ ] I do not buy, sell or produce native seeds
- [ ] Other (please specify)

15. Additional Comments

Figure S2. Data management rules

Participant information -“other” responses

Sector:

-Respondent 5023510838: changed sector from “other” (response: retired private) to “private”, also changed profession from “other” to “seed producer”.

-Respondent 4952701318 changed “other” (wildseed producer) to “private”.

-Respondent 4943073969 changed “other” (seed producer) to “private”.

- Respondent 4894388238 changed “other” (charity) to “NGO” and profession from “Ecologist” to “Consultant”

-Respondent 4887878208 changed “other” (voluntary) to “NGO” and profession from Garden Development worker to “Restoration/Conservation Practitioner”

-Respondent 4885854521 changed “other” (government retired “emeritus”) to “public”

-Respondent 4879362057 changed “other” (PhD student at private company) to “public”

-Respondent New1 changed “other” (academia) to “public”. I looked up university in email.

-Respondent 4916294809 changed “other” (private activities) to “private”.

-Respondent 5027632497 changed “other” (gardening/landscaping) to “private”

-Respondent 4962570400 changed “other” (nursery organization) to “ngo”

-Respondent 4895059033 changed “other” (university) to “public”. Checked university in email.

-Changed last two respondents (4886423780, 4957442818) in which I couldn’t determine sector to: “private” and “public” randomly.

Profession:

-Respondent 4992758108 changed “other” (seed analysts) to “seed analyst”.

-Respondent 5029036536 changed “other” (teacher/researcher) to “researcher”.

-Respondent 4950433876 changed “other” (office manager) to “administration”

-Respondent 4885296114 changed “other” (office manager) to “administration”

-Respondent 4879691123 changed “other” (regional representative) to “nursery”

-Respondent 4877317371 changed “other” (breed, produce, retail) to “producer”

-Respondent 4969521780 changed “other” (analyst, produce, retail) to “producer”

-Respondent 4885537530 changed “other” (“in bloom” group inverflora) to “landscape contractor”

-Respondent 4911130053 changed “other” (conservation officer) to “Restoration/conservation practitioner”

-Respondent 5075680690 changed “other” (conservation officer) to “Restoration/conservation practitioner”

-Respondent 4879137113 changed from “administration” to “landscape” as they are with a restoration group - Naturgarten

-Respondent 4892374177changed from “administration” to “trade” as they are with a restoration group:Valencia.es (Valencia tourism) who “sells uncertified seeds”.

-Respondent 4903910331 changed from “administration” to “research” as he is seed analyst/researcher who I met in the U.S.

-Respondent 5100077080 changed from “administration” to “research” as he/she is a seed analyst from the dept. of agriculture working with plant protection and certification in Estonia.

-Respondent 4885296114 changed from “other, manager of a social enterprise” to “research” as he/she is creating a seed library for the Isle of Bute, could be a seedbank or botanic garden.

-Respondent 4905345034 changed from “administration” to “research” as he/she is a seed analyst from the ministry of the environment in Finland.

-Respondent 4950433876 changed from “administration” to “trade” as they work at a company (private) in Germany.

-Respondents who fit both “land” and “trade” categories were randomly assigned to either group.

-Respondent 4898776409 and 4897636383 were assigned to “trade” and respondent 4876776046 and 5027632497 were assigned to “land”.

-Respondent 4975417827 changed from “policymaker” to “res” as he is a researcher and seed analyst from the university of Utah in the USA.

-Respondent 5027461711 changed from “policymaker” to “res” as he is a researcher from the UK specializing on forestry.

-Respondent 4876791134 changed from “policymaker” to “land” as they are a UK policymaker who buys seed for restoration, and does not cultivate them.

- Respondent 5042809549 was randomly assigned to “trade”.

Figure S3. R script

Importance of seed quality and certification

```
library(vcd)
lodds(~ seed_quality + profession2|sector, data = dat1) ##log odds
confint(lodds(~ seed_quality + profession2|sector, data = dat1),lines=T) #CI
summary(lodds(~ seed_quality + profession2|sector, data = dat1),lines=T) #summary stats

loddsratio(~ cert_quality + profession2|sector, data = dat1)
confint(lodds(~ cert_quality + profession2|sector, data = dat1),lines=T)
summary(lodds(~ cert_quality + profession2|sector, data = dat1),lines=T)

##Joint Independence A+B|C
mosaic(~ seed_quality + profession2|sector, data = dat1, residuals_type=c("deviance"), shade=T)
mosaic(~ cert_quality + profession2|sector, data = dat1, residuals_type=c("deviance"), shade=T)
```

Certification type, level and enforcement

```
lodds(~ cert_type+ profession2|sector, data = dat1, ref=1) ##log odds with corresponding ref.
confint(lodds(~cert_type + profession2|sector, data = dat1),lines=T, ref=1) #CI
summary(lodds(~cert_type + profession2|sector, data = dat1),lines=T, ref=1) #summary stats

##Joint Independence A+B|C
mosaic(~ cert_type + profession2|sector, data = dat, residuals_type=c("deviance"), shade=T)
mosaic(~ cert_level + profession2|sector, data = dat1, residuals_type=c("deviance"), shade=T)
mosaic(~ do_certification + profession2|sector, data = dat1, residuals_type=c("deviance"),
shade=T)
```

Seed quality attributes

```
library(MRCV)
mtable.one <- marginal.table(data = dat, I = 1, J = 19) ##Marginal table
mtable.one

##Test for MMI using the Bonferroni adjustment
test.mmi.bon <- MI.test(data = farmer1.irdframe, I = 1, J = 19, type = "bon", summary.data =
TRUE, plot.hist =TRUE)
test.mmi.bon

##boxplot using positive frequency responses only
boxplot(freq ~ Y, dat, las=2,par(mar = c(12, 5, 4, 2)+ 0.1), names = c("Collection date","Harvest
date","Origin","Provenance","Generations Multiplied","Seed
lot","Purity","Storage","Moisture","Viability","Seed health","Germination","Germination
rate","Pure live seed","dormancy","dormancy type","Seed vigour","Pre-treatment", "None"))
dat$Y <- with(dat, reorder(Y,freq)) #order by count
boxplot(freq ~ Y, dat, las=2,par(mar = c(12, 5, 4, 2)+ 0.1)) ## use to fix x labels
```

```
boxplot(freq ~ Y, dat, las=2,par(mar = c(12, 5, 4, 2)+ 0.1), ylab="Marginal positive response
(%)", names = c("None","Pure live seed","Seed vigour","Seed moisture content","Germination
rate","Pre-treatment","Dormancy type","Generations multiplied","Dormancy","Seed
health","Harvest date","Storage conditions","Seed lot","Collection
date","Provenance","Purity","Germination","Viability","Origin"))
```

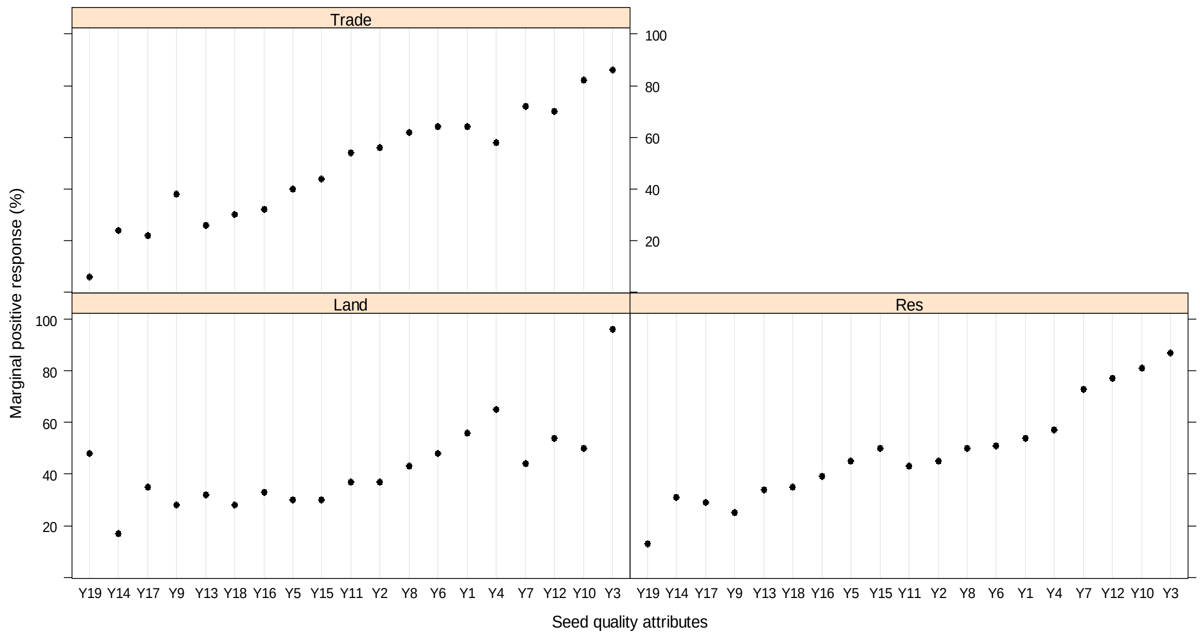

Figure S4. Percent frequency of marginal positive responses for seed quality attributes selected by each profession (trade, land, research).

Y19: none, Y14: pure live seed; Y17: seed vigour; Y9: seed moisture content; Y13: germination rate; Y18: pre-treatment; Y16: dormancy type; Y5: generations multiplied; Y15: dormancy; Y11: seed health; Y2: harvest date; Y8: storage conditions; Y6: seed lot; Y1: collection date; Y4: provenance; Y7: purity; Y12: germination; Y10: viability; Y3: origin.

Paper 4:

Abbandonato H, Liu U, Squire G, Iannetta PPM, Pritchard HW (2017) Applying Standard PREanalytical Codes to the marketing of herbaceous native seeds for ecological restoration. Plant Biology, special issue: Natural capital from native seeds, ***manuscript.***

Applying Standard PREanalytical Codes to the marketing of herbaceous native seeds for ecological restoration

Authors: Holly Abbandonato[1, 2, 3], Udayangani Liu[4], Geoff Squire[5], Pietro PM Iannetta[5], and Hugh W. Pritchard[4]

[1]MUSE – Science Museum, Corso del Lavoro e della Scienza, 3, 38122, Trento, Italy

[2]University of Pavia, Corso Strada Nuova, 65, 27100, Pavia, Italy

[3]Address correspondence to H. Abbandonato, email h.abbandonato@gmail.com

[4]Royal Botanic Gardens, Kew, Wellcome Trust Millennium Building, Wakehurst Place, Ardingly, West Sussex, RH17 6TN, UK

[5]The James Hutton Institute, Dundee, UK

Type: Problem oriented short research paper (max 5 typeset pages)

Abstract

With few supranational regulations applicable to the herbaceous native seed trade other than as animal feed, the certification of native seeds is scarce except in a handful of European countries. To better regulate this sector and support the restoration targets in Europe, we devised a labelling framework for the marketing of native seed for ecological restoration. To understand what defines “quality” for this purpose we consulted the survey on the native seed community and developed a user and full SPREC (Standard PREanalytical Codes) code, and quality assurance rank for 5 native species that are commonly collected from the wild, bulked and marketed: *Daucus carota*, *Hypericum perforatum*, *Lotus corniculatus*, *Papaver rhoeas* and *Silene vulgaris*. A DEXi model on native seed quality was developed for wild and produced species that defined quality as both capturing the original genetic diversity, and ensuring that seed produced for sale or storage met pre-defined standards following processing, handling and bulking. The label was then designed using SPREC and named U-SeeD (User-based, SPREC and DEXi) certification. Under this scheme, wild seed lots of the test species were well documented and demonstrated high quality; in germination, viability and purity. Produced seed lots showed more variation from low to high quality primarily due to the lack of information on genetic diversity, date of harvesting, origin, provenance and seed lot. This study provides a simplistic and transparent certification system with seed standards designed for ecological restoration accounting for both genetic diversity and product quality to facilitate a growing herbaceous native seed marketplace.

Keywords: bio-banking, certification, *ex situ*, regulation, seed industry, seed label, standards

Introduction

The findings of the ‘global native seed survey’ (**Paper 3**) identified that end-users preferred to know the quality of the native seeds they purchased. These desired seed quality attributes were the origin, provenance, germination, viability and purity. The issue of which quality standards should be both recorded and applied in the ‘restoration marketplace’ is widely debated. With each quality attribute assessed, the measure must be tested in a standardised manner and this may be arduous. For example, the definition of seed viability varies with each testing agency. The International Seed Testing Association (ISTA) and the Association of Official Seed Analysts (AOSA) use subtly different standards. ISTA focuses on the proportion of seeds in a lot that can germinate and produce young seedlings (so-called ‘normal germination’) (ISTA 2017). Such a standard is central to the issuing of seed lot certificates as the mainstay of quality assurance for seeds (agricultural, forestry, and horticultural) in a trade that is estimated to be in the region of 3.87 million metric tonnes per annum with a value in 2015 of US$ 10.7 billion (International Seed Federation 2017).

Whilst the global market in native species’ seed is currently small by comparison, quality standards are needed. Moreover, because the timing of restoration projects is somewhat less predictable than the annual sowing of agricultural crops, native seeds will likely be stored for an indefinite period of time before use in land restoration / rehabilitation projects. Consequently, it is important that the manner in which the seed lot has been stored and handled is recorded.

Recommendations and standards on the handling of seed for storage are available for agriculture species (FAO, 2013; Rao et al., 2006) and wild plant conservation collections, in Europe (ENSCONET, 2009a,b), Australia (Offord and Meagher, 2009), the United States of America (Seeds of Success, 2012) and across the world (Millennium Seed Bank Partnership, 2014). Such guidance generally covers how to make a seed collection that is genetically representative of the species’ population being sampled, what conditions to use for drying and storing seed and which environments are suitable for seed germination. Because there are multiple institutions (different pedoclimates and facilities), involved in such programmes, and many individuals (different behaviours) standardisations of seed testing across laboratories is very difficult to achieve. Also the best conditions for seed germination will vary with species and site of origin (pedoclimate).

Also, seed lifespan varies considerably between species and seed lots, and including seed batches stored within international standards seed banks (Walters et al. 2005; Li & Pritchard 2009). Therefore, this is also a critical question: '*how then can native seed lots be labelled in a way that is both consistent and informative?* Since, at least basic seed quality attributes should be disclosed, such as: collection - seed zone, sampling strategy; processing - pre-storage, drying, banking; and quality assessment - germination, viability. More specifically, is it possible to develop a coding system that allows retrospectively some interpretation of seed lot variability in quality as it enters the marketplace?

Standard PREanalytical Codes (SPREC) for biological specimens (biospecimen) management was developed in 2009 by the International Society for Biological and Environmental Repositories (ISBER). The aim was to help document the most important pre-analytical quality parameters of biospecimens used for research (Lehmann et al. 2012). SPREC was originally developed by the Integrated Biobank of Luxembourg to provide 'a comprehensive, but usually easy-to-implement tool to document the *in vitro* pre-analytical (collection, processing and storage) details of biospecimens'. The purpose of the study reported here was to develop annotation for native seeds based traits as such characteristics may help users determine their suitability in downstream uses. No such scheme appears to be in existence for native seeds, and the approach may have special merit as a means by which products may be labelled to help ensure quality and/or suitability in restoration based activities. However, there is little comprehension of how important each factor is to downstream seed quality other than the concern that old seed may produce poor quality plants.

If SPREC is to be successful in this application, it needs to be able to reach an overall assessment of a seed lot based on many, diverse properties. If such properties can be aggregated into subgroups, then the whole can be arranged in a hierarchical structure in which measured ‘lower level’ properties are combined into inferred ‘higher level properties’ in sequence until the seed lot can be given a final ranking. Such hierarchical ‘decision trees’ are increasingly used in agriculture and ecology to compare production systems, habitats and land management options. DEXi has been used to analyse the chain of effect assessing human intervention on ecosystem services, cropping systems, genetically modified crops, and provides a framework to rank and optimise innovative production systems (Squire et al. 2016; Bohanec et al. 2008; Pelzer et al. 2012).

This study therefore describes the development of a prototype: (a) a labelling framework for seed quality using SPREC and DEXi; (b) a weighted measure for seed quality assurance; and, (c) applying the code to seeds of widespread European native species of wild accessions and commercially produced seed lots since both sources are commonly used in conservation and restoration based activities.

Methods

Native seed quality DEXi multi-attribute decision tree

Seed quality attributes were reviewed from (Abbandonato et al. unpublished) and all measures were selected except for “storage conditions” which can be measured using seed “moisture content”. Pure live seed was considered an optional attribute since it is more commonly used in the United States, rather than Europe. Relationships between attributes were created to decide the root, aggregated and input attributes. The root attribute was Native Seed Quality, the aggregated attributes were Wild and Produced and the input attributes were designated in relation to Genetic Diversity and Product Quality which was further divided into Processing, Handling and Seed Properties (**Fig. 1**). The arrow connecting wild seed and produced seed in the DEXi model indicates the fluency between the quality of seed from wild to produced seed input attributes. The model consisted of sixteen final seed quality attributes. A multi-attribute decision tree was formulated using DEXi (version 5.02) and the DEXiTree software (version 0.94).

Each final attribute was then assigned a label code, level and a final weighted category or score (**Table 1**). Genetic diversity in Wild seed noted the Presence of Dormancy, whereas Produced seed only included the number of Generations multiplied since information on dormancy would be present under the Wild seed code. In addition, in Produced seed, the collection date is substituted for harvesting date, and provenance is added to represent the site of multiplication.

Table 1. Native seed quality attributes, label codes, levels and weighted categories for the DEXi multi-attribute decision tree.

Attributes	**Wild/produced**	**Label codes**	**Label levels**	**Weighted ranks**
Collection date	Wild	Same as level	dd/mm/year mm/year year	High Med Low
Harvest date	Produced	Same as level	dd/mm/year mm/year year	High Med Low
Origin	**Both**	Same as level	**GPS coords.** **Town, country** **Country**	**High** **High** **Low**
Provenance	**Produced**	Same as level	**GPS coords.** **Town, country** **Country**	**High** **High** **Low**
Presence of dormancy	Produced	D2 D0	Dormancy No Dormancy	High Low
Generations multiplied	Produced	M2 M1 M0	F0-F2 F3-F5 >F5	High Med Low

Germination	**Both**	**G2**	**67% - 100%**	**High**
		G1	**33% - 66%**	**Med**
		G0	**0% -32%**	**Med**
Germination rate	Both	GR2	67 - 100%/time	High
		GR1	33 - 66%/time	Med
		GR0	0 -32%/time	Med
Pre-treatments	Produced	PT2a	Pellet	High
		PT2b	Primer	High
		PT1	None	Med
Purity	**Both**	**P2**	**67% - 100%**	**High**
		P1	**33% - 66%**	**Med**
		P0	**0% -32%**	**Low**
Pure live seed*	Both	PS2	67% - 100%	High
		PS1	33% - 66%	Med
		PS0	1% -32%	Low
Seed health	Both	S2	Sterile	High
		S0	Not sterile	Low
Seed lot	Both	Same as level	Alphanumeric code	High
			No code	Low
Seed moisture content	Both	MC2	1% -32%	High
		MC1	33% - 66%	Med
		MC0	67% - 100%	Low
Seed viability	**Both**	**V2**	**67% - 100%**	**High**
		V1	**33% - 66%**	**Med**
		V0	**0% -32%**	**Low**
Seed vigour	Both	SV2	67% - 100%	High
		SV1	33% - 66%	Med
		SV0	0% -32%	Low

Under origin and provenance, GPS coordinates were not required for high quality since location of collection may be considered sensitive information depending on the source. Germination and germination rate did not consist of a “low” weighted level since the optimal conditions of some species may vary as a result of dormancy and thus testing viability in conjunction could account for quality misinterpretations.

Pure Live Seed (PLS) and seed vigour were removed from the code since they are not well used, but could still be proxies for seed quality in the future. The final quality of all numerically measured attributes could vary depending on species specific traits; however taking into consideration more than one attribute (e.g. germination and viability) and giving some attributes more weight than others helped to minimize over and under estimates of quality.

Seed quality attributes with only two weighted ranks are origin, provenance, germination, germination rate and pre-treatments. They are weighted either as high and medium, or high and low. Origin and provenance are high and low since local seed is preferred for restoration (Durka et al. 2016). Germination, germination rate and pre-treatments are ranked as high and medium only, since germination can depend on dormancy (Laverack et al. 2007; Marin et al. 2016) and may not be a complete quality proxy without a viability measure. Pre-treatments are not as common in native seeds yet, but seeds without them for the purpose of this study are considered medium quality since they act as an enhancer (Pedrini et al. 2017).

Seed lots shown in the final label were hypothetical to protect the identity of the supplier and grey labels represented wild seed and green represented produced seed. To determine the final quality of the each seed lot, each label code (0-2) was summed and divided by the total number of attributes. Then the quality was assigned based on the final value low: 0.00 - 0.67, medium: 0.68 - 1.33, and high (1.34 – 2.00).

Wild Seed Accessions

The sample dataset to be tested was retrieved from the Millenium Seed Bank Kew Database which contains over 80,000 seed collections. The initial data selection was based on the following mandated criteria (1) wild biological status, (2) verified identification at the species level, (3) known dates of seed collection and donation (4) known country, (5) at least five accessions in total, (6) at least one accession from Europe, and (7) at least three germination tests during the -20°C storage regime. After the initial selection the dataset consisted of 1039 accessions and 109 species.

To narrow down the species list, trees, shrubs and vegetables were removed. Species were required to be produced by a minimum of three producers in no less than three European countries. This narrowed the list to 37 species, of which five species produced in the most European countries were chosen. Five species were selected from distinct families and the following species were: *Daucus carota* L., *Hypericum perforatum* L., *Lotus corniculatus* L., *Papaver rhoeas* L., and *Silene vulgaris* (Moench) Garcke (**Table 2; Table S1**). Wild accessions with the lowest germination were selected for the labels. The moisture content used was from the seed bank dry rooms at 3-7% depending on the oil content of the seeds (Linington & Manger 2014). Purity was measured using an x-ray and a cut test to determine empty, infested and moldy seed, and debris. Wild seed accessions were not limited to Europe, but had to have at least one European accession. Non-European accessions were used in some cases since wild accessions in general are scarce, and in addition seeds of varying performances were needed to properly test the code and quality assurance.

Table 2. Species selection criteria and final accession origin and total.

Family	Species	Accession Country (n)	Number of Accessions	EU Countries produced
Apiaceae	*Daucus carota*	Canada (1); France (1); Lebanon (1); Morocco (1); United Kingdom (18)	21	6
Caryophyllaceae	*Silene vulgaris*	Bulgaria (1); Canada (1); Croatia (2); Germany (3); Greece (1); Morocco (1); Turkey (1); Slovenia (1)	11	7
Fabaceae	*Lotus corniculatus*	Canada (1); Greece (2); Italy (4); Morocco (1); United Kingdom (5)	13	8
Hypericaceae	*Hypericum perforatum*	Canada (1); France (1); United Kingdom (5)	7	6
Papaveraceae	*Papaver rhoeas*	Italy (1) Jordon (1) United Kingdom (2)	4	8

Produced Seed Accessions

Multiplied seeds from two commonly sold species *Silene vulgaris* and *Papaver rhoeas* were obtained from three European producers in Italy, Spain and the United Kingdom (**Table 3**). Purchased seeds were stored in a dry room at 16°C and 14% RH for approximately six months before germination tests. Seeds were sown in Petri dishes on 1% agar-water substrate for three months. The optimal germination (100%) temperature for both species was 21°C (12/12 h light / dark per day) or 16°C (12/12 h light / dark per day) from the *Seed Information Database* (RGBK 2008). However since both species can exhibit physiological dormancy (**Table S1**), warmer and cooler temperatures were tested in addition. Six temperature treatments were applied (15/5°C, 15°C, 20/10°C, 20°C, 25/15°C, 30°C) under 12/12 light / dark using six replicates and 25 seeds for each species. Seeds were scored twice a week for the first month and once a week during the second and third month. Scoring began two days after seeds were placed on the agar. Germination was defined as radicle emergence. After 89 days, a cut-test was used to determine infested, moldy or empty seed under a dissecting microscope. Seeds were also weighed and each producer was asked how many generations the seeds had been multiplied, the harvesting method and year of harvest (**Table 3**). Produced seed lots with the lowest germination were selected for the labels. Three replicates of 50 seeds each was weighed and extrapolated to determine the average thousand seed weight.

Table 3. Average thousand seed weight, number of generations multiplied, harvest type and year of harvest from each producer for *Papaver rhoeas* and *Silene vulgaris*.

Species	Producer	Seed weight (g)	Generation	Harvest type	Year of harvest
Papaver rhoeas	A	0.090	F13	Combine	2013
	B	0.132	F1	Hand	2014
	C	0.076	F0	Hand	2015
Silene vulgaris	A	1.286	F11	Hand	2014
	B	0.584	F1	Hand	2014
	C	0.682	F1	Hand	2015

Data Analysis

The germination estimate, standard error, p-values and germination rate were analyzed in R Statistical Computing Language and Platform version 3.3.3 (R Core Development Team 2016). The final germination included viable seeds only and was calculated using a generalized linear model with a binomial distribution using the packages *effects*, *MASS*, *plyr* and the germination proportion was plotted using *ggplot2*.

Results

The native seed quality DEXi multi-attribute decision tree consisted of 12 input attributes for wild seed and 14 input attributes for produced seed. However, due to the nascent native seed market, seed quality attributes associated with "+" symbols corresponded to the results from Abbandonato et al. (unpublished) on seed quality preferences decided by the users and stakeholders (**Fig. 1**). This was then applied to the final SPREC code under "User Code" and

"User Quality". Due to DEXi's design, no more than four final attributes were selected per aggregated attribute to run the quality assessment model most effectively.

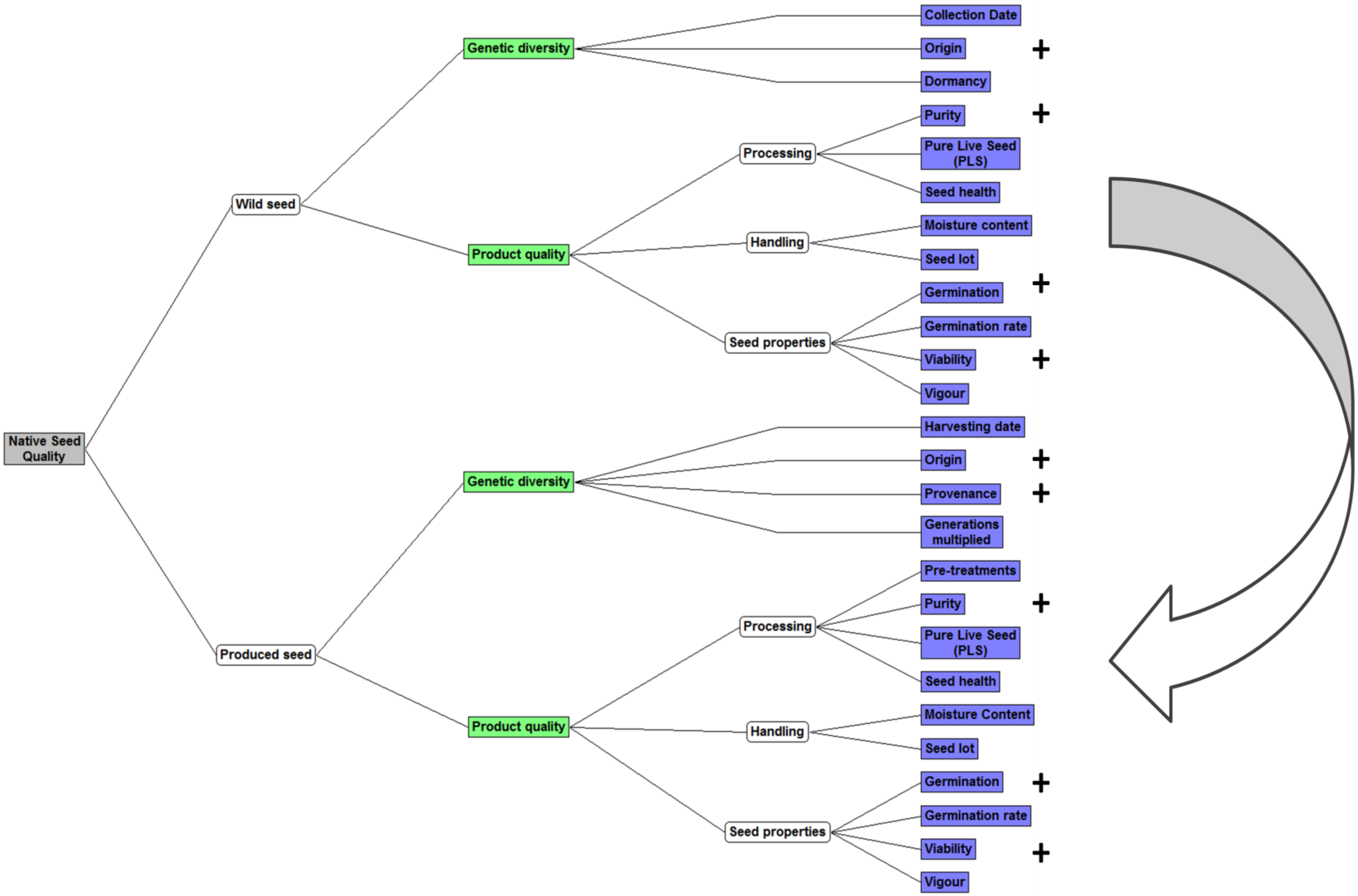

Figure 1. A DEXi multi-attribute decision tree for quality of wild and produced native seed. The "+" symbols indicate seed quality input attributes selected by more than 60% of seed users and producers as important from Abbandonato et al. (unpublished).

Each SPREC label noted the family, species name, and collection date/harvesting date, origin/provenance, seed lot, and then in the code: dormancy/generations multiplied, germination, germination rate, pre-treatment, purity, seed health, moisture content and viability. All wild accessions had a high quality under both the user and full weighted ranks; however, germination varied between high and medium (**Fig. 2**). *Hypericum*, *Papaver* and *Silene* had high germination (67-100%), whereas *Lotus* and *Daucus* had medium germination (33-66%) and (0-32%) respectively. Purity and viability varied between accessions, but all accessions met the high quality rank. The remaining attribute data was the same for each accession, except for the date and country.

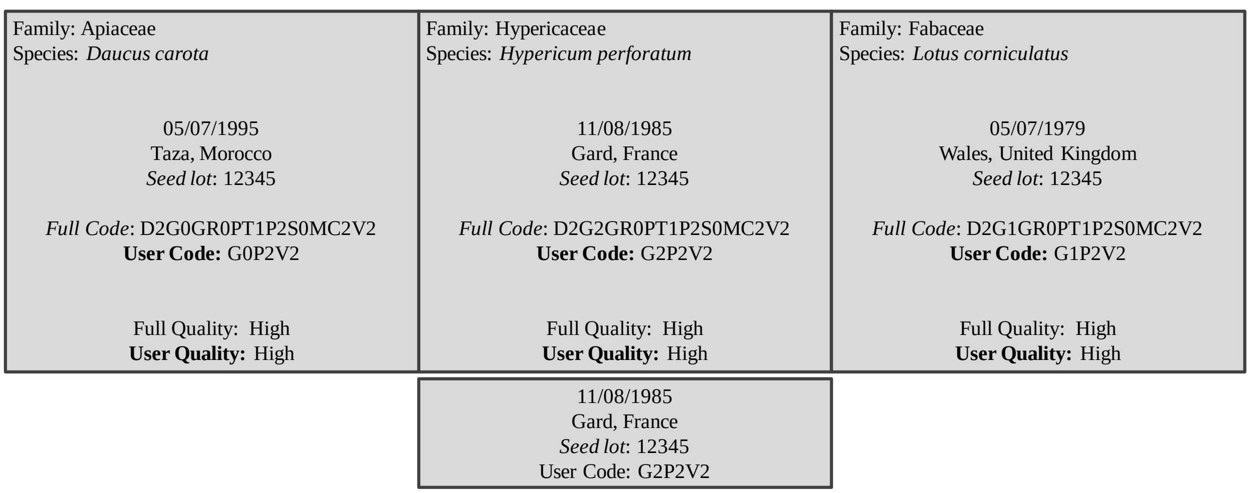

Figure 2. SPREC native seed label for wild (grey label) seed of *Daucus carota*, *Hypericum perforatum*, *Lotus corniculatus* using the DEXi multi-attribute model to access quality. Two quality results were given. “Full quality” uses the full model, whereas “User Quality” only accounts for the selected attributes found in (Abbandonato et al. unpublished). The small label is a compacted version of “User Quality” only.

For *Papaver rhoeas*, the wild accession also exhibited a high quality rank, whereas the produced seed lots varied between low and medium (**Fig. 3**). The low seed lot was a result of little information included on the packaging on the date of harvest, origin, provenance, and seed lot. The average thousand seed weight and the germination was the lowest from country C and the seeds sold were from the F0 generation (**Table 3**). Similarly, the other seed lots also had missing provenance data and germination and viability varied (**Table S2**).

Family: Papaveraceae Species: *Papaver rhoeas* 26/09/1977 England, United Kingdom *Seed lot*: 12345 *Full Code*: D2G2GR0PT1P2S0MC2V2 **User Code:** G2P2V2 Full Quality: High **User Quality:** High	Family: Papaveraceae Species: *Papaver rhoeas* 13/03/2013 Origin: Town, Country A Provenance N/A *Seed lot*: 12345 *Full Code*: M0G1GR0PT1P2S0MC0V1 **User Code:** G1P2V1 Full Quality: Medium **User Quality:** Medium
Family: Papaveraceae Species: *Papaver rhoeas* 10/2014 Origin: Country B Provenance N/A *Seed lot:* N/A *Full Code*: M2G0GR0PT1P2S0MC0V2 **User Code:** G0P2V2 Full Quality: Low **User Quality:** Medium	Family: Papaveraceae Species: *Papaver rhoeas* Date: N/A Origin: Country C Provenance N/A *Seed lot*: 12345 *Full Code*: M2G0GR0PT1P2S0MC0V2 **User Code:** G0P2V2 Full Quality: Medium **User Quality:** Medium

Figure 3. SPREC native seed label for wild (grey label) seed and produced (green label) seed of *Papaver rhoeas* using the DEXi multi-attribute model to access quality. Two quality results were

given. “Full quality” uses the full model, whereas “User Quality” only accounts for the selected attributes found in (Abbandonato et al. unpublished).

For *Silene vulgaris*, the wild accession also exhibited a high quality rank, whereas the produced seed lots varied between medium and high (**Fig. 4**). The product information given by each producer for *Silene* was the same as *Papaver*, the only main difference was the germination (**Table S3**) and viability was medium to high, and high respectively. The average thousand seed weight and the germination was the highest from country A and the seeds sold were from the F11 generation; however germination was higher from seeds from country C (**Table 3**).

Family: Caryophyllaceae Species: *Silene vulgaris* 18/07/1970 Zagreb, Croatia *Seed lot*: 12345 *Full Code*: D2G2GR0PT1P2S0MC2V2 **User Code:** G2P2V2 Full Quality: High **User Quality:** High	Family: Caryophyllaceae Species: *Silene vulgaris* 11/06/2014 Origin: Town, Country A Provenance N/A *Seed lot*: 12345 *Full Code*: M0G1GR0PT1P2S0MC0V2 **User Code:** G1P2V2 Full Quality: Medium **User Quality:** High
Family: Caryophyllaceae Species: *Silene vulgaris* 10/2014 Origin: Country B Provenance N/A *Seed lot:* N/A *Full Code*: M2G1GR0PT1P2S0MC0V2 **User Code:** G1P2V2 Full Quality: Medium **User Quality:** Medium	Family: Caryophyllaceae Species: *Silene vulgaris* Date: N/A Origin: Country C Provenance N/A *Seed lot*: 12345 *Full Code*: M0G2GR0PT1P2S0MC0V2 **User Code:** G2P2V2 Full Quality: Medium **User Quality:** Medium

Figure 4. SPREC native seed label for wild (grey label) seed and produced (green label) seed of *Silene vulgaris* using the DEXi multi-attribute model to access quality. Two quality results were given. "Full quality" uses the full model, whereas "User Quality" only accounts for the selected attributes found in (Abbandonato et al. unpublished).

Discussion

The User-based (U-SeeD) SPREC label was designed using DEXi software which helps to provide both a simplistic and extended code that is transparent, straightforward and a can measure quality of both wild and produced seed lots. This combination of approaches is novel in the context of handling seed collections, whether for food security, long-term conservation of wild species or short-term storage of seed lots for use in restoration programmes. Uniquely, an attempt has been made to standardise a format for reporting how a seed lot has been handled during the workflow from collection to use; a general biospecimen practice that is currently being implemented more and more in medical biobanks (Lehmann et al., 2012). This label design partially follows the agricultural quality labelling system for eggs (ECE/TRADE/C/WP.7/2009/14) in that it provides compulsory quality information to consumers who are knowledgeable in quality labels without being to revealing to indifferent consumers. This is critical since many seed users are familiar with agricultural quality standards and may not want to purchase seeds with low germination, but those seeds may in fact be high quality due to their have high viability and purity. Knowledge on seed biology, especially among seed consumers may not be well-known or understood, as many “land” professionals chose “none” for important seed quality measures in a recent survey (Abbandonato et al. unpublished). This labelling system provides transparency and the possibility of quality assurance to users such as researchers or restoration practitioners who may require it. It would require that the all producers and sellers follow the same seed quality labelling scheme, providing equal competition between companies.

The wild accessions easily satisfied both the aggregate attributes of genetic diversity and product quality. The wild seed were of very high quality as they were from seed bank curatorial accessions. The only missing data was on seed health, which was unavailable in all cases (wild and produced). The wild accessions and produced seed lots did not measure seed vigour of the collection and so it was left out of the final code.

Seed health and phytosanitation standards are rare in native seeds. The Nagoya protocol is meant to regulate and control the movement of genetic resources across country borders (EU Commission 2014); however monitoring and implementation of this protocol is still under developed in many European member states.

Much of the low to medium quality in produced seed resulted from the inability to meet the genetic diversity aggregated attributes at this time. Many of the input attributes such as harvest date, origin and provenance, and seed lot are normally recorded by producers and it should be relatively easy for these measures to be provided since they do not require any testing. Product quality attributes may be more costly for producers to test; however if producers start with the User code requiring only germination, viability and purity, it may be easier to implement.

Future testing of the value of this labelling system may find that some of the final measures are redundant, such as germination with germination rate, purity and viability with pure live seed, and the number of multiplied generations with the presence of dormancy. Or these attributes may need to be weighted less or removed as more species and lots are tested. The assigned weights do not take into consideration the method used to determine the level of each attribute. This information could be standardized by an external seed analyst or be traced back using the seed lot number to contact the retailer. The origin and provenance label levels denoted could change to delineated seed zones, once widely implemented across Europe rather than using GPS coordinates or city and country.

In conclusion, this study aimed to provide a solution to the current top-down seed directives being applied to native seeds (66/401/EEC and 2010/60 EU) in Europe by designing a more appropriate quality control system that considers the needs of all its users and the ecological value of restoration.

Acknowledgments

This research was funded by the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n°607785. The Royal Botanic Gardens, Kew receives grant-in-aid from Defra. I would like to thank my lab assistants Rosa Ranalli, Enrico Magazzino, and Angela Ruggiero; Peter Toorop for advice on germination tests; and Marin Marin and Marcello De Vitis for the producer availability data set.

References

Baskin CC, Baskin JM (2014) Seeds. Ecology, biogeography, and evolution of dormancy and germination. 2nd Edition. Elsevier Inc. San Diego, CA, USA.

Bohanec M, Messéan A, Scatasta S, Angevin F, Griffiths B, Krogh PH, Znidarsic M, Dzeroski S (2008) A qualitative multi-attribute model for economic and ecological assessment of genetically modified crops. Ecological Modelling 215:247-261

Durka W, Michalski S, Berendzen KW, Bossdorf O, Bucharova A, Hermann J-M, Holzel N, Kollmann J (2016) Genetic differentiation within multiple common grassland plants supports seed transfer zones for ecological restoration. Journal of Applied Ecology DOI 10.1111/1365-2664.12636

ENSCONET (2009a) ENSCONET Seed Collecting Manual for wild species. Eds. Royal Botanic Gardens, Kew (UK) & Universidad Politécnica de Madrid (Spain). http://ensconet.maich.gr/PDF/Collecting_protocol_English.pdf (accessed 10 August 2017)

ENSCONET (2009b) ENSCONET Curation Protocols & Recommendations. Ed Royal Botanic Gardens, Kew (UK). http://ensconet.maich.gr/PDF/Curation_protocol_English.pdf (accessed 10 August 2017)

European Commission (1966) Council Directive 66/401/EEC of 14 June 1966 on the marketing of fodder plant seed. Official Journal of the European Communities 2298:132-142

European Commission (2010) Commission Directive 2010/60/EU of 30 August 2010 providing for certain derogations for marketing of fodder plant seed mixtures intended for use in the preservation of the natural environment. Official Journal of the European Union 228:10-14

European Commission (2014) Council Directive 2014/283/EU of 14 April 2014 on the conclusion, on behalf of the European Union, of the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity. Official Journal of the European Union. 150:231-233

FAO (2013) Genebank Standards for Plant Genetic Resources for Food and Agriculture. Rome http://www.fao.org/fileadmin/templates/agphome/documents/PGR/genebank/GeneBank_ENG_WebFil e.pdf

Grimes JP, Hodgson JG, Hunt R (2007) Comparative plant ecology: a functional approach to common British species 2nd Edition. Castlepoint Press, Kirkcudbrightshire, UK

International Seed Federation (2017) Exports of seed for sowing by country – Calendar year 2015. http://259970.vserv2152.swisslink.ch/wp-content/uploads/2017/06/Seed_Export_2015.pdf (accessed 10 August 2017)

International Seed Testing Association (2017) International Rules for Seed Testing. ISTA, Switzerland. Online ISSN 2310-3655

Laverack G, Matthews S, Powell AA, Khajeh Hosswini M (2006) Scottish wildflower seeds: production and use. Botanical Journal of Scotland 58:49-58

Lehmann S, et al (25 co-authors) (2012) Standard preanalytical coding in biospecimens: review and implementation of the Sample PREanalytical Code (SPREC). Biopreservation and Biobanking 10:366-374

Li D-Z, Pritchard HW (2009) The science and economics of ex situ plant conservation. Trends in Plant Science 14: 614-621

Linington S, Manger K (2014) Seed bank design: seed drying rooms. Technical information Sheet_11. https://www.kew.org/sites/default/files/11-Seed%20drying%20room%20design%20web.pdf (accessed 15 July 2017)

Marin M, Toorop PT, Powell AA, Laverack G (2017) Tetrazolium staining predicts germination of commercial seed lots of European native species differing in seed quality. Seed Science & Technology 45:1-16

Merritt DJ, Dixon KW (2011) Restoration Seed Banks-A Matter of Scale. Science 332:424–425

Millennium Seed Bank Partnership (2014) Seed Conservation Standards for 'MSB Partnership Collections.'

https://www.kew.org/sites/default/files/MSBP%20Seed%20Conservation%20Standards%20-%20final%20draft_0.pdf (accessed 10 August 2017)

Offord CA, Meagher PF (2009) Plant germplasm conservation in Australia: strategies and guidelines for developing, managing and utilising ex situ collections. Fully Revised Edition. Australian Network for Plant Conservation Inc., Canberra

Pedrini S, Merritt DJ, Stevens J, Dixon K (2017) Seed coating: science or marketing spin? Trends in Plant Science 22:106-116

Pelzer E, Fortino G, Bockstaller C, Angevin F, Lamine C, Moonen C, Vasileiadis V, Guérin D, Guichard L, Reau R, Messéan A (2012) Assessing innovative cropping systems with DEXiPM, a qualitative multi-criteria assessment tool derived from DEXi. Ecological Indicators 18:171-182

Rao NK, Hanson J, Dulloo ME, Ghosh K, Nowell A, Larinde M (2006) Manual of Seed Handling in Genebanks by. xiv+147 pp. Rome, Italy: Bioversity International. http://www.bioversityinternational.org/e-library/publications/detail/manual-of-seed-handling-ingenebanks/ (accessed 10 August 2017)

Royal Botanic Gardens Kew (2008) KEW seed information database (SID). http://data.kew.org.sid/ (assessed 20 April 2016).

Runyeon H, Prentice HC (1997) Genetic differentiation in the Bladder campions, *Silene vulgaris* and *S. uniflora* (Caryophyllaceae), in Sweden. Biological Journal of the Linnean Society DOI: 10.1111/j.1095-8312.1997.tb01807.x

Seeds of Success (2012) Bureau of Land Management Technical Protocol for the collection, study, and conservation of seeds from native plant species for Seeds of Success. http://www.nps.gov/plants/sos/protocol/protocol.pdf

Squire G, Demade M, Young M, Angevin F, Messéan A (2016) Holistic assessment of cropped ecosystems: assessing production systems with a multi-attribute decision model (decision tree). James Hutton Institute poster presentation.

UN/ECE (United Nations Economic Commission for Europe) (2009) UNECE STANDARD EGG-1 concerning the marketing and commercial quality control of edible hen eggs-in-shell. https://www.unece.org/fileadmin/DAM/trade/agr/standard/eggs/Recommendations/EGG01_EggsInShell_2009_e.pdf (assessed 15 May 2017)

Walters C, Wheeler LM, Grotenhuis JM (2005) Longevity of seeds stored in a genebank: species characteristics. Seed Science Research 15: 1-20

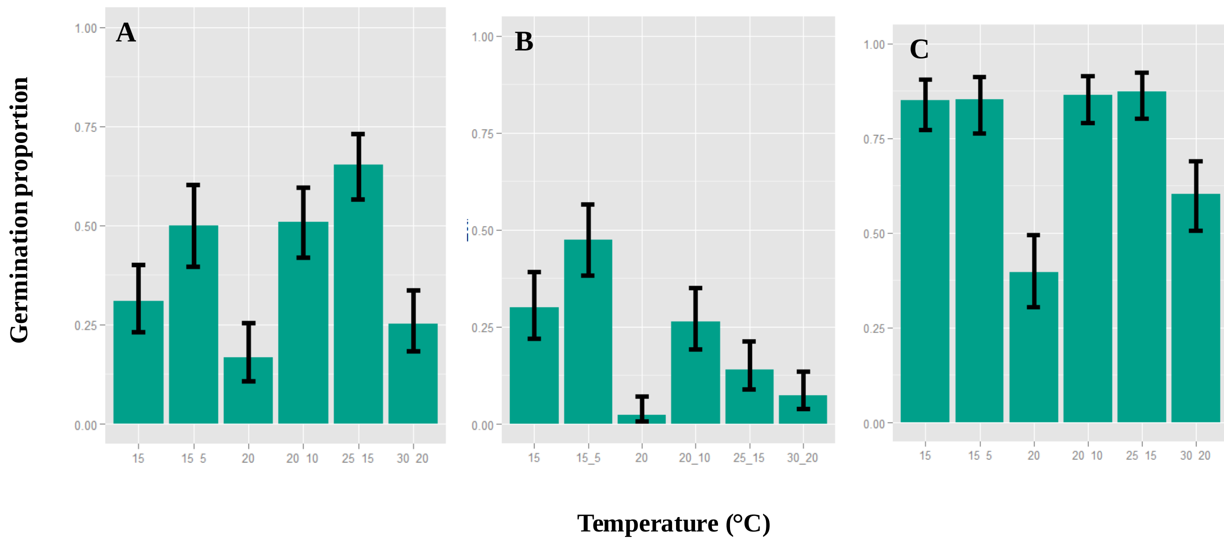

Figure S1. Germination proportion estimate and confidence intervals of *Papaver rhoeas* tested using six temperature treatments (15/5°C, 15°C, 20/10°C, 20°C, 25/15°C, 30°C) under 12/12 h light / dark sourced from three native seed producers (A, B, C) using a generalized linear model.

Table S1. Selected species life cycle, life form and seed dormancy (Baskin & Baskin 2014; Grimes et al. 2007; Runyeon & Prentice 1997)

Family	Species	Life cycle	Life form	Dormancy
Apiaceae	*Daucus carota* L.	Biennial or monocarpic perennial	Hemicryptophyte	Morphological
Caryophyllaceae	*Silene vulgaris* (Moench) Garcke	Perennial	Hemicryptophyte	Physiological
Fabaceae	*Lotus corniculatus* L.	Polycarpic Perennial	Hemicryptophyte	Physiological
Hypericaceae	*Hypericum perforatum* L.	Polycarpic Perennial	Hemicryptophyte	Physiological
Papaveraceae	*Papaver rhoeas* L.	Winter and summer annual	Therophyte	Morphophysiological

Table S2. Germination proportion estimates, standard error, p-values and germination rate for *Papaver rhoeas* from producer A.

Temperature treatment (°C)	Estimate	Standard error	p-value	Germination rate
Intercept	-0.8014	0.2035	8.19e-05	0.0078
15/5	0.8014	0.2947	0.0065	0.0153
20	-0.7962	0.3348	0.0174	0.0051
20/10	0.8342	0.2724	0.0021	0.0163
25/15	1.4346	0.2775	2.34e-07	0.0510
30/20	-0.2861	0.2932	0.3291	0.0037

Table S3. Germination proportion estimates, standard error, p-values and germination rate for *Papaver rhoeas* from producer B.

Temperature treatment (°C)	Estimate	Standard error	p-value	Germination rate
Intercept	-0.8014	0.2035	8.19e-05	0.0078
15/5	0.8014	0.2947	0.0065	0.0153
20	-0.7962	0.3348	0.0174	0.0051
20/10	0.8342	0.2724	0.0021	0.0163
25/15	1.4346	0.2775	2.34e-07	0.0509
30/20	-0.2861	0.2932	0.3292	0.0037

Table S4. Germination proportion estimates, standard error, p-values and germination rate for *Papaver rhoeas* from producer C.

Temperature treatment (°C)	Estimate	Standard error	p-value	Germination rate
Intercept	1.7311	0.2631	4.74E-11	-0.2084
15/5	0.0214	0.3994	0.9570	0.1992
20	-2.1531	0.3326	9.59E-11	0.0065
20/10	0.1212	0.3762	0.7470	-0.0611
25/15	0.2052	0.3815	5.91E-01	-0.0899
30/20	-1.3179	0.3285	6.00E-05	0.0465

Paper 5:

De Vitis M, Abbandonato H, Dixon K, Laverack G, Bonomi C, Pedrini S (2017) The European native seed industry - characterization and perspectives in grassland restoration. Sustainability, DOI:10.3390/su9101682

The European native seed industry – characterization and perspectives in grassland restoration

Marcello De Vitis [a], **Holly Abbandonato** [b,c], Kingsley W. Dixon [d], Giles Laverack [a], Costantino Bonomi [b], Simone Pedrini [d]

[a] Scotia Seeds, Farnell, Brechin, Angus, UK
[b] MUSE - Science Museum, Trento, Italy
[c] Department of Earth and Environmental Sciences, University of Pavia, Italy
[d] Department of Environment and Agriculture, Curtin University, Bentley, WA, Australia

Keywords: ecological restoration; native seed community; seed market; seed production; seed zones; stakeholder; survey.

ABSTRACT

The European Union committed to restore 15% of degraded ecosystems by 2020, and to comply with this goal, native plant material, such as seeds, is needed in large quantities. The native seed production of herbaceous species plays a critical role in supplying seed for restoration of a key ecosystem: grasslands. The objective of this work is to provide for the first time a characterization of the sector at a multi-country European level together with key information about the community of native seed users via intensive web-based research and a direct survey of industry participants. Based on more than 1 300 contacts and direct surveying of more than 200 stakeholders across Europe, responses indicated that: the European native seed industry consists

primarily of small to medium enterprises; responding native seed users purchase annually an average of 3 600 kilograms of seeds with an average expenditure of € 17 600; the industry (suppliers and consumers) favors development of seed zones and would participate in a European network for knowledge sharing. This study provides framework principles that can guide decisions in this sector, critical for fulfilling the growing demand for native seed as a primary tool for large-scale restoration on the continent.

INTRODUCTION

Native seed production is a nascent but emerging specialist area that, despite the important role it plays in supplying the material needed for restoring degraded ecosystems (Merritt and Dixon 2011), is often uncoordinated regionally and nationally. The European Union 2020 Biodiversity Strategy target to restore at least 15% of degraded ecosystems by 2020, highlights the significance of the native seed sector as well as the need to improve the large-scale production and availability of quality native seeds. For large programs, such as these, a shortage of native plant material has been recognized as a critical limitation to carry out ecological restoration at the scale needed (Merritt and Dixon 2011, Tischew et al. 2011).

Within Europe, trade and use of herbaceous seeds are less regulated when compared to forest reproductive material (Vander Mijnsbrugge et al. 2010). More attention should be given to grasslands conservation, as they are counted among both the most species-rich vegetation types in Europe (EEA 2010; Wilson et al. 2012) and among the most extensively degraded and least protected habitats at both European (EEA 2010) and global scale, making them identifiable as a biome at risk (Hoekstra et al. 2005).

Re-seeding degraded grasslands is now a widely-used restoration method in conservation practice (Török et al. 2011), especially for areas where spontaneous regeneration is slow, the risk of erosion is high (Jørgensen et al. 2016) and potential propagule sources are too distant to be effective in “recolonizing” an area (Török et al. 2011).

Native seeds are most often harvested directly from wild or semi-managed populations by public, private or non-profit enterprises who may also use this seed for growing-on, with or without selecting specific traits and creating cultivars (Chivers et al. 2016). In certain circumstances, the multiplication of native seeds for ecological restoration in a farm setting becomes necessary when harvesting large volumes of seeds directly from natural habitats would damage the reproductive capabilities of the local populations (Laverack et al. 2006, Broadhurst et al. 2008, Meissen et al. 2015), or donor communities of sufficient size have disappeared due to human impact (Kiehl et al. 2010). Moreover, sourcing local seeds and maintaining the genetic variability of the native populations is key to ecosystem conservation through improvement in long-term restoration trajectories (Manchester et al. 1999, Broadhurst et al. 2008, Vander Mijnsbrugge et al. 2010, Török et al. 2011). Based on the newly released International Standards for the Practice of Ecological Restoration (McDonald et al. 2016) and other published works (Kiehl et al. 2010, Tischew et al. 2011), restoration practitioners should avoid using seed mixtures that include non-native species, seed of unknown origin or seed sourced from genetically uniform populations. Thus reliable, local seed sources are paramount in an effective approach to regional restoration outcomes.

To implement the use of local seed origins, the geographic delineation of seed zones, within which seeds are to be collected, propagated and sown, may be critical (Nevill et al. 2016, Durka et al. 2017). In Europe, the first attempts to delineate national seed zones for herbaceous plants have been made only recently (Durka et al. 2017). The definition of transnational seed zones may be crucial (Tischew et al. 2011) to ensure ecological adaptation of plant species instead of the current fixation on administrative borders that often bear little relevance in an ecological or biological sense. This is highlighted by the United Kingdom's million pound, 10 year plus reintroduction program based on propagation from seed of the sole surviving lady's slipper orchid (*Cypripedium calceolus*) despite genetically similar, highly fecund plants occurring in large numbers just across the English Channel (Dixon et al. 2003). The advancement of seed technology such as seed priming (Paparella et al. 2015) and seed coating (Pedrini et al. 2017), the occurrence of species-specific seed zones, the creation of new market niches for seed growers, the collaboration among researchers, seed regulatory agencies, private seed industry and public and private end users, have been recognized as political and economic challenges hindering the development of local to regional native seed programs (Tischew et al. 2011).

In Europe, native plant material production seems to be limited by the high production costs and the lack of propagation/production experience (Tischew et al. 2011). In particular, the production of site-specific seed mixtures requiring pure-bred lines is significantly more expensive and riskier than for conventional seed production (Krautzer et al. 2010). On the other hand, many problems in seed production, storage and use have been overcome by practice and experience, but many shortfalls in knowledge remain, which require further scientific research (Laverack et al. 2006, Merritt and Dixon 2011).

In response to the knowledge gaps, several initiatives at national and international levels have initiated the process of connecting native seed stakeholders, facilitating interaction and exchange in the knowledge-production-use continuum, which is the key for improving the success of broad scale seed-based ecological restoration but frequently remains difficult (Görg et al. 2016).

Among them, the Kew UK Native Seed Hub; the Native Seed Network (www.nativeseednetwork.org/) in USA; the Native Seed Science, Technology and Conservation Initial Training Network (NASSTEC; www.nasstec.eu) in Europe and the ISTA/AOSA/Kew Wild Seed Working Group and the International Network for Seed-based Restoration (INSR; www.ser-insr.org) globally.

To our knowledge, no information about the economic value of the production sector for native and indeed herbaceous seeds at the European level is available. We chose the EU as the existing funding framework through NASSTEC provides the platform and resources necessary to perform the requisite and extensive multi-national survey of native seed supply, demand and standards. Such data would be useful for many people in the field of production, ecological restoration, policy, as well as for potential investors and the general public, to understand the economic value of the native seed industry. Understanding the dynamics of native seed demand would be of particular interest in developing focused production and investment strategies for the regions.

Furthermore, a general characterization of this sector, such as the degree of development (i.e. number of native seed companies) and the structure (e.g. existence of associations of native seed producers), together with perspectives of the native seed users, would benefit practitioners and policy makers (Wheaton et al. 2006). It has already been stressed that governments are in need of practical and efficient tools for ecosystem management and preservation (Jørgensen et al. 2016).

The aim of this study is therefore to provide a snapshot of the state of the native seed community of users in Europe, with a focus on the production of herbaceous plant seeds. Here we will characterize the native seed production sector in Europe; detail the outcomes of the direct survey method for the European native seed community; and, review EU funded projects covering grassland restoration as an indication of the scale required in planning for native seed utilization. The goal of this study is to raise awareness of the challenges, needs, opinions and impacts of this community of stakeholders, as well as highlighting the potential beneficial impact for the plant material industry, local communities and, ultimately, for improving environmental outcomes.

METHODS

Identification of European native seed stakeholders and characterization of the native seed industry

Native seed stakeholders were assessed through a thorough web-based search using the keywords “native” and “seed” alone and combined and translated into 15 languages (Bulgarian, Croatian, Czech, Danish, Dutch, Finnish, French, German, Greek, Hungarian, Italian, Portuguese, Romanian, Slovenian, Spanish) supplemented by direct inquiries to experts in the fields of native seed science and grassland restoration in the European academic community. The contacts found were included in the native seed stakeholder list. For native seed producers, we selected the enterprises (NGOs, private or public) producing and selling seeds of native grassland plants as single species or as mixtures. The number of people working on native seed production in each enterprise was obtained through available information on the web or through direct inquiry, and was used as an indicator of the native seed production sector size. Available information on seed zones, native seed certification systems and associations of native seed producers were also obtained through the web supplemented by direct inquiries of European native seed producers, researchers and restoration practitioners.

A survey of the native seed community

A web-based survey was developed using SurveyMonkey (http://www.surveymonkey.com) to obtain data about European native seed stakeholders. The survey was originally prepared in English and then translated into four other languages (Spanish, French, German and Italian). A link to the survey was circulated to the contacts of the native seed stakeholder list twice (August and October 2016).

Nineteen questions were formulated and organized into sections: participant information (1-5), native seed market (6-10), seed zones (11, 12), native seed standards (13, 14) and collaboration, networking and outreach (15-19; **Table 1**). All questions were optional. Question 6 provided ranges in both Euros and British pounds. Similarly, question 7 provided answers as ranges in different units (i.e. kilos, ounces, pounds). For both questions 6 and 7, the answers were converted to Euros and kilos, respectively; then the mid-range [(max *x* + min *x*)/2] value was calculated for each range and the overall mean value was calculated by the following equation: <eqn1> where *x* is the range provided in the answer, *frequency* is the number of responses for the *x* range, and *n* is the total number of responses received.

Table 1. Questions formulated for the native seed community survey and total response (n) for each question.

Questions	n
1. Which sector are you working in?	215
2. Which of the following best describes your current profession?	215
3. In which country is your profession or your main affiliation based?	216
4. Which species do you work with?	188
5. Do you use native seeds for your work?	174
6. On average, approximately how much do you spend on purchasing native seeds each year?	77
7. Which amount of native seeds do you buy or sell per year?	83
8. Which action related to native seeds or restoration is the most expensive for you?	119

9.	Which category do your major customers belong to?	81
10.	Is the demand for native plant material over the last 10 years increasing, stable or decreasing?	136
11.	Are you in favor of the development of seed zones?	123
12.	If a standard method is used, should seed zones cross country boundaries?	122
13.	Do you use external protocols/guidelines for any of the following activities such as seed collection, cleaning, storage and treatment?	99
14.	If yes, do you modify these protocols/guidelines to fit native seed requirements?	48
15.	Do you have an active dialogue/collaboration with any academic/research institutes?	112
16.	If No, would you like to have the scientific support of an academic/research institute?	22
17.	If a trade association of native seed producers existed both at the European and national level, which one would you join?	114
18.	Would you like to join a European online network to find other people who use native seeds to share material, knowledge and resources?	113
19.	Are you involved in outreach activities aimed to promote the use of native plant material?	115

Questions 15 and 16 considered collaboration with, and support from, the scientific community, because researchers share a common language (scientific English), have contacts with many different stakeholders, and have access to international literature, so they may represent a bridge between different stakeholder categories and facilitate knowledge transfer.

The answer frequencies were calculated using Microsoft Excel (2010). Given the possibility that different categories may have different perspectives, in some cases, answer frequencies were calculated by category.

EU funding for grassland restoration

The EU's funding frameworks covering environmental protection and restoration are the ERDF (European Regional Development Fund), the EAFRD (European Agricultural Fund for Rural Development) and the LIFE program, EU's main funding instrument for environment and climate action. For the purpose of this study, only the LIFE program was considered because, through the LIFE Project Database of the Environment Department of the European Commission website (http://ec.europa.eu/environment/life/project/Projects/index.cfm), it is possible to obtain details on specific projects. In particular, the LIFE Project Database was queried for projects financed between 2004 and 2014 containing the keywords “grassland ecosystem” and “restoration measure”. The list of projects was filtered, selecting those in which active grassland restoration was among the objectives. For these projects, funding year, lead partner country, duration, total budget, European contribution, and ha of habitat restored/to be restored were recorded. Finally, the total LIFE budgets funded during the 2007-2013 and 2014-2020 periods, were compared.

RESULTS

Identification of European native seed stakeholders and characterization of the native seed industry in Europe

A total of 1 342 contacts from 31 European countries were assessed. Of these, 888 related to agencies, associations, botanical gardens, charities, cooperatives, federations, foundations, governmental and local bodies, landscapers, native seed producers, networks, NGOs, nurseries, parks, research institutes and restoration practitioners; the remaining 454 comprised personal contacts in academia, consultancy, government, NGOs and private companies.

A total of 100 native seed producers from 21 countries were found (**Table A1.1)** with prevalence of private companies. The highest numbers of native seed producers (6-12) occurred in Central Europe (Austria, Germany and Switzerland), France, Spain and United Kingdom. In most of the other countries the number of companies was between one and three. Across 27 native seed enterprises from 15 countries, the total number of people working in native seed production was 166 with an average of 6.1 ± 8.3 (mean ± standard deviation) persons, with the majority employing 1-3 workers (**Fig. 1**). Through correspondence with these companies, we also found that in a quarter of cases (25%) seed collection and multiplication was carried out by contracted seasonal staff or farmers.

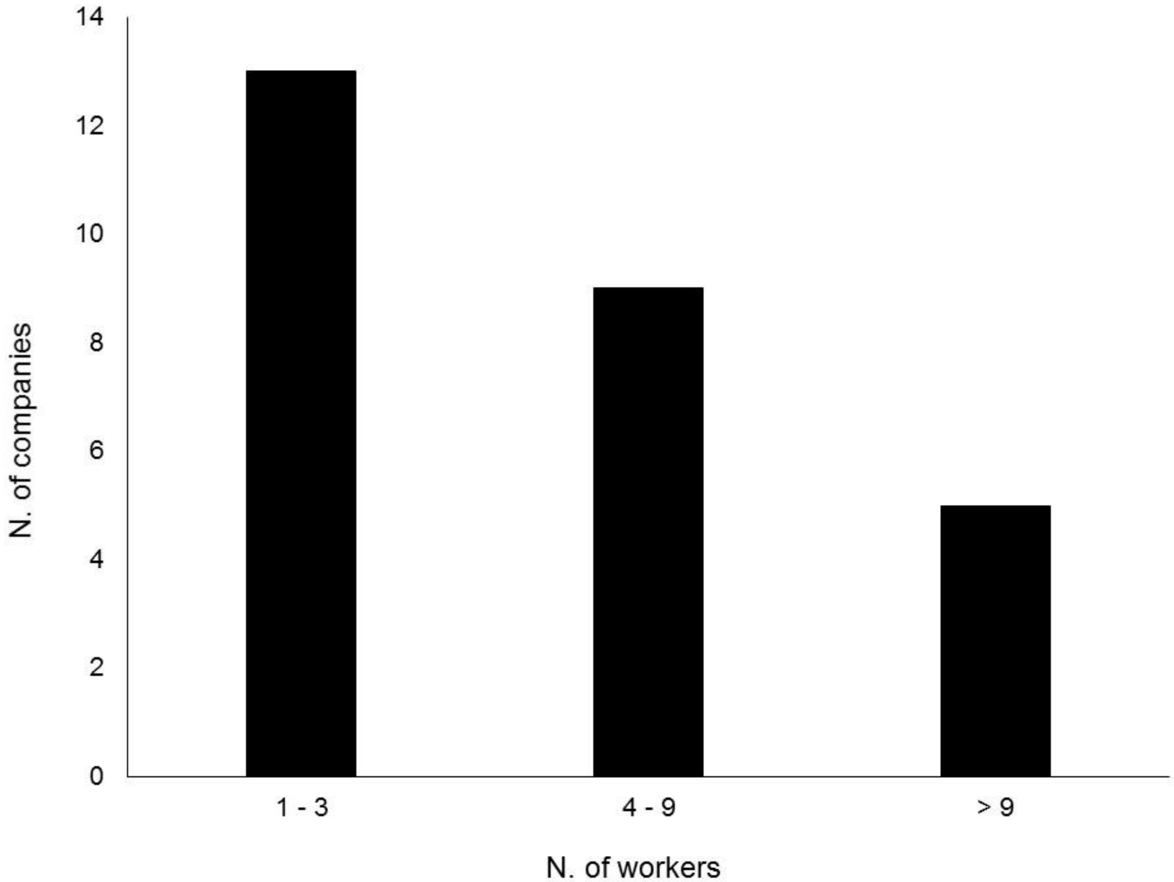

Fig. 1. Class frequency for the number of workers in native seed production across 27 herbaceous seed producers in 15 European countries.

Associations of native seed producers and native seed certification systems were found in three countries (Austria, Germany and France) while seed zones were identified in seven countries (**Fig. 2**; **Table A1.1**).

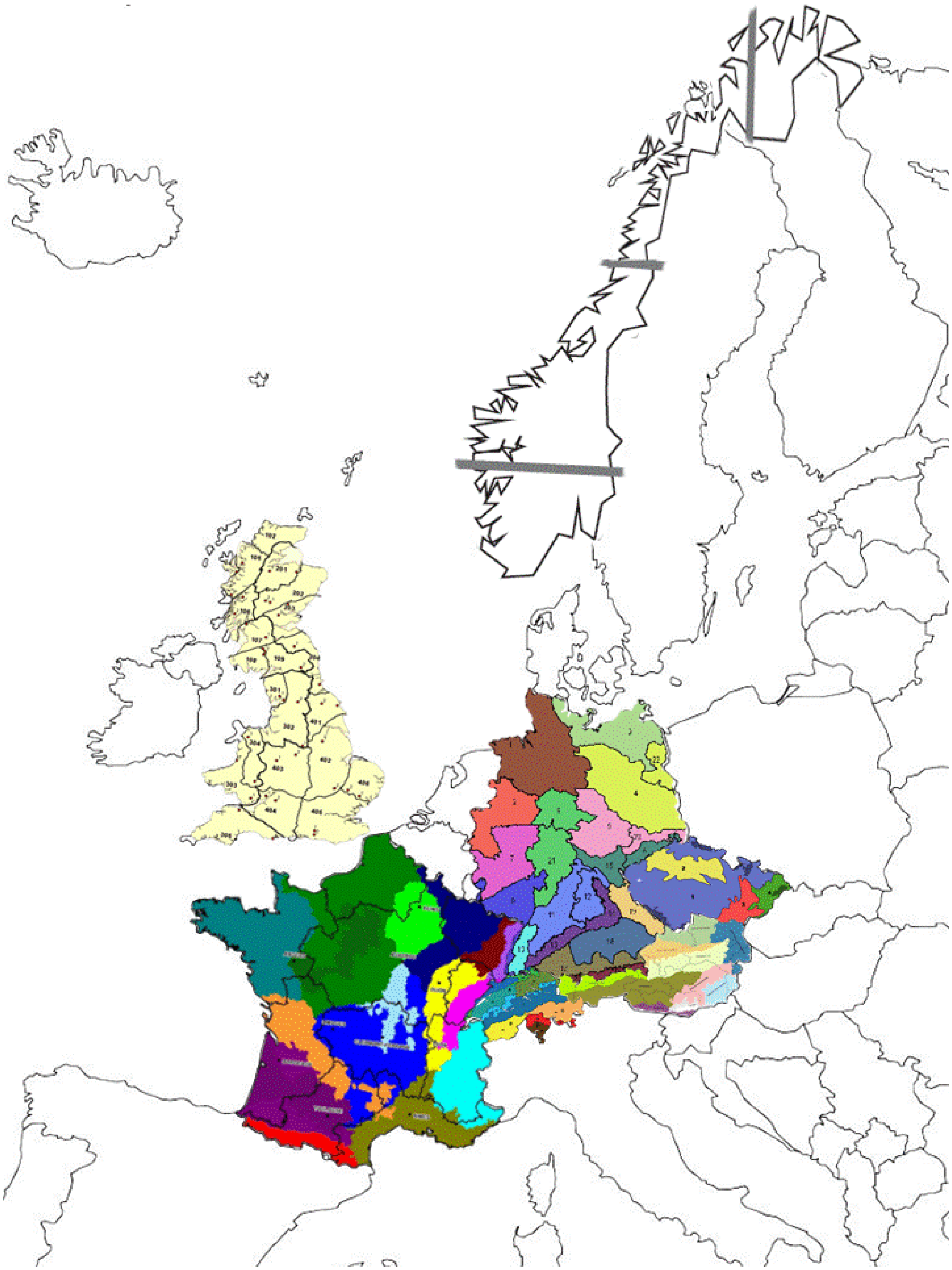

Fig. 2. National seed zones currently available in Europe. Sources : Austria – REWISA, V (2010); Czech Republic - Ševčíková et al. (2014); France – Fédération des Conservatoires

botaniques nationaux (http://www.fcbn.fr/vegetal-local-vraies-messicoles); Germany – Prasse et al. (2010); Great Britain – Forestry Commission (2016); Norway - Jørgensen et al. (2016); Switzerland - SKEW (2009).

A survey of the native seed community

Table 1 outlines the 19 questions formulated within the survey and for each one, the number of responses.

Participant information

Two-hundred and sixteen responses were received from 20 countries, of which the majority (77%) came from five countries (United Kingdom, France, Germany, Italy and Spain, in decreasing order). For the purpose of this study, responses to questions 4 and 5 were filtered to exclude forestry seed users, narrowing the selection to users of native seeds of herbaceous plants (148 responses from 16 countries). These respondents were mostly (49.6%) from the public sector, with 35.4% from the private sector, and 15.0% from NGOs; and belonged to 16 different professional fields: academia (33.6%), native seed production (16.4%), restoration practice (15.1%), seed analysis and conservation (6.2%), consultancy (6.2%), with other less represented fields such as nursery, administration, policy, gardening and landscape contracting.

Native seed market

For questions 6 and 7 the response rates are reported in **Table 2**. From these data, it was possible to estimate that a single user responding to the survey (individual or entity) purchases on average 3 616 kilograms of native seeds and expends 17 599 Euros annually (**Table 2**), for a total of 1 355 139 Euros and 300 115 kilograms of native seeds purchased annually across 77-83 users

(Note: because the two questions are unrelated it was not possible to derive the median price per kg of seed).

Table 2. Range, mid-range, frequency, total and mean values regarding native seed users' expenditure (€) and quantity traded (kg) per year.

Range	Mid-range	Frequency	
Expenditure (€)			
1-100	50.5	26	
101 – 5,000	2 550.5	26	
5,001 – 10,000	7 500.5	7	
10,001 – 100,000	55 000.5	17	
100,001 – 500,000	300 000.5	1	
> 500,000	500 000†	0	
Total		77	
Mean			17 599.2
Traded quantity (kg)			
0.01-0.1	0.055	8	
0.2-1	0.6	11	
2-10	6	21	
11-100	55.5	12	
101-500	300.5	6	
501-1,000	750.5	8	
1,001-10,000	5 500.5	13	
10,001-100,000	55 000.5	4	
> 100,000	100 000†	0	
Total		83	
Mean			3 615.8

†For these classes, the minimum value was taken as mid-range.

The most expensive activity for 30.0% of the native seed producers (n = 20), was the management of production fields before crop multiplication, followed by seed harvesting from the managed crops (20.0%), seed collection from the population of origin and seed purchasing (both 15.0%; **Fig. 3**). The top four responses for the remainder of respondents, excluding seed producers (n = 99) were: seed collection from the population of origin (28.3%), research

(17.2%), site management before restoration (12.1%), and seed purchasing (11.1%). When users were questioned about their major customers, 81 responses were received, but for the purpose of this work, only those from native seed suppliers (n = 21) were considered, with the top three customer categories being: land contractors (29.0%), individuals and governmental bodies (19.0% each; **Fig. 4**), followed by retailers and nurseries.

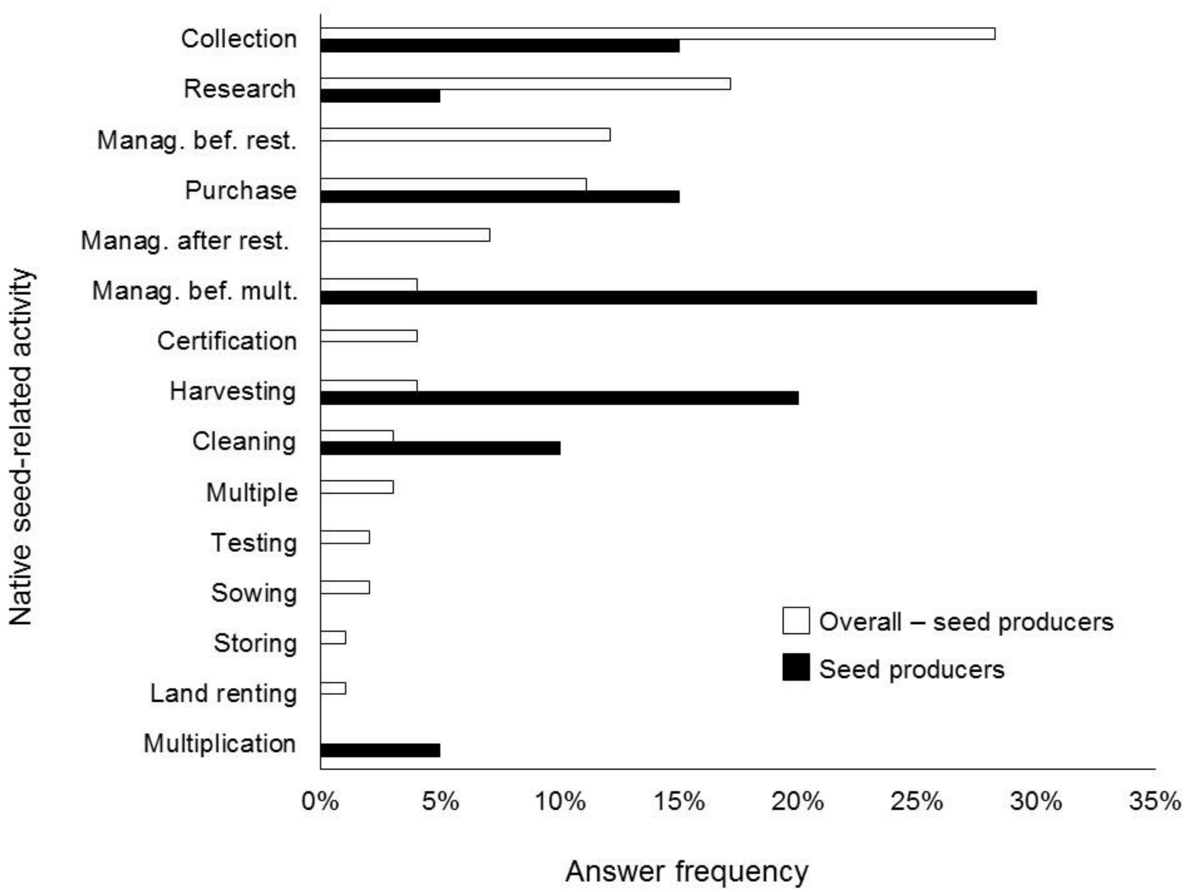

Fig. 3. Perceived costliness of seed-related activities. Answer frequency of respondents to question 8 “Which action related to native seeds or restoration is the most expensive for you?”. In figure, both the answers by native seed producers (n = 20) and the remainder of the community (overall minus seed producers; n = 99) are shown. Some of the choices reported in the graph are abbreviations of the options available in the survey: collecting seeds from the

native population; site management before restoration; site management after restoration; field management before crop multiplication (e.g. ploughing, weeding, application of fertilizers); harvesting seed from crops; land renting/contract growing for crop multiplication.

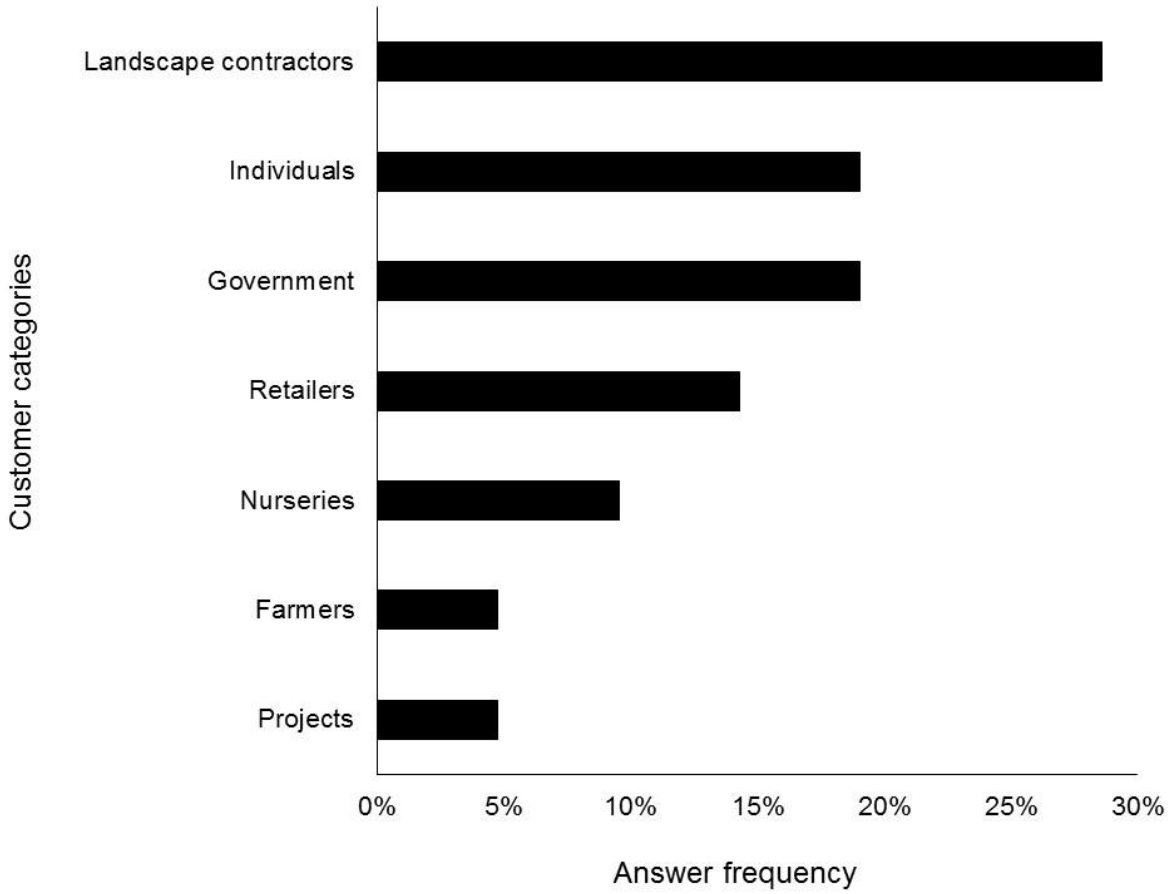

Fig. 4. Answer frequencies to question 9 “Which category do your major customers belong to?” by native seed producers (n = 21).

The answers to question 10 (n = 136), relate to the state of the native plant material demand in the last decade, and were sorted based on native plant material suppliers (seed producers + nurseries; n = 27) and the remainder of the native seed community (n = 109). The majority of the native seed community (75.2%) perceived an increase in demand, 12.8% felt it was stable, 10.2% stated a level of uncertainty, while 1.8% reported a decline. A similar trend was detected in the responses provided by the native plant material suppliers (increase: 74.1%; stable: 11.1%; uncertain: 11.1%; and decline: 3.7%).

Seed zones

Most of the overall native seed community (73.2%; n = 123), as most of the researchers (81.4%; n = 43) and producers (64.7%; n = 17), expressed support towards the development of seed zones, while minority of groups were not in favor or unsure. Again, the majority of the respondents (62.3%; n = 122) was in favor of trans-national boundaries for seed zones, both from the research (68.2%; n = 44) and production (70.6%; n = 17) sectors.

Native seed standards

The respondents were divided when questioned about the adoption of "external" quality and handling guidelines (Yes: 54.5%; No: 45.5%). The participants who responded positively were asked to provide the name of these guidelines/protocols and if they would amend them to match native seed requirements. The listed guidelines included: ENSCONET (European Native Seed Conservation Network) listed nine times by users from seven different countries; ISTA (International Seed Testing Association) by eight users from four different countries; APAT (Agency for Environmental Protection and Technical Services) four times by Italian and Spanish users; VWW (Association of German Wild Seed and Wild Plant Producers) by four German users; Flora Locale (https://www.floralocale.org/HomePage) three times by users from the United Kingdom and Republic of Ireland; with FAO, Royal Botanic Gardens of Kew, Forestry

Commission, and GZert guidelines only referred to by one or two users. The majority (64.6%) of the respondents did adapt those guidelines to be relevant to their native seeds. Among the native seed producers (n = 20), 70.0% were positive about the use of external protocols, and less than half (41.7%) of these respondents said they did modify the protocols to match native seed requirements, though it is unclear as to why.

Collaboration and outreach

The majority of the overall native seed community (76.8%; n = 82, without the category "researchers") reported an active collaboration or dialogue with a research institute (question 15) with similar values (80.0%) conveyed by native seed producers (n = 20). Respondents without active collaboration with a research institute, expressed the will to engage with academia in 81.8% of the overall native seed community and 75.0% of native seed producers.
For question 17, there were 114 responses. However, we took into consideration only native seed producers (n = 20) as we specifically asked about "a trade association of native seed producers". Six producers (30.0%) would support such a national association, three (15.0%) a Europe only association, nine (45.0%) both a national and European association, and for two (10.0%) respondents the question was non-applicable. Finally, the vast majority (82.6%) of the native seed community would join a European network to connect with other native seeds users and 74.3% undertook outreach activities to promote the use of native plant materials.

EU funding for grassland restoration

Interrogation of the LIFE project Database produced 52 results. Of these projects, 30, coordinated by 15 different countries, were considered, as they indicated in their objectives, the direct restoration of grassland habitat. The total area of grassland habitat under or proposed for restoration represented an 18-year period (the duration of the selected projects was between 2004 and 2022) totaling 16 174 ha, ranging between 15 and 4 439 ha attributable to single projects. For these projects, the EU contribution was over half of the total budget (58 ± 11%, mean ± standard deviation). The total expenditure in the decade 2004-2014 for these projects was € 102.55 million, ranging between € 412 891 to € 9 587 813 per single project (**Fig. 5**). The fourth phase of the LIFE program ran from 2007 to 2013 with a budget of € 2.14 billion (http://ec.europa.eu/environment/life/about/#evaluation), while in the new LIFE Programme (2014-2020), which aims to achieve 5% of ecosystem services restored and to improve the conservation status of 25% of target habitats and species, € 3.40 billion is allocated (http://ec.europa.eu/environment/life/about/#evaluation), an increase of 59% over the previous period.

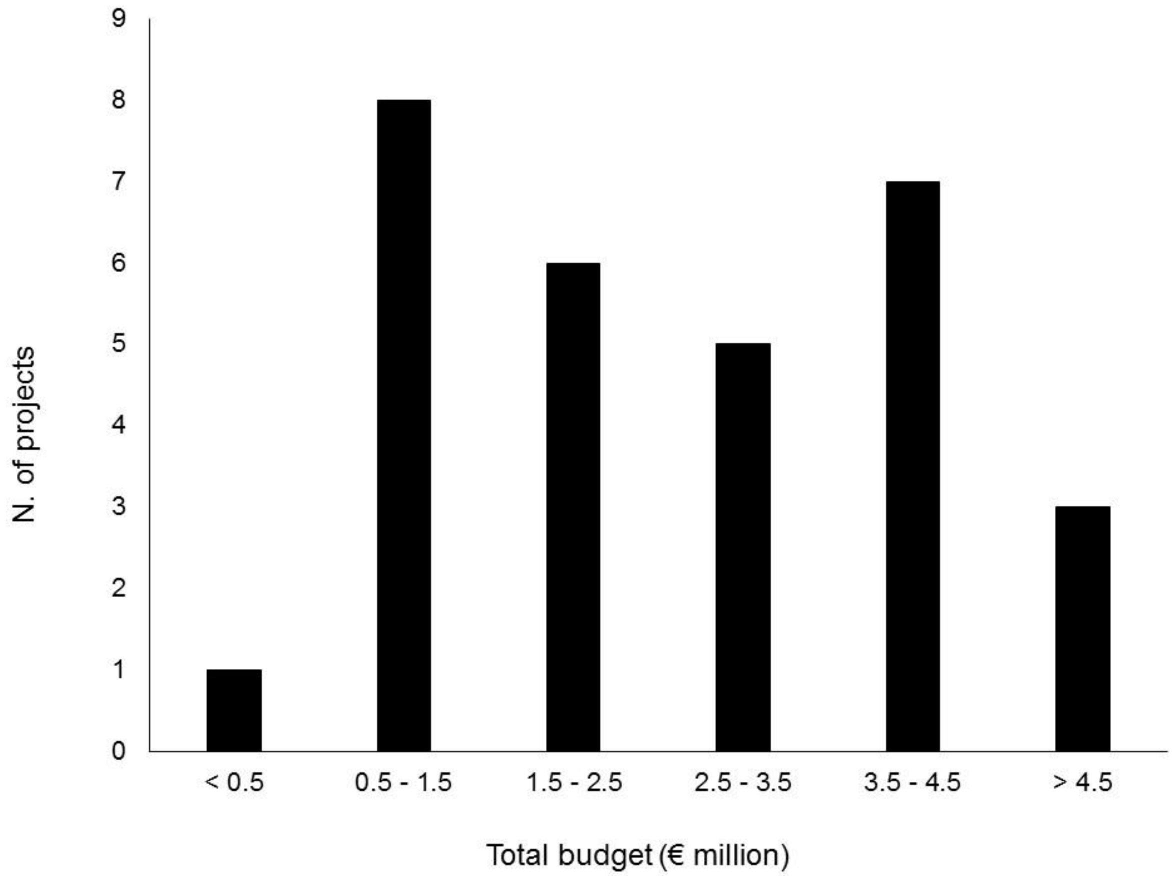

Fig. 5. Total budget for grassland restoration projects funded in the decade 2004-2014 through the EU LIFE program (n = 30).

DISCUSSION

This is the first multinational study to characterize the native seed production sector with an emphasis on ecological restoration in Europe. This study is comprehensive as respondents included small, private businesses in countries (e.g. Hungary, Italy, the Netherlands, Norway, Sweden) that are not part of the main European spoken languages (i.e. English, Spanish, French, German).

The native seed companies found during this study were the most likely to contribute to ecological restoration because they were known or reported by other stakeholders, such as researchers, practitioners and other companies.

The degree of development of the native seed industry in Europe focused on herbaceous plants related to the need for grassland restoration across the continent. In north-western and Central European countries (e.g. Great Britain, France and Germany), where, in the last decades, the phenomenon of species-rich grassland decline particularly occurred, due to intensive agricultural management (Kiehl et al. 2010), we found the highest numbers of companies and the largest as assessed by the number of employees.

Since most of the surveyed companies employed 1-9 workers, we assume that they belong to the category of SMEs (small- and medium-size enterprises) and family-run/owner-operator businesses.

In most European countries, there are no controls on seed movement (e.g. seed zones), mechanisms to support the producers (e.g. associations), and processes that value native over non-native seed (e.g. certification systems). However, with the advent of the International Standards for the Practice of Ecological Restoration (McDonald et al. 2016), locally sourced seed based on a local reference community is an expected component in achieving full recovery (i.e. restoration) of an ecosystem.

Though seed zones have been developed at national levels only in seven European countries (Austria, Czech Republic, France, Germany, Great Britain, Norway, and Switzerland), did the majority of the European native seed community agree with the development of seed zones that reflect ecological rather than geopolitical boundaries. The development of such zones, would enlarge seed catchment opportunities and lead to new economic development opportunities within Europe including assisting in rural industry diversification.

There was a strong link between the presence of associations of native seed producers and a seed certification system (Austria, France and Germany), with the association being involved in developing the certification system. This means that creating an association of producers may be a crucial step in developing a certification system. Developing a national seed association or activating an existing association to develop seed certification represents a vital next step in harmonizing European native seed standards. Indeed, respondents showed great interest in being part of a network aimed at knowledge sharing. The International Network for Seed-Based Restoration (INSR; http://www.ser-insr.org), a thematic section of the Society for Ecological Restoration, represents one opportunity since it brings together native seed stakeholders and shares existing knowledge on native seed with the aim of promoting and enhancing seed-based solutions in restoration. The US Native Seed Network and National Seed Strategy are a stand-out example of a national approach to the generation and use of native seed. The Network (http://nativeseednetwork.org/) is an online platform for both restoration practitioners and native seed producers that provides search tools (e.g. seed search and selection) and information on all aspects of native seeds. The Strategy is an overarching plan formulated by a coalition of federal agencies, non-profit organizations and private sector businesses with the aim of ensuring the availability of genetically appropriate seed reserves to restore viable, productive plant communities and sustainable ecosystems (Oldfield and Olwell 2015).

In Europe, the major purchasers of native plant seeds were found to be landscape contractors, single individuals, governmental bodies, retailers and nurseries, in order of relevance for native seed suppliers. Seed collection was found to be one of the most expensive activities related to the seed production to restoration chain, according to our survey and to previous reports (Tucker et al. 2013), making it a potential economic constraint and where a focus on technology development would yield significant economic benefits. For native seed producers, other most expensive activities were related to field labor, such as field preparation for crop multiplication and seed harvesting which, for some species, is still conducted by hand, as it results in higher seed quality (Marin et al. 2017).

Our data provided the first estimation, albeit rough, of quantities of and expenditure on native seeds on a yearly basis by European users. So far, quantitative data on quantities and expenditures were provided only for Austria (potential need of site-specific mixtures of alpine seeds for alpine meadow restoration = 200 metric tons annually; Krautzer et al. 2010), Germany (market turnover of € 12 M and native seed sold annually = ca. 200 metric tons; source: http://ser-insr.org/webinars/2016/11/17/native-seed-production-in-germany); and the UK (overall native seed market = 70-120 metric tons and £ 5-6 M, with expected growth to 120-240 metric tons and £ 6-17 M by 2019-2020; UK Native Seed Hub 2011). And all evidence points to demand for herbaceous native seed in the region to be increasing e.g. expansion of the EU's LIFE program.

The present study revealed that the majority of European native seed companies, and of the overall native seed community, has established links with research institutes or was willing to do so. This is promising in terms of advancing native seed standards and in the improvement of the pool of species available from seed suppliers, which imposes a critical biodiversity filter in ecological restoration projects ("restoration species pool" sensu Ladouceur et al. 2017). Seed growers are often reluctant to take on new species because of production and marketing uncertainties (Tischew et al. 2011), and, as shown by our survey, the community working with native seeds often needs to modify existing protocols including collection, cleaning, storage and treatment to match native plant requirements. Collaboration with researchers and technologists may play a key role in improving guidelines and finding solutions for production of difficult grassland species (Ladouceur et al. 2017).

In Europe, inadequacy in native seed supply to meet current and emerging demand may result from the lack of appropriate production planning, statutory recognition and protection for native seed collection, production and trade, which in turn may limit the market for native seeds and facilitate the use of cheap seed mixtures of ecologically unsuitable species (Krautzer et al. 2010). Adequate planning would harmonize production to meet seed demand. However, achieving this goal will require improved and facilitated communication between users and producers.

Importantly, providing a sound regulatory framework covering native seeds, together with incentives from the EU, local governments and the communities will ensure the native seed industry develops in a way that is economically and ecologically sustainable.

In Germany, one of the most advanced European countries in native seed production and grassland restoration, the Federal Nature Conservation Act (BNatschG 2010) requires that from 2020, all restoration of natural areas requires the use of native seed. The German Association of wild seed and wild plant producers (VWW; http://www.natur-im-vww.de/) calculated that, to comply with this requirement, 2 000 metric tons of native seeds would be needed by 2020, that will require tenfold increase in production over the next four years (source: http://ser-insr.org/webinars/2016/11/17/native-seed-production-in-germany). However, this national aspiration contradicts the legal constructs under EU Directives (see European Commission 2010: Commission Directive 2010/60/EU, art. 8 “quantitative restriction”) that limits the maximum value of native seed to 5% of the fodder species market. In Europe, as it has been already stressed in US (Oldfield and Olwell 2015), the policy directives should shift away from agronomic towards ecological models if we are to meet the needs of restoration on the scale required in the coming century.

CONCLUSION

As demand grows for knowledge-informed policy decisions in environmental issues (Nesshover et al. 2016), the creation of a European native seed network/association is pivotal to developing effective production and deployment strategies. Such a network could be charged with ensuring the accuracy and adequacy of knowledge transfer to decision-makers, contributing to policy frameworks that support the expansion of the native seed industry in the Europe. Importantly, such a network would lead to a united voice and provide impetus for harmonization of seed policies across Europe.

We believe that in this age of restoration, in Europe as for other countries around the world, greater attention should be focused on the emerging native seed production sector, supported by robust regulatory processes that promote, enhance and provide incentives for the use of native plant material. In order to achieve positive and successful outcomes, a vibrant, diverse native seed community is essential to ensure that collective wisdom leads to the most cost effective and enduring outcomes for improving nature and natural environments.

ACKNOWLEDGMENTS

The authors are grateful to C. Blandino, E. Fernández-Pascual, R. Fiegener, S. Frischie, F. Guest, P.P.M. Iannetta, E. Ladouceur, M. Marin and C. Trivedi for valuable comments on the survey draft; to E. Fernández-Pascual, S. Frischie, Jürgen Schneider, M. Tudela Isanta, V. Carrier for the translations of the survey; and to H.W. Pritchard for useful comments to improve the manuscript. The research leading to these results received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n°607785.

LITERATURE CITED

BNatSchG. 2010. Act on Nature Conservation and Landscape Management (Federal Nature Conservation Act – BNatSchG) of 29 July 2009. Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety. Federal Law Gazette, p. 2542. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Germany. http://www.bmub.bund.de/fileadmin/Daten_BMU/Download_PDF/Naturschutz/bnatschg_en_bf.pdf

Broadhurst, L. M., A. Lowe, D. J. Coates, S.A. Cunningham, M. McDonald, P. A. Vesk, and C. Yates. 2008. Seed supply for broadscale restoration: maximising evolutionary potential. Evolutionary Applications 1(4):587-597. http://onlinelibrary.wiley.com/doi/10.1111/j.1752-4571.2008.00045.x/epdf

Chivers, I. H., T. A. Jones, L. M. Broadhurst, I. W. Mott, and S.R. Larson. 2016. The merits of artificial selection for the development of restoration-ready plant materials of native perennial grasses. Restoration Ecology 24(2):174-183.

Dixon, K. W., S. P. Kell, R. L. Barrett, and P. J. Cribb. 2003. Orchid Conservation. Natural History Publications, Kota Kinabalu, Sabah.

Durka, W., S. G. Michalski, K. W. Berendzen, O. Bossdorf, A. Bucharova, J. Hermann, N. Hölzel, and J. Kollmann. 2017. Genetic differentiation within multiple common grassland plants supports seed transfer zones for ecological restoration. Journal of Applied Ecology 54(1):116-126. http://onlinelibrary.wiley.com/doi/10.1111/1365-2664.12636/epdf

EEA. 2010. EU 2010 Biodiversity Baseline. EEA Technical Report No 12/2010, European Environment Agency, Copenhagen. https://www.eea.europa.eu/publications/eu-2010-biodiversity-baseline

European Commission. 2010. Commission Directive 2010/60/EU of 30 August 2010 providing for certain derogations for marketing of fodder plant seed mixtures intended for use in the preservation of the natural environment. Official Journal of the European Union 228:10–14. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0060&from=EN

Forestry Commission. 2016. Regions of provenance and native seed zones. https://www.forestry.gov.uk/forestry/infd-72kldl.

Görg, C., H. Wittmer, C. Carter, E. Turnhout, M. Vandewalle, S. Schindler, B. Livorell, and A. Lux. 2016. Governance options for science-policy interfaces on biodiversity and ecosystem services: comparing a network versus a platform approach. Biodiversity and Conservation 25(7):1235-1252. https://link.springer.com/content/pdf/10.1007%2Fs10531-016-1132-8.pdf

Hoekstra, J. M., T.M. Boucher, T. H. Ricketts, and C. Roberts. 2005. Confronting a biome crisis: global disparities of habitat loss and protection. Ecology Letters 8(1):23-29.

Jørgensen, M. H., A. Elameen, N. Hofman, S. Klemsdal, S. Malaval, and S. Fjellheim. 2016. What's the meaning of local? Using molecular markers to define seed transfer zones for ecological restoration in Norway. Evolutionary Applications 9(5):673-684. http://onlinelibrary.wiley.com/doi/10.1111/eva.12378/epdf

Kiehl, K., A. Kirmer, T. W. Donath, L. Rasran, and N. Hölzel. 2010. Species introduction in restoration projects – evaluation of different techniques for the establishment of semi-natural grassland in Central and Northwestern Europe. Basic and Applied Ecology 11(4):285-299.

Krautzer, B., W. Graiss, and A. Blschka. 2010. Seed production of site-specific grasses and herbs in Austria. Proceedings of the 7th European Conference on Ecological restoration, Society for Ecological Restoration, 23-27 August 2010, Avignon, France.

Ladouceur, E., B. Jiménez-Alfaro, M. Marin, M. De Vitis, H. Abbandonato, P. P. M. Iannetta, C. Bonomi, and H. W. Pritchard. 2017. Native seed supply and the ecological restoration species pool. Conservation Letters, http://onlinelibrary.wiley.com/doi/10.1111/conl.12381/epdf.

Laverack, G., S. Matthews, A. A. Powell, and M. Khajeh Hosseini. 2006. Scottish wildflower seeds: production and use. Botanical Journal of Scotland 58(1):49-58. http://dx.doi.org/10.1080/03746600608685106

Manchester, S. J., S. McNally, J. R. Treweek, T. H. Sparks, and J. O. Mountford. 1999. The cost and practicality of techniques for the reversion of arable land to lowland wet grassland – an experimental study and review. Journal of Environmental Management 55(2):91-109.

Marin, M., P. Toorop, A. A. Powell, and G. Laverack. 2017. Tetrazolium staining predicts germination of commercial seed lots of European native species differing in seed quality. Seed Science & Technology 45(1):1-16.

McDonald, T., J, Jonson, and K.W. Dixon. 2016. National standards for the practice of ecological restoration in Australia. Restoration Ecology 24(S1):S4-S32. http://onlinelibrary.wiley.com/doi/10.1111/rec.12359/epdf

Meissen, J.C., S. M. Galatowitsch, and M. W. Cornett. 2015. Risks of overharvesting seed from native tallgrass prairies. Restoration Ecology 23(6):882-891.

Merritt, D. J., and K. W. Dixon. 2011. Restoration seed banks—a matter of scale. Science 332(6028):424-425.

Nesshöver, C., B. Livoreil, S. Schindler, and M. Vandewalle. 2016. Challenges and solutions for networking knowledge holders and better informing decision-making on biodiversity and ecosystem services. Biodiversity and Conservation 25(7):1207-1214. https://link.springer.com/content/pdf/10.1007%2Fs10531-016-1124-8.pdf

Nevill, P. G., S. Tomlinson, C. P. Elliott, E. K. Espeland, K. W. Dixon, and D. J. Merritt. 2016. Seed production areas for the global restoration challenge. Ecology and Evolution 6(20):7490-7497. http://onlinelibrary.wiley.com/doi/10.1002/ece3.2455/epdf

Oldfield, S., and P. Olwell. 2015. The right seed in the right place at the right time. BioScience 65(10):955-956. https://academic.oup.com/bioscience/article-lookup/doi/10.1093/biosci/biv127

Paparella, S., S. S. Araújo, G. Rossi, M. Wijayasinghe, D. Carbonera, and A. Balestrazzi. 2015. Seed priming: state of the art and new perspectives. Plant Cell Reports 34:1281-1293.

Pedrini, S., D. J. Merritt, J. Stevens, and K. Dixon. 2017. Seed coating: science or marketing spin? Trends in Plant Science 22(2):106-116.

Prasse, R., D. Kunzmann, and R. Schröder. 2010. Entwicklung und praktische umsetzung naturschutzfachlicher mindestanforderungen an einen herkunftsnachweis für gebietseigenes wildpflanzensaatgut krautiger pflanzen. Institute for Environmental Planning of the Gottfried Wilhelm Leibniz Universität, Hannover. https://www.dbu.de/OPAC/ab/DBU-Abschlussbericht-AZ-23931.pdf

REWISA, V. 2010. Prüfrichtlinie für die Gewinnung und den Vertrieb von regionalen Wildgräsern und Wildkräutern (REWISA®). Published by Lehr- und Forschungszentrum für Landwirtschaft Raumberg-Gumpenstein, Irdning, Austria. http://www.rewisa-netzwerk.at/Naturgarten/files/8c/8cbe2495-95bc-44d3-832b-d7060dbb9944.pdf

SKEW 2009. Empfehlungen für den anbau und die Verwendung von pflanz- und saatgut einheimischer wildpflanzen. Zeitschrift Agrarforschung 9:1-14. https://www.infoflora.ch/de/assets/content/documents/recommandations_pltes_sauvages_D_F/Empf_Wildpflanzen.pdf

Ševčíková, M., I. Jongepierová, and K. Prach. 2014. Standardy péče o přírodu a krajinu. Nature Conservation Agency of the Czech Republic and University of South Bohemia in České Budějovice. http://standardy.nature.cz/res/archive/162/021148.pdf?seek=1400575046

Tischew, S., B. Youtie, A. Kirmer, and N. Shaw. 2011. Farming for restoration: building bridges for native seeds. Ecological Restoration 29(3):219-222. https://www.fs.fed.us/rm/pubs_other/rmrs_2011_tishew_s001.pdf

Török, P., E. Vida, B. Deák, S. Lengyel, and B. Tóthmérész. 2011. Grassland restoration on former croplands in Europe: an assessment of applicability of techniques and costs. Biodiversity and Conservation 20(11):2311-2332.

Tucker, G., E. Underwood, A. Farmer, R. Scalera, I. Dickie, A. McConville, and W. van Vliet. 2013. Estimation of the financing needs to implement Target 2 of the EU Biodiversity Strategy. Report to the European Commission. Institute for European Environmental Policy, London, UK. http://ec.europa.eu/environment/nature/biodiversity/comm2006/pdf/2020/Fin%20Target%202.pdf

UK Native Seed Hub. 2011. Royal Botanic Gardens, Kew. UK Native Seed Hub Initiative. 10 Year Business Plan. Chris Blandford Associates. http://www.kew.org/sites/default/files/UK%20Native%20Seed%20Hub%2010%20Year%20Business%20Plan.pdf

Vander Mijnsbrugge, K., A. Bischoff, and B. Smith. 2010. A question of origin: where and how to collect seed for ecological restoration. Basic and Applied Ecology 11(4):300-311.

Wheaton, J. M., S. E. Darby, D. A. Sear, and J. A. Milne. 2006. Does scientific conjecture accurately describe restoration practice? Insight from an international river restoration survey. Area 38(2):128-142.

Wilson, J. B., R. K. Peet, J. Dengler, and M. Pärtel. 2012. Plant species richness: the world records. Journal of Vegetation Science 23:796-802. http://onlinelibrary.wiley.com/doi/10.1111/j.1654-1103.2012.01400.x/epdf

Appendix 1.

Table 1. For the countries where native seed producers of herbaceous plants were identified†, the number is reported, specifying if they are NGO, private or public enterprises. Where they occur, the number of seed zones (STZ) are also reported.

	Native seed producers				STZ‡
Country	NGO	private	public	total	
Austria	1	9		10	10
Belgium		3		3	
Bulgaria		2		2	
Czech Republic		3		3	4
Denmark		2		2	
France		6		6	11
Germany		12		12	22
Greece			1	1	
Hungary		2		2	
Iceland			1	1	
Italy		4	1	5	
Netherlands		4		4	
Norway		2	1	3	4
Poland		2		2	
Portugal		2	1	3	
Republic of Ireland		2		2	
Romania		2		2	
Spain		10		10	
Sweden		3		3	
Switzerland		12		12	11

United Kingdom	1	11		12	24
Tot.	2	93	5	100	

†Some producers were not verified if actually producing native seeds from local populations and if following recognized guidelines.

‡ Sources. Austria : REWISA, V (2010); Czech Republic : Ševčíková et al. (2014); France : Fédération des Conservatoires botaniques nationaux (http://www.fcbn.fr/vegetal-local-vraies-messicoles); Germany : Prasse et al. (2010); Great Britain: seed zones were developed for tree species by the Forestry Commission (2016) but they are used by herb seed producers too; Norway: four seed zones are suggested by Jørgensen et al. (2016) on the basis of genetic analysis on six species; Switzerland: SKEW (2009).

APPENDIX

Native Seed Supply and the Restoration Species Pool

Emma Ladouceur[1,2], Borja Jiménez-Alfaro[3,4], Maria Marin[2,5], Marcello De Vitis[5], Holly Abbandonato[1,2], Pietro P.M. Iannetta[6], Costantino Bonomi[1], & Hugh W. Pritchard[7]

[1] Botany Section, Museo Delle Scienze (Muse), Trento, Italy
[2] Department of Earth and Environmental Science, University of Pavia, Pavia, Italy
[3] The German Centre for Integrative Biodiversity Research (iDiv), Halle-Jena-Leipzig, Deutscher Platz 5e, 04103 Leipzig, Germany
[4] Geobotany and Botanical Garden, Institute of Biology, Martin Luther University Halle Wittenberg, Am Kirchtor 1, 06108 Halle (Saale), Germany
[5] Scotia Seeds, Mavisbank, Farnell, Brechin, UK
[6] The James Hutton Institute, Dundee, UK
[7] Royal Botanic Gardens, Kew, Wellcome Trust Millennium Building, Wakehurst Place, West Sussex, UK

Keywords
Biodiversity; ecological restoration; European grasslands; grasslands; revegetation; seed-based restoration; seed germination; seed policy; seed production .

Correspondence
Emma Ladouceur, Museo Delle Scienze di Trento (Muse), Corso del Lavoro e della Scienza, 3, Trento, Trentino 38122, Italy. Tel: +39 380 121 7641.
Email: emma.ladouceur@muse.it, emmala@gmail.com

Received
20 January 2017
Accepted
28 May 2017

Editor

doi: 10.1111/conl.12381

Abstract

Globally, annual expenditure on ecological restoration of degraded areas for habitat improvement and biodiversity conservation is approximately $18bn. Seed farming of native plant species is crucial to meet restoration goals, but may be stymied by the disconnection of academic research in seed science and the lack of effective policies that regulate native seed production/supply. To illustrate this problem, we identified 1,122 plant species important for European grasslands of conservation concern and found that only 32% have both fundamental seed germination data available and can be purchased as seed. The *"restoration species pool,"* or set of species available in practice, acts as a significant biodiversity selection filter for species use in restoration projects. For improvement, we propose: (1) substantial expansion of research and development on native seed quality, viability, and production; (2) open-source knowledge transfer between sectors; and (3) creation of supportive policy intended to stimulate demand for biodiverse seed.

Introduction

One-tenth of global wilderness has been destroyed in the last two decades (Pennisi 2016), and two-thirds of terrestrial environments are officially classed as degraded (Merritt & Dixon 2011). Ecological restoration (ER) accelerates the recovery of a degraded ecosystem with respect to health, integrity, and sustainability (SER 2004), and is recognized as a key complementary action for habitat conservation. Current global ER targets aim to restore 150 million ha or 15% of degraded ecosystems by 2020 (Menz *et al.* 2013). The estimated $18bn/year restoration cost is far exceeded by the potential global ecosystem service benefits of $85bn annually (Menz *et al.* 2013). Critical to success is the urgent need for access to high-quality seed through the farming of native species, as part of a range of flexible strategies to improve ER (Broadhurst *et al.* 2016).

Several large-scale ER initiatives are underway globally, such as the Australian Gondwana Link (Merritt & Dixon 2011), the Bureau of Land Management U.S. initiatives (Oldfield & Olwell 2015), the African Great Green Wall (Sacande & Berrahmouni 2016), and the European Union (EU) Natura 2000 (European Commission 1992). Seed-based plant conservation and use strategies (Merritt & Dixon 2011; Royal Botanic Gardens Kew 2015), seed-based research (Jiménez-Alfaro *et al.* 2016), and seed supply all play critical roles in successful ER. However, native seed sourcing, collection, production, and storage is more challenging than for agricultural species (Bischoff *et al.*

2008; Broadhurst *et al.* 2008) for which cultivars have been bred to be stable, uniform, and distinct (European Commission 1966).

ER depends on selecting appropriate species to cope with abiotic and biotic characteristics of degraded habitats. In ecological communities, scientists describe the species pool as the set of species that potentially occur at a site (Zobel 1992). The conditions limiting or facilitating species assembly will determine successional and recovering legacies of a system, including responses following ER (Temperton *et al.* 2004). Hand-collecting seed in large quantities from a broad range of species is unrealistic for most ER projects and wild populations risk depletion. Often the material used is restricted to that available from commercial or institutional seed suppliers. The "*restoration species pool*" ("*RSP*"), or pool of species available from these seed suppliers, thus imposes a critical biodiversity filter in ER projects. Where native supply lacks, easily available agronomic or horticultural seeds are used as a substitute, which is ecologically unacceptable. An *RSP* of native species, which has been systematically sourced between and within populations and species distribution ranges, is necessary for the support of genetic diversity in seed supplies and restored ecosystems (Hoban & Schlarbaum 2014).

Seed yields and germination of wild species can be naturally low and variable (Fenner 2000), and while cropping of native species can facilitate controlled production, some seed ecological traits (Fenner & Thompson 2005) can determine obstacles to harvesting. Not all wild species are candidates for commercial production as variation in seed morphological traits necessitates the use of appropriate harvesting and conditioning equipment, the costs of which can be very high if a large number of species are being produced. Proper seed management from collection to postconditioning storage is essential to maintain seed viability, which is variable between suppliers and can be very low (Marin *et al.* 2017). These challenges require collaborative efforts between seed suppliers and researchers to fully realize the potential of providing native farmed seeds for ER. This encompasses research on seed germination, dormancy (a process that regulates germination so that plants emerge under environmental conditions favourable for seedling establishment; Table S1), seed traits relevant for ER (Jiménez-Alfaro *et al.* 2016), and other bottlenecks that can be encountered such as adaptations for cultivation or genetic diversity maintenance (Chivers *et al.* 2016). However, research findings are rarely accessible to public stakeholders involved in ER.

Here, we assess the potential of the *RSP* to meet conservation needs in European grasslands, which are priority habitats as detailed in European policies on nature conservation. Human-induced habitat loss has impacted grassland biomes to the greatest rate and extent, largely due to agricultural conversion and the lack of conservation protections (Hoekstra *et al.* 2005). This neglect is in stark contrast to the biodiversity value of temperate grassland habitats, which across continental Europe are global biodiversity hot spots (Wilson *et al.* 2012). Using European grasslands of conservation concern as a case study, we analyze how many species have both detailed seed quality data and commercial seed lots available across taxa and across three species groups of relevance to European policies on *ER*. Addressing the availability of seed and related scientific information is important for the design of effective policy, research agendas, the foci of commercial seed suppliers, and reducing the risk of falling short in reinstating functional ecosystems in ER (Menz *et al.* 2013).

Methods

Study systems and target species

The European initiative Natura 2000 aims to establish a network of diverse, representative high-quality protected habitats of conservation concern, much of which will require intensive ER (European Commission 1992). Our study is focused on six major temperate grassland habitat types of conservation concern in Europe: lowland meadows (Natura 2000 number: 6510); high altitude hay meadows (6520); dry grasslands (6210); species rich *Nardus* grasslands (6230); calcareous alpine grasslands (6170); and acidic alpine grasslands (6150).

We created a database of 1,122 target species with potential interest for *ER* within these habitats, regulated by EU legislation that affects strategies of seed quality and use (Table S2). This includes 116 *protected* species subjected to legal protection, in most cases endangered or narrow endemic species; 929 *indicator* species, which are indirectly protected when occurring in protected habitats but unregulated in seed production; and 77 *fodder* species controlled for quality as domestic stock feed (European Commission 1966; 2014), as well as for preservation of genetic diversity (European Commission 2010; Table 1).

To assess the availability of seed quality data, we collected trait information on germination temperature and dormancy type of the target species available from the *Seed Information Database* (Royal Botanic Gardens Kew 2008), and the most recent review of seed germination studies (Baskin & Baskin 2014). As these are the main traits related to the germinability of a seed lot, we assume that having this information implies a minimum contribution of the scientific community for a given

Table 1 Relevant legislation details related to each target species group

Species group	Description	Legislation	Impact
Protected species (*N* = 116)	Includes species of conservation concern, in most cases endangered or narrow endemics, listed by name in relevant policy, and occurring in focus habitats.	Specific species for which member states must protect and conserve when found to occur under Annex II & IV of the EU policy on Conservation of Natural Habitats Wild Fauna and Flora (European Commission 1992).	Species seed cannot be collected without a rigorous permit process.
Indicator species (*N* = 929)	Species that are diagnostic or dominant for any of the selected habitats at the continental scale according to Schaminée *et al.* (2016) and vegetation ecology literature (Georg Grabherr & Mucina 1993).	These species are indirectly conserved in Annex II as reflected in the designation of special protected areas for the habitats in that they occur under the EU policy on Conservation of Natural Habitats Wild Fauna and Flora (European Commission 1992).	Species are of interest for use in restoration and have no direct EU policy restrictions on their collection, reproduction, or use but may have local regulations.
Fodder species (*N* = 77)	Grass and legume species used for animal forage, also considered valuable for preservation of the natural environment and conservation of genetic resources in grasslands listed by name under relevant policies.	Specific species and genera important for domestic stock and grazing (European Commission 1966, 2010, 2014).	Controlled for quality including high purity standards and minimum germination thresholds in EU Commission Directive 1966. Expanded in Directive (2010) to include harvest method, seed weight, quantity, region of origin, source area (collection site and multiplication), habitat type, and year of collection. Native seed production cannot exceed 5% of the total commercial cultivar production market in their country.

N = number of species in each group.

species. A systematic online search was conducted from November 2014 to May 2016, and the lists of species available commercially as seed were downloaded, or requested to seed suppliers. As there are multiple seed sources in some countries, the supplier providing the highest number of target species was selected since the inclusion of smaller companies did not influence the total number of available species. This resulted in seed availability lists from 17 seed suppliers across 17 countries (Table S3). Species names were verified against *The Plant List* (Missouri Botanical Gardens, Royal Botanic Gardens Kew 2013). Possible limitations of these data are that species reported as available may be an overestimate as lists may be outdated, inaccurate, or in some cases represent cultivars rather than native species, particularly in the *fodder* group. Nonetheless, the list is an accurate representation of the current state of native seed acquisition in Europe. We use the term *supplier* instead of *producer* because in the majority of cases, seed is reproduced in a native seed farm or orchard, but in some cases seed may be hand-collected.

Analyses

Data were collected as binomial variables. To assess *Germination Data Availability (GDA)*, each species was assigned as data being available (1) or not (0). Similarly, species were either *Commercially Available (CA)* (1) or not (0).

The proportions (%) of species with *CA* and with *GDA* were calculated for each plant family represented in the target species list to elucidate taxonomic representation as a surrogate of phylogenetic variation. A Generalized Linear Model (*GLM*) was fitted to assess the variation of *CA* as a function of *GDA* and species groups. The *GLM* was computed with binomial error distribution and logit link function in order to assess the influence of policy groups and *GDA* (explanatory variables) on *CA* (response variable; *CA* ~ *GDA* + policy group). All analyses were performed in *R Statistical Computing Language and Platform version 3.2.2* (R Core Development Team 2016), and figures created in the package *ggplot2* (Wickham 2009) and *yarrr* (Phillips 2016). The package *Effects* (Fox 2003) was used to create probability estimates of *CA* based on each variable

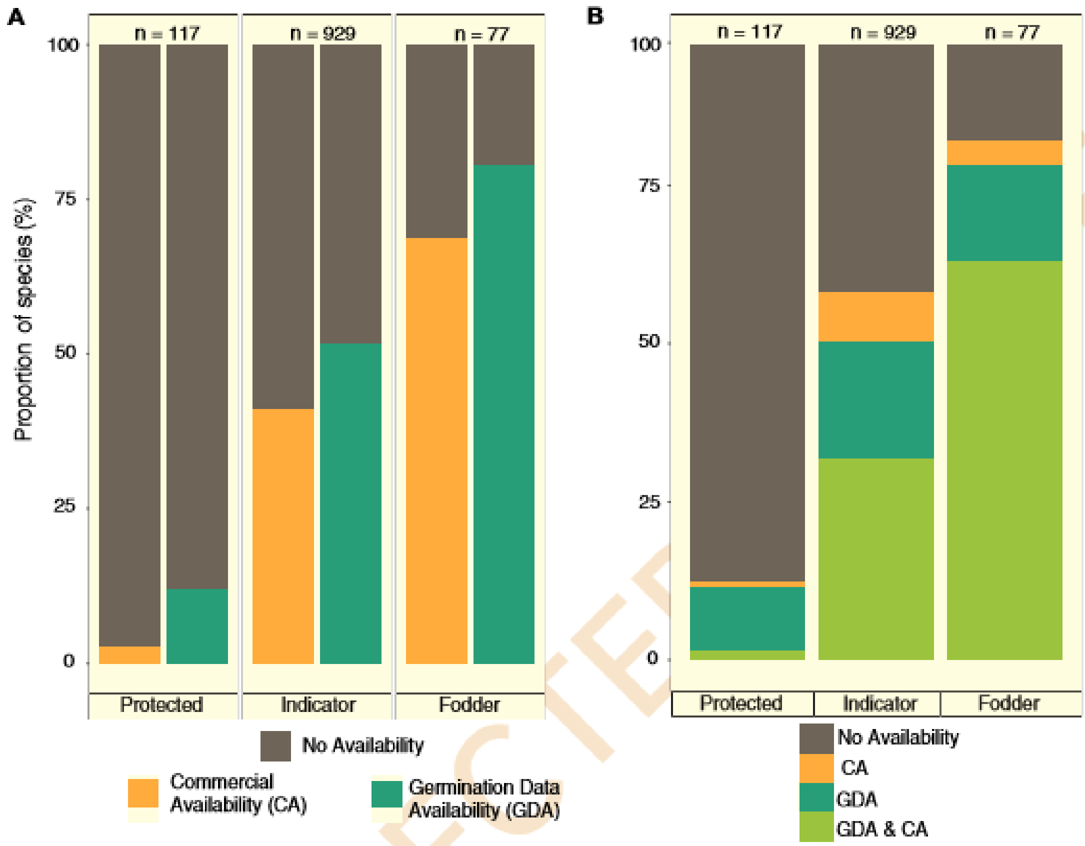

Figure 1 (A) Proportion (%) of species that are commercially available (*CA*) and with germination data availability (*GDA*) (B) proportion (%) of species that are commercially available (*CA*) with germination data availability (*GDA*), and with the combination of *CA* + *GDA*.
N: number of species represented within each group.

and package *PMCMR* for post hoc pairwise Kruskal-Wallis tests (Pohlert 2014).

Results

The 1,122 target species with potential interest for *ER* within European grassland habitats are spread across 59 plant families, with highest representation in Compositae (146 species) and with the top 5 and 10 families comprising 43% and 62% of the species list, respectively. Information on *GDA* and *CA* alone extended to 49% (i.e., 556) and 39% (i.e., 439) of target species, respectively (Figure 1A). Information for both seed *GDA* and *CA* details are available for only 32% (i.e., 358) of species on the target list (Figure 1B). Supplied seed is not available across all suppliers (Figure S1), although *indicator* and *fodder* species with *GDA* are available across a higher proportion of suppliers than those without *GDA* and with *protected* status (Kruskal-Wallis $s^2 = 338.81$, $P \leq 0.001$; Tables S2 and S4).

The majority of taxonomic families completely lacking *GDA* are also completely lacking *CA*, although the sample size is small in these cases (Figure 2, Table S5). The vast majority of families with large sample sizes have ~50% *GDA* and *CA*. Within this case study, there are seven families, spanning nine genera and 15 species, for which germination data are unknown. Twelve families (20% of total) lie within the lower quartile of *CA*, covering 158 species (14% of total).

Strong predictive patterns based on the *GLM* are exhibited for the estimate of *CA* of target species across all variables (Figure 3, Table 2). The model predicts that *protected* species have a 0.04 probability of being *CA*, *indicator* species 0.37 ($P < 0.001$), and *fodder* species 0.54 ($P < 0.001$; Figure 3A, Table 2). Species with no *GDA* have 0.13 probability of being *CA*, and species with *GDA* have a 0.58 probability of being *CA* overall ($P < 0.001$; Figure 3B). The combination of predictors (Figure 3B) provides a further level of outcomes. *Protected* species for which there is no *GDA* have 0.01 probability of *CA*; this

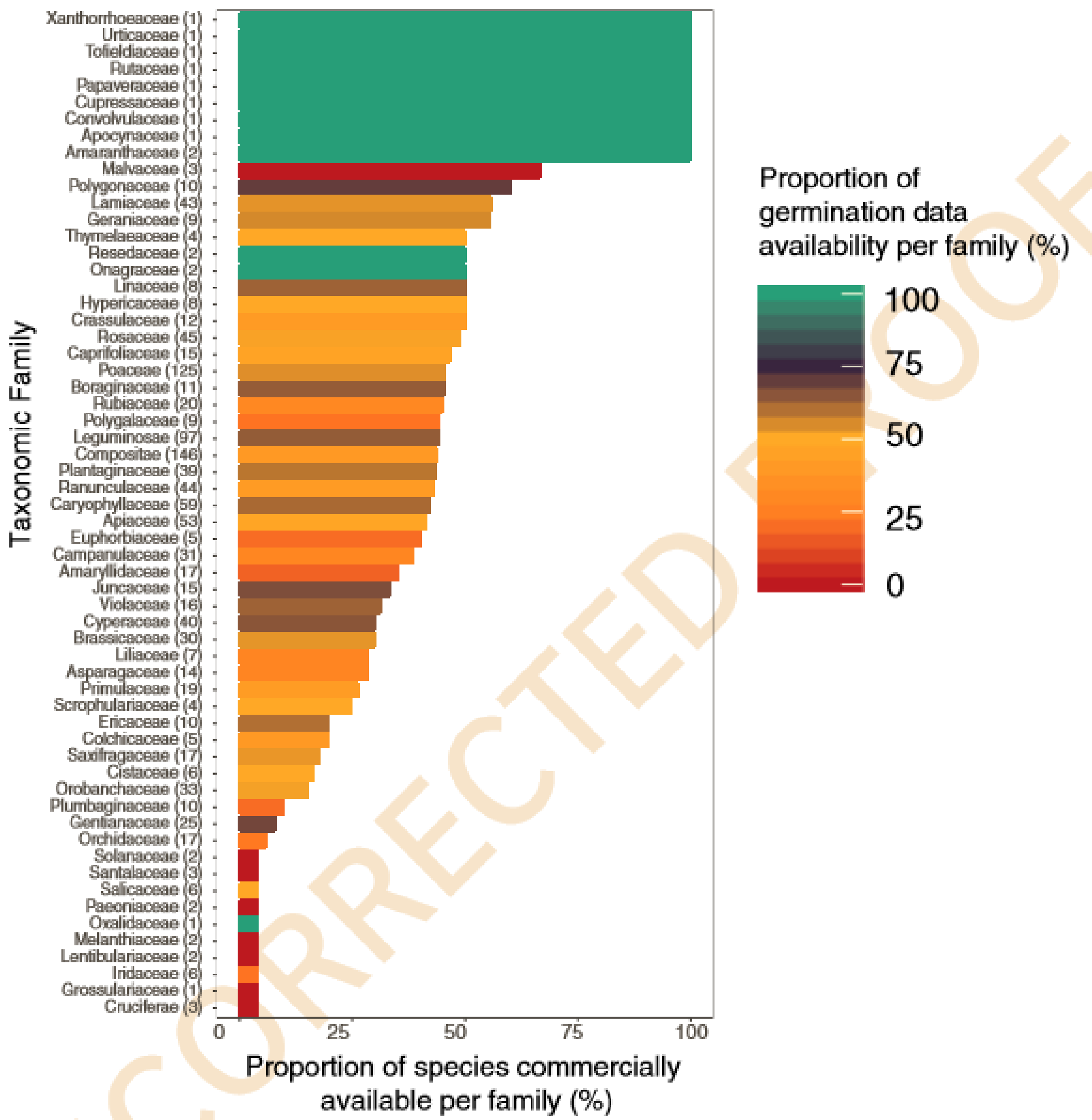

Figure 2 Bars show the proportion (%) of species per taxonomic family that have seed which has *commercial availability*. The degree and proportion of *germination data availability* is represented by the color scale according the seed information database (*Royal Botanic Gardens*, Kew 2008) and Baskin & Baskin (2014). The numbers in brackets next to each family name represents how many species are included in the data set from that given family.

probability increases to 0.11 when there is *GDA*. Comparable values for *indicator* species without and *GDA* are 0.17 and 0.64, respectively; and 0.29 and 0.78 probability, respectively, for *fodder* species.

Discussion

The *RSP* in European grasslands

To our knowledge, no studies have investigated the availability of commercial seed and related germination data for native seed in a large-scale case study. In Europe, the relatively high availability of native seeds for *fodder* species demonstrates that commercial availability of native seed is subject to economic demand and a long-standing regulatory framework. This framework follows an agricultural model meant for animal feed rather than *ER* (European Commission 1966), yet is recognized for ER use (European Commission 2010). The opposite trend is evident for *protected* species, as the availability of commercial and germination data is extremely low, despite their conservation concern in EU regulations. There are

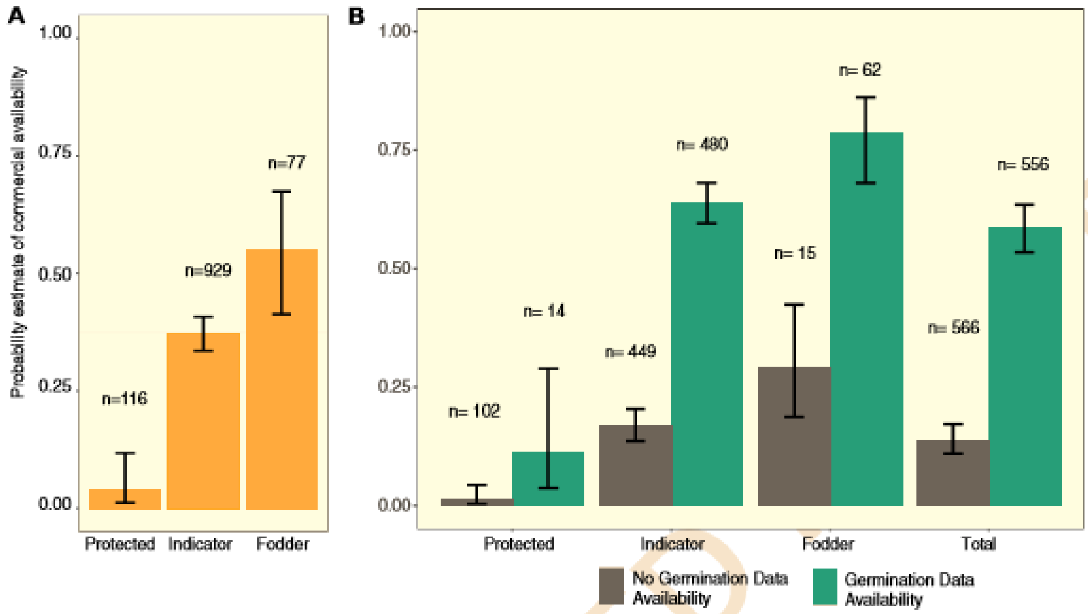

Figure 3 Predicted effect plots showing the *commercial availability* of species grouped per species category. Probability was estimated using *GLM* (binomial error, logit link) fitted to the commercial production data of each species (*commercial availability* ~ *germination data availability* + species group). The same model was used to fit each group, and results were grouped based on: (A) species groups (*protected*, *indicator*, *fodder*) (B) species group + *germination data availability*.
Bars represent the probability that a given group of species is commercially available. Brackets represent the upper and lower limits of that estimate. *N* = number of species represented by each prediction.

Table 2 Generalized linear model (binomial error, logit link) analysis testing the effect of *germination data availability* and species group on *commercial availability*

Coefficient	Effect estimate	Standard error	Z	P
Intercept (protected)	−4.2541	0.6016	−7.071	< 0.001
Germination data availability	2.1759	0.1524	14.281	< 0.001
Indicator species	3.3685	0.6570	5.127	< 0.001
Fodder species	2.6502	0.6021	4.401	< 0.001

Results were estimated using *GLM* fitted to the commercial production data for each species.

relatively high levels of *indicator* species represented in the *RSP*, but this does not necessarily indicate availability from many suppliers. Seed availability and use is compounded by the origin of the seed, as some supplies may not be appropriate for use in every region (Bischoff *et al.* 2008). Species for which there is a lack of *GDA* are also less likely to be *CA* and more likely to be omitted from the *RSP*. This indicates the urgent need for research and development on European grassland native seed biology, including knowledge transfer to support the commercial sector.

When there are little or no germination data for species within a family, congeneric species can offer predictions of potential dormancy (Table S1), that is, *implied dormancy*, and thus the type of environmental conditions to trigger germination (Baskin & Baskin 2014). Implied dormancy for the large majority of study species (~75%) indicates probable complex germination characteristics (Table S1). Currently, most revegetation projects in Europe have no requirement to improve biodiversity outputs, thus there is lack of consistent demand, and little capacity to improve the range of species with *CA*, particularly for species that may be complex to supply. Without change, *ER* of grassland habitats could continue to demonstrate species bias limiting biodiversity, facilitating the persistence of degraded systems in alternatively stable states (Suding *et al.* 2004). Improving the *RSP* will reduce risk in *ER* projects as a complimentary conservation resource.

For the *RSP* to better support ER, industry also requires cooperative market sharing, improved provision and storage strategies. In Australia, United Kingdom, and the United States, there are examples of government, community, or nonprofit groups working cooperatively with seed suppliers to enable the inclusion of species that have challenging seed traits in the commercial *RSP* supply chain. The U.S. Native Plant Program (Oldfield & Olwell 2015) contracts production of seed across all available suppliers, to partition demand and market share, then stored in government infrastructure for purchase. As a unique example in Europe, Germany has mandated that only native species may be used for all revegetation by 2020 (BNatSchG, Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety 2010). Compared to German native seed demand in 2015, production of local native seeds must grow 10-fold to meet 2020 targets (Pers. Comm., Ann Kareen Mainz, Association of German Wild Seed Producers), an increase which will require expansion of their *RSP*. Demand creation, contracting, storage, and provision solutions must be developed in tandem to effectively expand *RSP* capacity.

Policy recommendations

Current legislation relating to *protected* (European Commission 1992) and *fodder* (European Commission 2010) species recognize the need to produce seed specifically for ER, but do not match the native seed market appropriately. Policy relating to the use of seed mixtures mandates that commercially produced seed must come from the same source area in which it is being used, and germination minimums are required (European Commission 2010), which are easily achievable in cultivars, but unrealistic for native species. These quality standards are too restrictive (Tishew *et al.* 2011), to which there is low adherence and enforcement, as they are contradictory to a much-needed industry with a small market niche. Supportive regulation is needed and future EU policy should require that all public revegetation projects use only native material. Creating demand through policy while aligning the contracting of supply offers immense potential to enable growth of the *RSP*. We strongly support initiation of policies to contract annual native seed production of baseline *indicator* and *fodder* species across available producers to store for large-scale projects. Policy should require vegetation biodiversity targets to be met in *ER* and revegetation. Sourcing and contracting of site-specific seed material beyond yearly *indicator* and *fodder* stores (including but not limited to *protected* species) should be required at project inception to allow time for realistic production. New policies should be designed to embrace consultation with the native seed industry and restoration professionals.

Conservation seed banks for native species can support these strategies in a small capacity and can provide access to relevant small-scale seed processing and quality assessment equipment (Nevill *et al.* 2016). The largest ex situ plant conservation programme globally, the *Millennium Seed Bank Partnership (MSBP)*, managed by the Royal Botanic Gardens, Kew, UK, has successfully banked 13% of the world's wild seeds, aiming to bank 25% by the year 2020 (Royal Botanic Gardens Kew 2015). Seed from the *MSBP* has been used for small-scaled re-establishment, generally targeted for threatened species. An exemplar is FAO-RBG Kew "Africa's Great Green Wall" program within which collaborating country seed banks supply ~25,000 kg of seed per annum of about 200 species of trees, shrubs, and grasses (Sacande & Berrahmouni 2016). Nevertheless, a new form of *Restoration Seed Banks* (Merritt & Dixon 2011) is needed if a sustainable seed supply chain of the right scale is to be supported for the *RSP*. To improve *ER* outcomes, wide expansion of current capacity and collaboration across sectors is needed to provide the requisite tons of native seed needed (Merritt & Dixon 2011). In addition, research in seed biology and vegetation science applied to seed sourcing, applications, and bottlenecks related to collection and use are required.

Current research in seed biology and regeneration processes remains specialized, in need of urgent expansion (Larson & Funk 2016). In addition, long-term interdisciplinary and collaborative open-source knowledge sharing platforms are needed to facilitate the exchange of research (Royal Botanic Gardens Kew 2015). We suggest future germination research focus on the development of efficient dormancy breaking treatments, the thermal control of germination (thresholds and rates), and improvements in native seed production practices for European grassland species not currently covered by the *RSP*. Integration of research and industry knowledge sharing where any research project connected to native seed germination delivers findings to the private sector could hold wide benefits. Research projects for *protected* or underrepresented taxa could ideally include commercial or cooperative seed production contracts for direct use in conservation and reintroduction as industry output components. Supplying *protected* species must be strictly designed, implemented, and controlled with the direct use of vanguard science through extremely collaborative approaches (Shirey *et al.* 2013).

Conclusions

Our analysis presents the first study investigating seed germination data availability and the commercial "*RSP*." We present a continental case study, reflecting a global issue of global importance to habitat conservation. In sum, we encourage further exploration of the reconsideration of public policy, compilation of open-access knowledge sharing across sectors, and multinational efforts to provide infrastructure and support, expand, and realize the full potential of the emerging native seed industry.

Improving the breadth of research of seed biology research and knowledge sharing between sectors has potential to support the expansion of the commercial native seed and the *RSP*. Improved commercial availability could reduce species bias and risk in ER.

Acknowledgments

Special thanks for inputs from collaborators in the NAtive Seed Science TEchnology and Conservation (NASSTEC), Initial Training Network (ITN) consortium. The research leading to these results received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement no. 607785. The Royal Botanic Gardens, Kew receives grant-in-aid from Defra. The James Hutton Institute is supported by the Scottish government.

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Figure S1 Observed percentage (%) of suppliers (total 17) with *commercial availability* of seed with and without *germination data availability*.

RDI plots (raw data, descriptive and inference statistics) show jittered points of raw data, center bars indicate the mean of the data, beans outline the smoothed density of the data, whiskers mark the 10% and 90% quantiles of the data, and inference bands show the Bayesian 95% high-density interval inferential statistics for each group. Letters show statistical differences between groups (Table S4).

Table S1 Simplified seed dormancy types (adapted from Baskin & Baskin 2014)

Table S2 Full species list, associated category, and associated data

CA = commercial availability (yes [1], no [0]), *GDA* = germination data availability (yes [1], no [0]).

Table S3 Seventeen seed suppliers across 17 countries used for data collection

Table S4 Statistics representing differences between variables in the percentage of suppliers with seed of each species commercially available compared across species groups (Figure S1)

Kruskal-Wallis χ^2 test and post hoc pairwise Tukey and Kramer (Nemenyi) χ^2 test, *P*-value statistics, indicating significance between group variables. Germination data available = "+*GDA*," germination data not available = "–*GDA*."

Table S5 The complete data set summarized by taxonomic family in descending order of percentage of commercial availability (*CA*)

= number, % = percentage, Sp. = species, *CA* = commercially availability, *GDA* = germination data availability.

References

Baskin, C.C. & Baskin, J.M. (2014). *Seeds: ecology, biogeography, and evolution of dormancy and germination*. 2nd edn. Elsevier.

Bischoff, A., Steinger, T. & Muller, S.Ä.H. (2008). The importance of plant provenance and genotypic diversity of seed material used for ecological restoration. *Restor. Ecol.*, **18**, 338-348.

BNatSchG, Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety. (2010). Act on Nature Conservation and Landscape Management (Federal Nature Conservation Act – BNatSchG) of 29 July 2009. *Federal Nature Conservation Act*. **1**.

Broadhurst, L.M., Lowe, A., Coates, D.J., *et al.* (2008). Seed supply for broadscale restoration: maximizing evolutionary potential. *Evol. Appl.*, **1**, 587-597.

Broadhurst, L.M., Jones, T.A., Smith, F.S., North, T. & Guja, L. (2016). Maximizing seed resources for restoration in an uncertain future. *BioScience*, **66**, 73-79.

Chivers, I.H., Jones, T.A., Broadhurst, L.M., Mott, I.W. & Larson, S.R. (2016). The merits of artificial selection for the development of restoration-ready plant materials of native perennial grasses. *Restor. Ecol.*, **24**, 174-183.

European Commission. (1966). Council Directive 66/401/EEC of 14 June 1966 on the marketing of fodder plant seed.

European Commission. (1992). Council Directive 92/43/EEC of 21 of May 1992 on the conservation of natural habitats and wild fauna and flora.

European Commission. (2010). Commission Directive 2010/60/EU of 30 August 2010 providing for certain derogations for marketing of fodder plant seed mixtures intended for use in the preservation of the natural environment. Text with EEA relevance. Official Journal of The European Union.

European Commission. (2014). Commission Implementing Decision 2014/362/EU of 13 June 2014 amending Decision 2009/109/EC on the organisation of a temporary experiment providing for certain derogations for the marketing of seed mixtures intended for use as fodder plants pursuant to Council Directive 66/401/EEC.

Fenner, M. (2000). *Seeds: the ecology of regeneration in plant communities*. 2nd edn.

Fenner, M. & Thompson, K. (2005). *The ecology of seeds*. Cambridge University Press, Cambridge.

Fox, J. (2003). Effect displays in R for generalised linear models. *J. Stat. Soft.*, **8**, 1-27.

Georg Grabherr, von H. & Mucina, L. (1993). *Die Pflanzengesellschaften Osterreichs*. Gustav Fischer Verlag Jena, New York.

Hoban, S. & Schlarbaum, S. (2014). Optimal sampling of seeds from plant populations for ex-situ conservation of genetic biodiversity, considering realistic population structure. *Biol. Conserv.*, **177**, 90-99.

Hoekstra, J.M., Boucher, T.M., Ricketts, T.H. & Roberts, C. (2005). Confronting a biome crisis: global disparities of habitat loss and protection. *Ecol. Lett.*, **8**, 23-29.

Jiménez-Alfaro, B., Silveira, F.A.O., Fidelis, A., Poschlod, P. & Commander, L.E. (2016). Seed germination traits can contribute better to plant community ecology. *J. Veg. Sci.*, **27**, 637-645.

Larson, J.E. & Funk, J.L. (2016). Regeneration: an overlooked aspect of trait-based plant community assembly models. *J. Ecol.*, **104**, 1284-1298.

Marin, M., Toorop, P., Powell, A.A. & Laverack, G. (2017). Tetrazolium staining predicts germination of commercial seed lots of European native species differing in seed quality. *Seed Sci. Technol.*, **45**, 1-16.

Menz, M.H.M., Dixon, K.W. & Hobbs, R.J. (2013). Hurdles and opportunities for landscape-scale restoration. *Science*, **339**, 526-527.

Merritt, D.J. & Dixon, K.W. (2011). Restoration seed banks - a matter of scale. *Science*, **332**, 424-425.

Missouri Botanical Gardens, Royal Botanic Gardens Kew. (2013). The plant list. http://www.theplantlist.org/ (visited May 4, 2016).

Nevill, P.G., Tomlinson, S., Elliott, C.P., Espeland, E.K., Dixon, K.W. & Merritt, D.J. (2016). Seed production areas for the global restoration challenge. *Ecol. Evol.*, **6**, 7490-7497.

Oldfield, S. & Olwell, P. (2015). The right seed in the right place at the right time. *BioScience*, **65**, 955-956.

Pennisi, E. (2016). We've destroyed one-tenth of Earth's wilderness in just 2 decades. *Science*. http://www.sciencemag.org/news/2016/09/we-ve-destroyed-one-tenth-earth-s-wilderness-just-2-decades?utm_source=sciencemagazine&utm_medium=facebook-text&utm_campaign=wilderness-7205 (visited Oct. 15, 2016).

Phillips, N. (2016). yarrr: a companion to the e-book "YaRrr!: the pirates guide to R." http://nathanieldphillips.com/thepiratesguidetor/ (visited Aug. 5, 2016).

Pohlert, T. (2014). The pairwise multiple comparison of mean ranks package (PMCMR).

R Core Development Team. (2016). R: a language and environment for statistical computing.

Royal Botanic Gardens Kew. (2008). KEW seed information database (SID). http://data.kew.org.sid/ (visited May 4, 2016).

Royal Botanic Gardens Kew. (2015). Kew science strategy 2015–2020.

Sacande, M. & Berrahmouni, N. (2016). Community participation and ecological criteria for selecting species and restoring natural capital with native species in the Sahel. *Restor. Ecol.*, **24**, 479-488.

Schaminée, J.H.J., Chytrý, M., Hennekens, S.M., *et al.* (2016). Review of grassland habitats and development of distribution maps of heathland, scrub and tundra habitats of EUNIS habitats classification. *Alterra Institute*.

Shirey, P.D., Kunycky, B.N., Chaloner, D.T., Brueseke, M.A. & Lamberti, G.A. (2013). Commercial trade of federally listed threatened and endangered plants in the United States. *Conserv. Lett.*, **6**, 301-316.

Society for Ecological Restoration, Science and Policy Working Group (SER) (2004). SER international primer on ecological restoration. Society for Ecological Restoration International. http://www.ser.org/page/SERDocuments (visited Oct. 4, 2016).

Suding, K.N., Gross, K.L. & Houseman, G.R. (2004). Alternative states and positive feedbacks in restoration ecology. *Trends Ecol. Evol.*, **19**, 46-53.

Temperton, V.M., Hobbs, R.J., Nuttle, T. & Halle, S. (2004). *Assemby rules and restoration ecology*. Island Press.

Tishew, S., Youtie, B., Kirmer, A. & Shaw, N. (2011). Farming for restoration: building bridges for native seeds. *Ecol. Restor.*, **29**, 219-222.

Wickham, H. (2009). ggplot2: elegant graphics for data analysis. Springer-Verlag, New York.

Wilson, J.B., Peet, R.K., Dengler, J. & Partel, M. (2012). Plant species richness: the world records. *J. Veg. Sci.*, **23**, 796-802.

Zobel, M. (1992). Plant-species coexistence - the role of historical, evolutionary and ecological factors. *Oikos*, **65**, 314-320.