# A research program for adapting social-ecological systems for the long term

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Document présenté pour obtenir

L'HABILITATION A DIRIGER LES RECHERCHES (HDR)

Par

Juan Fernández Manjarrés

# A research program for adapting social-ecological systems for the long term

Séance prévue le 13 Juin 2018, devant la commission d'examen :

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| Anne Atlan | Rapporteure |
| Harold Levrel | Rapporteur |
| Pierre Pech | Rapporteur |
| François Sarrazin | Rapporteur |
| Denis Couvet | Examinateur |
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# Contents

## Acknowledgements

There are so many people and institutions to acknowledge in every person's life that any list that we attempt to do will be unfair to our family, friends, students, professors and colleagues that have helped us in one way or another to become the persons that we are. Nevertheless, I feel obliged to mention some people that have been key in letting me become the researcher I am today in my adoptive country, France.

First of all, I would like to thank with all my heart Nathalie Frascaria-Lacoste, who hired me for a 2 year post-doc on the hybridization of ash trees. He not only trusted me, but saw in me talents that I was unware of. Without her support, I would not have become the researcher I am today. I would also like to thank the colleagues and students that have embarked in the creation of an interdisciplinary team, which is helping all of us to achieve new goals. I refer to Jane Lecomte, Bruno Colas, Samuel Roturier, Sébastien Ollier, and more recently, Anne Charlotte Vaissière.

I am also very indebted to three people that have participated in the core of my research this last years, regarding assisted migration of trees: Roxane Sansilvestri, Marta Benito-Garzón and Louis Tschanz, Martina Temunovic and Muriel Thomasset, without whom the difficult task of conducting mulit- and interdisciplinary research would not have been possible. I also thank Paola Bertolino and Pierre Gerard as the best colleagues one can have. Last, but not least, I thank Paul Leadley that helped me make the transition during my first stages in the CNRS by letting me collaborate in far reaching publications and in the thinking process of complex problems at the scale of the planet, which was new for me, and to Gerry Douglas for financing the work with hybrid Ashes in Ireland.

Of course, I thank my wife Mireille, for all his support and patient all these years as she also believed I could do more things that I thought I was able to.

## Résumé étendu en Français

Ce document a pour but d'accompagner la soutenance orale pour l'obtention du diplôme d'Habilitation à diriger des Recherches. Dans ce cadre, je présente l'approche de recherche que j'ai développée depuis mon recrutement au CNRS en 2009 par la commission 45 (aujourd'hui commission interdisciplinaire 52 '*Environnements sociétés : du fondamental à l'opérationnel*'). Mon projet d'intégration au CNRS était centré sur les concepts et outils nécessaires à l'adaptation des forêts en Europe en partant d'une vision écologique dans le contexte des politiques publiques. Cet angle de recherche est issu de ma formation doctorale (PhD, Université de Missouri-Saint Louis, USA, 2002) où j'ai traité les effets génétiques de la fragmentation sur les forêts des chênes en Colombie et de mon travail de post-doc au sein du laboratoire d'Ecologie Systématique et Evolution ESE), à l'université Paris-Sud, à Orsay. Pendant mes années de post-doc (2002-2008), j'étais encadré par Nathalie Frascaria-Lacoste (Professeure à AgroParisTech) et de nombreuses recherches ont été menées autour de la connaissance et la gestion des zones naturelles d'hybridation du frêne oxyphylle avec le frêne commun. Ces cas d'hybridations naturelles montraient les limites des politiques publiques pour gérer une biodiversité dynamique. En effet, ces populations hybrides ne pouvaient être commercialisées pour le reboisement même si elles faisaient partie du paysage et du patrimoine écologique et culturel de la Loire.

Après mon recrutement en 2009, je me suis consacré au développement d'outils écologiques et juridiques pour la gestion des forêts dans un climat changeant, soutenu par un projet financé par l'ANR dont j'étais le coordinateur (2010-2015). Dans l'introduction de ce document,

j'explique comment depuis, je m'implique dans une approche interdisciplinaire basée sur quatre notions :

(i) l'indéterminisme écologique et social qui fait écho aux problèmes d'incertitude scientifique et aux contraintes sociales (conflits d'intérêts, visions opposées du monde…) dans la gestion à long terme des socio-écosystèmes,

(ii) les idées de « concept frontière » et « d'objet frontière », c'est-à-dire des idées qui peuvent être partagées entre plusieurs disciplines et des objets qui servent à amorcer des études multidisciplinaires pour préparer la voie à une interdisciplinarité,

(iii) la nécessité de détacher du quasi-dogme du « système complexe » le concept de socio-écosystème pour pouvoir parler des « ensembles socio–écologiques ». Cette nouvelle définition a pour but de faciliter le dialogue avec les sciences sociales pour lesquelles les visions de la société sont différentes de l'approche mécanistique de l'écologie,

(iv) enfin, je souligne le besoin d'inculquer aux étudiants une conscience sociale et éthique vis-à-vis de la gestion à long terme des ensembles socio-écologiques.

Tout au long de ce texte, j'explique comment j'utilise les politiques publiques en tant que concept/objet frontière pour mes études sur la gestion des forêts dans le cadre du changement climatique. C'est ainsi que j'ai encadré Roxane Sansilvestri (2012-2015) dans le cadre d'un projet de migration assistée des forêts en tant que mesure de compensation pour les effets du changement climatique. Ensuite, je présente un projet en cours qui montre en quoi les politiques publiques du bois énergie dans la région méditerranéenne française sont à la fois une source d'incertitude écologique mais aussi sociale. Elles font actuellement l'objet d'un blocage et nous collaborons avec une équipe interdisciplinaire pour réduire cette incertitude. Ce projet, financé par un appel d'offres de l'université Paris-Saclay en 2016, doit prendre fin courant 2018.

Enfin, je présente les politiques publiques liées à l'agroforesterie comme point de départ de futures recherches en Amérique latine équatoriale, où j'ai l'intention de concentrer mes efforts, notamment à travers la formation de docteurs. L'économie de cette région est fortement dépendante de l'agroforesterie que l'on a tendance à présenter de plus en plus comme une forme d'adaptation au changement climatique et une source de revenus pour les paysans et indigènes démunis. Or, une agroforesterie mal planifiée n'est pas forcément compatible avec une gestion de la biodiversité locale qui est l'une des plus riches au monde. Ce programme de recherche sera construit autour du principe de « restauration socio-écologique » (Fernandez-M. et al. 2018, *Ecological Restoration*, sous presse) en tant que concept frontière adapté aux régions où la biodiversité est très importante et les crises humanitaires surgissent de manière récurrente.

# 1. Curriculum Vitae

## Research keywords

Forest ecology and management, climate change adaptation, social-ecological systems, public policies

## Personal Information

Date and Place of Birth: 14/01/1966 Cali, Colombia
Nationality: Colombian, French

## Address

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## Education

**PhD** - Plant Conservation Genetics- 2002 – University of Missouri – St. Louis, USA. Dissertation: Conservation genetics of the Andean Oak *Quercus humboldtii* Bonpl., Advisor: Dr. Victoria L. Sork.

**MSc** -Tropical Biology and Conservation - 1997 – University of Missouri – St. Louis, USA, graduate programme in association with the Missouri Botanical Gardens (Fulbright Scholarship)

**BS** - Biology with minor in Botany- 1990 – Universidad del Valle, Cali, Colombia

## LANGUAGES

Spanish (mother tongue); English, fluent; French, fluent

## CURRENT ADMINISTRATIVE RESPONSIBILITIES

- Coordinator, elected, research team TESS: Coordinator research team TESS: "Trajectoires EcologiqueS et Societé" http://www.ese.u-psud.fr/rubrique131.html
- Council member, appointed, Laboratoire d'Écologie, Systématique et Évolution
- Academic Council (elected), Saclay University

## WORK AND RESEARCH EXPERIENCE

| | |
|---|---|
| 2009 - present | Researcher (CNRS CR1 recruited by **Section 45** – (**currently 52**)) at the laboratory of Ecology, Systematics and Evolution UMR 8079, Université Paris-Sud |
| 2007 - 2009 | Post-doc and Consultancy to the National Council for Forest Research and Development COFORD from Ireland.) |
| 2005 – 2006 | Teaching and Research Associate: Université Paris Sud XI, Biology Department. |
| 2002 - 2005 | Post-doctoral position: Laboratoire Ecologie, Systématique et Evolution, Université Paris Sud |
| 1997-2002 | PhD studies and Research Assistant, Department of Biology, University of Missouri – Saint Louis. |
| 1995-1997 | M. Sc. Studies, University of Missouri – St. Louis, Fulbright Fellowship |
| 1990- 1995 | Staff-Biologist: Data Center for Conservation, Cali, Colombia |

## Recent Grants

| | |
|---|---|
| 2017 - 2018 | Saclay University: Institute of Environmental Changes: Adaptation to environmental changes: a multi-scale and transdisciplinary approach; Post-doctoral grant 71 k€. role: **Partner** |
| 2017 - 2018 | BASC LabEx: Social and Ecological Networks Adaptation to a Changing world (SENAC); 20 k€. role: **Coordinator** |
| 2015 - 2016 | BASC LabEx: 6 k€. Network project: Assessing processes, methods and variables for the Potential Mediterraneanization of socio-ecosystems in Western Europe. 6 k€. role: **Coordinator** |
| 2011 - 2015 | French National Research fund (ANR): Project **AMTools:** Ecological and legal tools for the assisted migration of forests. 350 k€. role: **Coordinator** |
| 2010 | French National Center for Research (CNRS): Ecological engineering small grants (2010). role: **Coordinator** |

## Teaching

| | |
|---|---|
| 2012 - 2017 | La notion du changement dans les socio-écosystèmes. "Dominante d'Approfondissement : Science politique, écologie et stratégie (SPES), AgroParisTech. Coordinator, Cécile Blatrix.<br><br>http://www.agroparistech.fr/Science-politique-ecologie-et-strategie-SPES.html |
| 2011 - 2017 | Forest management and climate change, Paris-Sud University, Master programme in Biodiversity Ecology and Evolution. Coordinator: Claire Damesin;<br><br>http://www.u-psud.fr/fr/formations/diplomes/masters/biodiversite-ecologie-evolution.html |
| Avril 2008 | Lecturer: Kenya Training course on "Molecular Marker for Development of Improved Crop Varieties": subject: molecular data analyses. FAO/IAEA joint agricultural programme |
| June 2007 | Lecturer: Senegal, South Africa in Regional (AFRA) Training course on "Molecular Marker for Development of Improved Crop Varieties": subject: molecular data analyses. FAO/IAEA joint agricultural programme. |
| August 2006 | Lecturer: Pretoria; LRN/ Agricultural Research Council, South Africa in Regional (AFRA) Training course on "Molecular Marker for Development of Improved Crop |

| | |
|---|---|
| | Varieties": subject: molecular data analyses. FAO/IAEA joint agricultural programme. |
| May 2006 | Lecturer 6th FAO/IAEA Interregional Training Course on Mutant Germplasm Characterization using Molecular Markers at Seibersdorf, Vienna. Subject: Population genetics data interpretation |
| Decembe r 2005 | Biostatistics consulting at the FAO/IAEA in Vienna, Breeding Unit laboratory: data analysis of cultivars and wild accessions collections. |
| August 2005 | Lecturer 5th FAO/IAEA Interregional Training Course on Mutant Germplasm Characterization using Molecular Markers at Seibersdorf, Vienna. Subject: Population genetics data interpretation. Technical Officer: Dr. Chikelu Mba (Unite head) |
| May 2001 | Workshop on using Genetic Markers in Conservation Biology, Humboldt Institute Laboratory at the International Center of Tropical Agriculture CIAT, Colombia |

## STUDENTS TRAINED

| Period | Student, institution and Program | Responsability |
|---|---|---|
| 2017 | Jilmar Castaneda, Master student, Université Saint Quinten en Yvelines, Gestion du territoire et développement local, parcours Gouvernance des Territoires, des Risques et de l'Environnement Master internship | Tutor |
| 2012-2015 | Roxane Sansilvestri, doctoral student, Université Paris-Sud | Tutor |
| 2010-2015 | Martina Temunovic, doctoral student, Zagreb Forest Faculty, Zagreb, Croatia | Co-tutor |
| 2010-2015 | Muriel Tomasset, doctoral student, Trinity College, Dublin, Ireland | Co-tutor |
| 2010 | Louise Tschanz, Master student, Université Paris-Sud, Law School | Tutor |
| 2005-2008 | Rosalba Ruiz, PhD student, Unviversidad del Valle, Biology faculty | Co-tutor |

## Journal Manuscript Revisions

Acta Oecologica, American Journal of Botany, Annals of forest Science, Caldasia, Canadian Journal of forestry Research, Ecology Letters, Environment and Planning C: Government and Policy, Evolution, Forest Policy and Economics, Genetica, Journal of Heredity, Journal of Forestry Research, Land**,** Mitigation and Adaptation Strategies for Global Change, Molecular Ecology, Sustainability

## List of Publications (Peer Reviewed)


Aggarwal, R. K., J. Allainguillaume, M. M. Bajay, S. Barthwal, P. Bertolino, P. Chauhan, S. Consuegra, A. Croxford, D. L. Dalton, E. den Belder, E. Diaz-Ferguson, M. R. Douglas, M. Drees, J. Elderson, G. D. Esselink, J. F. Fernandez-Manjarres, N. Frascaria-Lacoste, Set al. 2010. Permanent Genetic Resources added to Molecular Ecology. **Molecular Ecology Resources** 11:219-222.

Albaladejo, R. G., L. F. Carrillo, A. Aparicio, J. F. Fernandez-Manjarres, and J. P. Gonzalez-Varo. 2009. Population genetic structure in *Myrtus communis* L. in a chronically fragmented landscape in the Mediterranean: can gene flow counteract habitat perturbation? **Plant Biology** 11:442-453.

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Benito-Garzon, M., and J. Fernandez-Manjarres. 2015. Testing scenarios for assisted migration of forest trees in Europe. **New Forests** 46:979-994.

Benito-Garzón, M., N. González Muñoz, J.-P. Wigneron, C. Moisy, J. Fernández-Manjarrés, and S. Delzon. 2017. The legacy of water deficit on populations having experienced negative hydraulic safety margin. **Global Ecology and Biogeography** 27:346-356. In press.

Benito-Garzon, M., P. W. Leadley, and J. F. Fernandez-Manjarres. 2014. Assessing global biome exposure to climate change through the Holocene-Anthropocene transition. **Global Ecology and Biogeography** 23:235-244.

Benito-Garzon, M., H. D. Minh, N. Frascaria-Lacoste, and J. Fernandez-Manjarres. 2013. Habitat Restoration and Climate Change: Dealing with Climate Variability, Incomplete Data, and Management Decisions with Tree Translocations. **Restoration Ecology** 21:530-536.

Benito-Garzon, M., H. D. Minh, N. Frascaria-Lacoste, and J. F. Fernandez-Manjarres. 2013. Extreme Climate Variability Should Be Considered in Forestry Assisted Migration. **Bioscience** 63:317-317.

Douglas, G. C., A. Pliura, J. Dufour, P. Mertens, D. Jacques, J. F. Fernandez-Manjarres, J. Buiteveld, G. Parnuta, M. Tudoroiu, Y. Curnel, M. Thomasset, V. Jensen, M. A. Knudsen, E. Foffová, A. Chandelier, and M. Steenackers. 2013. Common Ash (*Fraxinus excelsior* L.). Chapter 9. Page 527 p.  Forest tree breeding in Europe. Springer.

Fernandez, J. F., and V. L. Sork. 2005. Mating patterns of a subdivided population of the Andean oak (*Quercus humboldtii* Bonpl., Fagaceae). **Journal of Heredity** 96:635-643.

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Fernandez, J. F., V. L. Sork, G. Gallego, J. Lopez, A. Bohorques, and J. Tohme. 2000. Cross-amplification of microsatellite loci in a neotropical *Quercus* species and standardization of DNA extraction from mature leaves dried in silica gel. Plant Molecular **Biology Reporter** 18:397-397.

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Gerard, P. R., E. K. Klein, F. Austerlitz, J. F. Fernandez-Manjarres, and N. Frascaria-Lacoste. 2006. Assortative mating and differential male mating success in an ash hybrid zone population. **Bmc Evolutionary Biology** 6.

Gerard, P. R., M. Temunovic, J. Sannier, P. Bertolino, J. Dufour, N. Frascaria-Lacoste, and J. F. Fernandez-Manjarres. 2013. Chilled but not frosty: understanding the role of climate in the hybridization between the Mediterranean *Fraxinus angustifolia*Vahl and the temperate *Fraxinus excelsior* L. (Oleaceae) ash trees. **Journal of Biogeography** 40:835-846.

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Sork, V. L., F. W. Davis, P. E. Smouse, V. J. Apsit, R. J. Dyer, J. F. Fernandez, and B. Kuhn. 2002. Pollen movement in declining populations of California Valley oak, *Quercus lobata*: where have all the fathers gone? **Molecular Ecology** 11:1657-1668.

Sork, V. L., J. Nason, D. R. Campbell, and J. F. Fernandez. 1999. Landscape approaches to historical and contemporary gene flow in plants. **Trends in Ecology & Evolution** 14:219-224.

Stoeckel, S., J. Grange, J. F. Fernandez-Manjarres, I. Bilger, N. Frascaria-Lacoste, and S. Mariette. 2006. Heterozygote excess in a self-incompatible and partially clonal forest tree species - *Prunus avium* L. **Molecular Ecology** 15:2109-2118.

Temunović, M., J. Franjić, Z. Satovic, M. Grgurev, N. Frascaria-Lacoste, and J. F. Fernández-Manjarrés. 2012. Environmental Heterogeneity Explains the Genetic Structure of Continental and Mediterranean Populations of *Fraxinus angustifolia* Vahl. **PLOS ONE** 7:e42764.

Temunovic, M., N. Frascaria-Lacoste, J. Franjic, Z. Satovic, and J. F. Fernandez-Manjarres. 2013. Identifying refugia from climate change using coupled ecological and genetic data in a transitional Mediterranean-temperate tree species. **Molecular Ecology** 22:2128-2142.

Thomasset, M., J. F. Fernandez-Manjarres, G. C. Douglas, P. Bertolino, N. Frascaria-Lacoste, and T. R. Hodkinson. 2013. Assignment testing reveals multiple introduced source populations including potential ash hybrids (*Fraxinus excelsior x F. angustifolia*) in Ireland. **European Journal of Forest Research** 132:195-209.

Thomasset, M., J. F. Fernandez-Manjarres, G. C. Douglas, N. Frascaria-Lacoste, C. Raquin, and T. R. Hodkinson. 2011. Molecular and morphological characterization of reciprocal F-1 hybrid ash (*Fraxinus excelsior X Fraxinus angustifolia*, oleaceae) and parental species reveals asymmetric character inheritance. International **Journal of Plant Sciences** 172:423-433.

Thomasset, M., T. R. Hodkinson, G. Restoux, N. Frascaria-Lacoste, G. C. Douglas, and J. F. Fernandez-Manjarres. 2014. Thank you for not flowering: conservation genetics and gene flow analysis of native and non-native populations of *Fraxinus* (Oleaceae) in Ireland. **Heredity** 112:596-606.

## BOOKS AND BOOK CHAPTERS

Fernández-Manjarrés, J. F., and M. Benito-Garzón. 2015. El debate de la migración asistida en los bosques de Europa Occidental. Pages 463-468 in H. A. and Z. M. A., editors. Los Bosques y la Biodiversidad frente al Cambio Climático: Impactos, Vulnerabilidad y Adaptación en España. Ministerio de Agricultura, Alimentación y Medio Ambiente, Madrid.

Leadley, P., H.M. Pereira, R. Alkemade, J.F. Fernandez-Manjarrés, V. Proença, and J.P.W. Scharlemann et al. 2010. Biodiversity Scenarios: Projections of 21st century change in biodiversity and associated ecosystem services. Secretariat of the Convention on Biological Diversity, Montreal.

Sansilvestri, R., S. Roturier, B. Colas, J. Fernández-Manjarrés, and N. Frascaria-Lacoste. 2015. Intégrer le facteur climatique dans la compensation écologique : l'exemple des écosystèmes forestiers.in L. Harold, F.-L. Nathalie, H. Julien, M. Gilles, and P. Sylvain, editors. Restaurer la nature pour compenser les impacts du développement. QUAE.

Thomasset, M. J. F. Fernández-Manjarrés, G. C. Douglas, N. Frascaria-Lacoste, and T. R. Hodkinson. 2011. Hybridisation, introgression and climate change: a case study for the tree genus *Fraxinus* (Oleaceae). Pages 320-344 in M. B. J. Trevor R. Hodkinson, Stephen Waldren, John A. N. Parnell, editor. Climate Change, Ecology and Systematics. Cambridge University Press, United Kingdom.

**ONLINE PUBLICATIONS (PEER REVIEWED)**

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Proença, and J. Fernández-Manjarrés. 2015. Regime Shifts in Social-Ecological Systems. Actionbioscience. www.actionbioscience.org, http://www.actionbioscience.org/environment/proenca_fernandezmanjarres.html.

## 2. Introduction

This document is organized in a very simple form. First, I describe my research approach and why I reach for interdisciplinary research and interdisciplinary collaborations. The interdisciplinarity arises from using public policies as a boundary object and from the need of dealing with ecological and social indeterminism (uncertainty) when planning for the long term. All of these concepts will be developed below and as clearly as possible for reviewers with different backgrounds. Next, I describe my current research that is centered on three public policies intended for the adaptation of forests to climate change that are perceived as ecosystem perturbations: a) the assisted migration of tree species in managed forests in temperate areas; b) fuel-wood energy policies in the Mediterranean; and c) the development of agro-forestry in tropical zones viewed as an adaptation option to cope with social unrest. I finalize the document with a discussion about the emergent idea of social-ecological restoration as a unifying concept for the recovery and long term adaptation of social-ecological systems.

I purposely omitted in this document one very important part of my earlier research concerning the natural hybridization process in tree ashes (*Fraxinus excelsior* L. and *Fraxinus angustifolia* Vahl, Oleaceae) as today it is a finished research venue although, you never know if old passions come back in the future.

## 2.1 Research question and interdisciplinary research

I currently summarize my research as:

- *The development of concepts and tools for understanding and implementing long term adaptation of social-ecological systems[1] in a changing world*.

Please note from the beginning that in the context of this document and of my research, 'adaptation'[2] is referred as the local decisions and actions people make in managed ecosystems to adjust to new conditions caused by climate change and changes in land use, among others. It is different from Darwinian adaptation[3] processes as change is intentional, and of course all the mechanisms are different.

To develop my line of reasoning, I will explain first why interdisciplinary research is needed to address the kind of questions I ask. The first consideration is that management problems face two different levels of uncertainty that are better understood with different disciplines. The second consideration for undertaking interdisciplinary approaches is the choice of a social-ecological system as a study object.

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[1] The most common definition of social-ecological system is "…integrated systems in which people interact with natural components…" Liu et al. (2007). But see discussion in the text.

[2] As noted by the IPCC in 2014, adaptation is "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects".

[3] The process of evolutionary modification which results in improved survival and reproductive efficiency (from Lincoln et al. 1998, A dictionary of Ecology, Evolution and Systematics, Cambridge, 361 pp.)

When managing ecosystems for the long term, two different sources of uncertainty interact: *ecological* (natural) and *social indeterminism* (Tyre & Michaels, 2011; Michaels & Tyre, 2012). These authors define these terms very clearly, so instead of reformulating I will cite them verbatim:

> "*Natural indeterminism is the form of indeterminism familiar to ecologists arising from, for example, changes in the environment, demographic stochasticity, and not knowing which of two or more hypotheses is more correct. Social indeterminism arises from at least three attributes associated with human activity: random process, shortsightedness and intentionality*" (Michaels & Tyre 2011, p290).

This view implies that many management programs occur within a feasibility gradient determined by the levels of unknowns of ecological and biological knowledge and the levels of social unknowns that need to be understood and accepted as often human process are unpredictable (stochastic) and even irrational in intent (Figure 1). **The longer the temporal scale of the ecosystem in question, the larger both types of uncertainty become.** Of course, what these authors call natural indeterminism could be decomposed in stochastic events (ecological uncertainty *sensu stricto*) within ecosystems and uncertainty related to the current degree of knowledge of a system (uncertainty in the sense of not having enough evidence to make a decision), but for coherence with the source, I will keep them together.

This framework is my starting point for conducting research requiring concepts and methods from fields different from ecology when facing a management problem, like species choice for managed forests under climate change. This approach requires not only an understanding of the ecology and demography of the species in question (ecological indeterminism) but also of the content of public policies, the way they are perceived by different actors, the reasons for which they are implemented or not (social indeterminism), and of course, the potential ecological impacts of the interaction of these types of uncertainty in the long run. Please note that in this document, I will use uncertainty and indeterminism interchangeably.

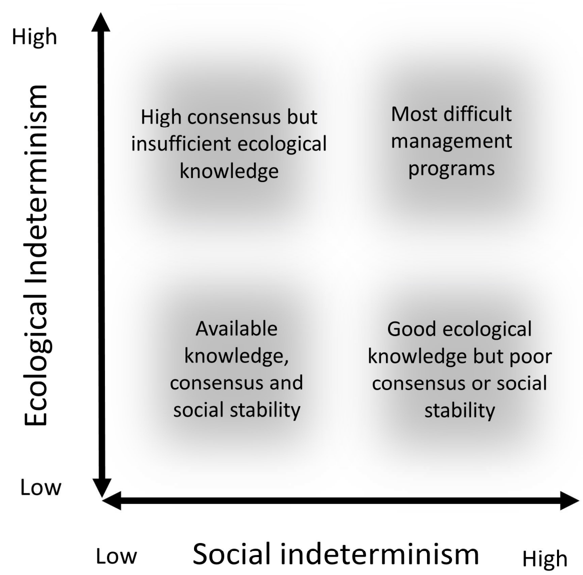


**Figure 1**. Modified conceptual model of Michaels and Tyre (2012) that shows how management programs for which ecological (natural) indeterminism is the highest, as well as social unknowns are very high, are the most difficult to implement.

Accepting that ecosystem management problems involve two different kinds of uncertainty or indeterminism (ecological and social), strongly suggests that the use of interdisciplinary approaches is necessary. Interdisciplinarity research can be a very confusing concept but once a working definition is accepted, it allows for conducting a research program in an organized way.

For my work I use a general definition like that of the U.S. National Science foundation[4] that needs to be clear enough to guide researchers when submitting proposals:

- "…*Interdisciplinary research is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice...(Porter et al., 2006)*"

In principle, interdisciplinary research is conducted through the use of **'boundary concepts**' or '**boundary objects**' (Star & Griesemer, 1989). Boundary concepts are ideas that are well defined within a field but general enough to be used in different fields. A typical example is resilience (Brand & Jax, 2007; Baggio et al., 2015), which is used in the field of material properties, engineering, psychology and ecology, among others. Boundary objects are elements like species, processes or part of ecosystems, or even human practices, which are perceived differently by different actors, but that represent a common object of research (Star & Griesemer, 1989; Hertz & Schlüter, 2015). For instance, forests in Europe are perceived as carbon stocks by policy makers concerned with international agreements, as a long term investment for foresters, as landscape values by citizens and as biodiversity repositories for scientists concerned with endangered species. In practice, however, it is more frequent to start only from boundary objects because boundary concepts are more difficult to come by.

To provide a familiar example of interdisciplinary research to ecologists, we can take a brief look at the field of 'molecular ecology'. According to the journal Nature[5], molecular ecology

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[4] https://www.nsf.gov/od/oia/additional_resources/interdisciplinary_research/definition.jsp
[5] https://www.nature.com/subjects/molecular-ecology

is "…*the use of molecular genetic tools to study ecological questions*". Here, the molecular tools (sequences, neutral markers, gene products, …) serve as a boundary object to answer ecological questions as migration rates for a given species. In this context, Sewall Wright's (1889 – 1988) infinite island model would be a founding concept in the field that works as a boundary concept allowing to ask genetic (correlation of alleles at different levels) and ecological questions (migration and population effective size). With the advent of sequence data, methods began to be refined in the 1990's to take advantage of the evolutionary information contained in DNA sequences (Hudson et al., 1992), and several methods have been developed since (see for example Samarasin et al., 2017). More importantly, this example highlights that frequently, ***interdisciplinarity emerges from related fields within a broad discipline and that it is more difficult to emerge between distant disciplines***.

In my own research, I use forest ecosystems (semi-natural and human-made) as a boundary object upon which I look for concepts that are relevant for minimizing ecological and social uncertainty during their management. In the case of assisted migration of forests, the precautionary principle was identified as a possible candidate along with the concept of 'provenance' that has both a legal and biological interpretations (see section 3). Hence, my original research question can be rephrased in a more general form as:

- How can we minimize ecological and social uncertainty through new concepts and tools for understanding and implementing the long term adaptation of social- ecological systems in a changing world through interdisciplinary research?

## 2.2 Social-ecological systems (SES) as the research object

It can be argued that after the idea of resilience of ecosystems[6] (Holling, 1973), the next major concept to appear was that of social-ecological systems or SES, if the concept of resilience was to be applied to the interaction of human societies and their supporting ecosystem. In fact, we can say that it was a real necessity to create this concept of an extended-ecosystem, so that all the studies that began to see humans as important in the structure and function of ecosystems could have a unifying concept. Clearly, this was to a large extent a 'discovery' for the ecological sciences, but many disciplines before had already integrated the notion of humans as part of ecosystems, as is the case of anthropology, ethnography, cultural ecology and of course geography, among others examples.

Let us look first into a little history of the SES concept. C.S. Holling was not the person that coined the term social-ecological system, but one of the first to use it widely (Holling, 2001; Folke et al., 2002; Walker et al., 2004; Olsson et al., 2006). A WEB of Science topic research and a SCOPUS database research performed at the time of writing (early 2018) found that the oldest explicit reference for SES occurs in 1969 from a M.Sc. thesis by E.D. Ratzlaff entitled 'Applications of engineering systems analysis to the human social-ecological system' from the University of California at Davis. The next record appeared then in fields as different as psychology (Coleman 1971), followed by Ellen and Burnham in 1979 Current Anthropology who edited the same year

[6] " ….Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb change of state variable, driving variables, and parameters, and still persist…" (Holling, 1973)

an A.S.A. monograph on the subject. During the 80's, and early 90's one article in epidemiology about "The system of epidemic process" (Cherkassikii, 1988) and two primatology (Emory, 1988; Dumbar 1991) appear in the databases. Probably the first mention of SES as we understand it today appears to be that of Bachainskii (1990) when using remote sensing over a region in Ukrainia, but I have no access to this publication.

The current use of SES as we understand it today (i.e., as a complex adaptive system between humans and the supporting ecosystems) probably happened in a series of articles that were co-authored by the economist and Nobel Prize winner Elinor Ostrom (1933, 2012), that deeply marked the field in the following decades up to these days. The first one that appears clearly with the expression "social-ecological system" was by Wilson et al. (1999) where they analyze the problem of mismatching the scope of human decisions with the spatial and temporal scale of natural processes. Afterwards, between the year 2000 and 2017, more than 1000 papers have been published according to Web of Science at the time of writing (early 2018, results not shown).

- In the current understanding of SES as found in the literature, "social" stands for both the *governance* and *economic* structures and dynamics related to the use of resources by a group of people.

But in my opinion, the popular definition of SES as "complex adaptive systems" (Liu et al., 2007) has opened lots of research agendas that have blindly embraced the systems approach for looking at emergent properties[7], like resilience, adaptive capacity[8] and transformability[9] (Folke et al., 2010). These concepts, while easy to define for simple systems, become abstract properties that **are very difficult to demonstrate in practice because they are defined as emergent properties of the whole system (that we can never measure) and because they need to be monitored over long periods of time (i.e., you need a time machine to travel in time)**. In consequence, because we cannot measure these properties directly, the literature is full of studies that rely on 'indicators' or 'surrogates' of these abstract properties (Carpenter et al., 2005). My former doctoral student Roxane Sansilvestri had to use the same approach for parts of her dissertation as we wanted to estimate the adaptive capacity of different forest regions in France (Sansilvestri, 2015). The exercise proved extremely difficult, and almost 70 indicators were needed to draw a picture of how different actors could cope with the long term challenges posed by climate change.

Because of the difficulties of using a systems approach at all levels, I am using a working hypothesis that avoids the use of systems theory in its definition for SES:

> "*Ensembles of human and non-human populations that share the same space, in which their interactions produce structures and dynamics that otherwise would not exist* (Fernandez-Manjarrés, unpublished)".

This definition explicitly avoids the use of 'complex adaptive systems' and related concepts like those found in Levin et al. (2013) because of the difficulty of demonstrating emergent

[7] Properties of the whole system that are not found on the individual components. Usually described as "the whole is more than the sum of the parts".

[8] The capacity of actors in a system to influence resilience (Folke et al. 2010)

[9] The capacity to transform the stability landscape itself in order to become a different kind of system, to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable (Folke et al. 2010)

properties as mentioned earlier in the social components of the definition. It also solves *de facto* a research program that will invariably invoke resilience as a research objective when addressing SES as adaptive systems. In fact, this definition allows to concentrate on the evolution (in the broad sense) or trajectory of the relation between humans and non-human components in the supporting ecosystems. Pushing forward this definition, I could use the expression ***social-ecological ensembles*** to avoid completely the use of 'system', but for clarity and coherence with the literature, I retain for the time being the term SES, bearing in mind that I do not reject the ideas of complexity, just the difficulty of using them when social dynamics are involved. Clearly, this is a working definition adapted for **local scales** and apt for dealing with studies where the human population group is clearly defined as well as the resources they are using.

By explicitly stating the condition of a *shared space*, an idea that is fundamental in geography and in sustainability science for example (Matthews & Herbert, 2008; MacGillivray & Franklin, 2015), my definition narrows the use of the term to smaller geographical areas. In fact, it can be argued that for many uses, SES is similar to a territory, or that at least, shares many of the characteristics. This analysis was brilliantly made some years ago by the French geographer Alexandre Moine who actively embraced the territory as a complex system:

> "*le territoire est un système complexe évolutif qui associe un ensemble d'acteurs d'une part, l'espace géographique que ces acteurs utilisent, aménagent et gèrent d'autre part*" (Moine, 2006).

While I agree with Moine's overall view (that is in fact a practical view to enhance the use of the term territory) I am less inclined to see everything as a complex system. The continued process of irrational decision making, i.e., irrational as going against the same human species, makes me doubt as how much SES can respond and adapt to external and internal drivers. Nevertheless, from geography, as Moine did, I recover the idea of space and place (*territoire*) for my own definition. The idea of shared spaced is also linked to the frequent use of the term SES within the context of the resource users of the commons[10] (Ostrom, 2007; 2009) in which people can self-organize to use the resource and avoid its depletion (Figure 2).

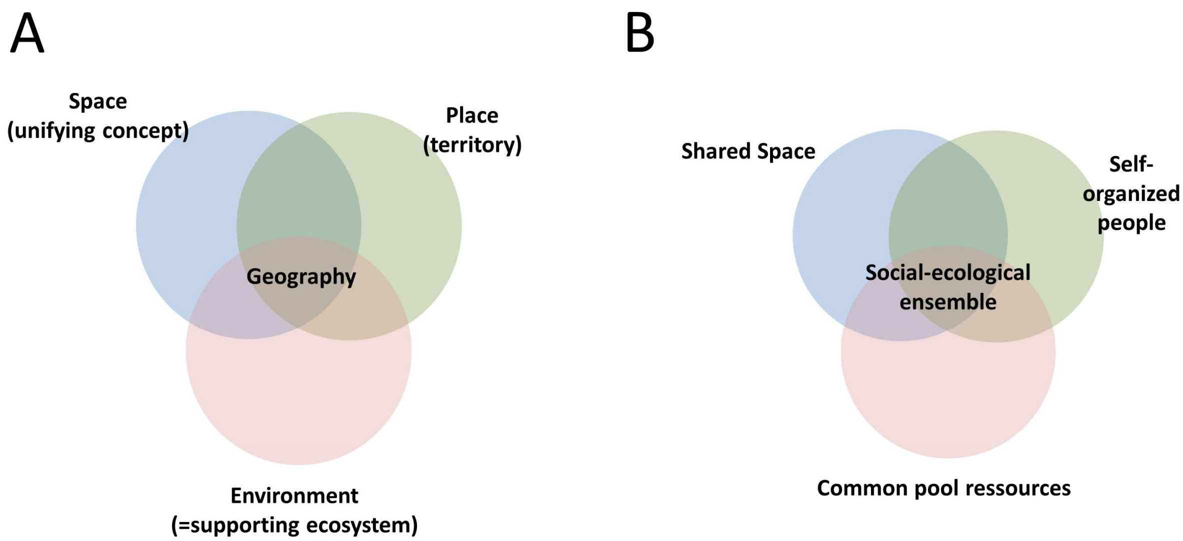


**Figure 2.** Parallel between the core concepts of geography according to (Matthews & Herbert, 2008) and the concept of social-ecological ensemble when used in the framework of Ostrom

This spatial restriction, or better, the notion of space as in geography, is to avoid ambiguity with a) the loose definition of SESs to almost continental areas where the recent concept of

[10] A commons (or a common-pool resource (CPR) in economics) is a type of good consisting of a natural or human-made resource systems (e.g. an irrigation system or fishing or forestry area) that makes it very costly to exclude other users.

antrhome[11] (Ellis et al., 2010; Ellis, 2011) would be more suited; and b) the use of SES for highly human populated areas like cities which in my opinion are better described as urban systems[12] because of their own particularities. I agree that drawing a line into what constitutes a SES and a urban-system can be very difficult. The former can be thought of being mostly self-sufficient, while the latter highly dependable on imported food, water, goods and energy. So again, for practical reasons, I refrain to the local scale of the definition, looking into areas that are mostly rural where forestry and related practices are dominant.

It is also important to note that this general definition allows for greater interdisciplinarity. By avoiding the use of complex adaptive systems theory in my definition of SES, it allows me to detect more freely the causes of social uncertainty and to dialogue better with colleagues from social sciences as the system approach is not frequent and allows me for a more inductive approach, more typical of social sciences (Bennett et al., 2017). In fact, the systems view remains controversial for many researchers of the social sciences (Baecker, 2001; Olsson et al., 2015). The systemic, neutral view of resilience of SES viewed as complex systems has been explicitly criticized as highly incompatible with many current approaches in social sciences as it does not explicitly address human behavior particularities, sources of conflict, knowledge, and power asymmetries (Olsson et al., 2015).

[11] Anthropogenic biomes that refer that current biomes need to integrate the human modifications.

[12] Areas characterized by a high density of human populations and human construction, where primary ecosystem productivity is slow and energy, water and goods are imported. These areas produce and export large amounts of pollutants, used water and non-recyclable waste including construction debris. In urban systems the population is detached from a direct relation with supporting ecosystems and depend on others.

In the next section, I will analyze a major issue that conditions to a very large extent the trajectories of ecosystems: public policies.

## 2.3 Ecosystem management and public policies

Management programs within SES do not emerge randomly and are highly tight to public policies that seek specific goals. Public policies are difficult to define (even more for an ecologist) but a general definition useful for our purposes can be adapted:

> "*Public policy is a course of government action or inaction in response to public problems. It is associated with formally approved policy goals and means*" (adapted from Rose, 2005).

The type of public policies I am interested in are those related **to the adaptation of forest ecosystems to climate change**. These public policies can have lasting ecological consequences on forests and other ecosystems as they can change species composition, productivity, alter mineral cycles, physical structure, etc. for centuries to come (Fernandez & Tchanz, 2010), just as perturbations like fire, floods, or invasive species and pest outbreaks do. For instance, natural, semi-natural and highly managed forests in Europe are currently managed for contradictory goals related to climate stabilization, carbon sequestration and green biomass because of the multiple engagements by many countries in the world to reduce and eventually reverse climate change (see for example Makkonen et al., 2015 and references therein).

The type of public policies I am interested in are **adaptation policies**[13]. When working with forests ecosystems that act as carbon sinks, stabilize climate, harbor biodiversity, protect water sheds and so forth, it is difficult to avoid the influence of adaptation policies. Global and local concern that the impact of human activities are going too fast and everywhere makes this kind of policy frequent at many levels, but not always. In the particular case of climate change, adaptation policies are often opposed to mitigation policies (i.e., to tackle directly the sources of climate change), and to a large extent there is a consensus that a good policy for the climate should envision both. To some extent, adaptation/mitigation policies are possible with forest ecosystems (Thuy et al., 2014) but there is no consensus about this.

Also, the choice of starting the question from a public policy perspective may seem surprising for someone whose main discipline is ecology, conservation biology and botany. This vision has very likely emerged from personal experience and from my early years as a biologist in Colombia. From 1990 to 1995, I worked intermittently with the regional government that managed both the energy production by making river dams and the conservation of the 'other' natural resources, basically the vegetation of the basins for water production. In that organization, I had the responsibility of maintaining a database and synthetizing data for endangered plant species and ecosystems. As the reader can imagine, it was a quite complicated situation as biologists were (and still are) viewed as opposed to 'development'. The expressions '*politicas de desarrollo*', '*politicas de seguridad electrica*', '*politicas de seguridad alimentaria*' (policies of development, energy security and food security, respectively) and many others, were

[13] Adaptation policies are public policies, national or international, that seek to prepare ecosystems and societies to ongoing or future challenges related to global changes (my own definition).

heavily bounding the efforts of the small team I was working with. Since then, many policies in Colombia and elsewhere have been created, but habitat destruction and species overexploitation have not stopped but have actually increased. Things seem to have changed little. After this small digression, let me go back to the central idea of policies binding ecosystem management.

The fact is that managing ecosystems for their restoration is not only heavily bounded in our current world by public policies but also by the way people perceive these policies. For example, during our work with forest adaptation to climate change, questions like "*how can I manage my forest because if I change species because of climate change, I will violate current European policies of forests genetic resources and loose my subsidies?*" emerged frequently, showing how public policies (or the lack of them) complicates the everyday life of ecosystem managers (Sansilvestri 2015).

In my research, I consider then that certain public policies become effectively *ecological perturbations* because they either lock in the systems in obsolete management practices or push the stakeholders to engage in management practices that have not been sufficiently tested or evaluated (we will see this in the section describing the wood fuel energy programs). Moreover, public policies directly affect the governance of these ecosystems (in the sense of Robertson & Choi, 2010) that is an essential component of the SES concept.

Hence, given the different impacts public policies have and how different actors perceive them (including researchers of course) I consider that public policies can act as a 'boundary object' to conduct interdisciplinary research as explained above. For institutions, they represent the limits of their actions but also the right to perform certain actions. For the researcher and the ecosystem manager, a public policy must be interpreted in ecological terms. For the different stakeholders in general, policies are both opportunities and threats and will be accepted or refused if found against their own convictions. In fact, without making it an intentional approach, it has become central to my work to understand all the nuances related to public policy interpretation by stakeholders as this is a key component of social indeterminism regarding ecosystem management.

As I will explain later, the choice for addressing public policies would be a comparative, mechanistic, hypothesis-free approach in which the object of study are the different instances of implementation of a given public policy (Rose 2005), like forest management programs in different parts. We will see this when I address the example of assisted migration: who is implementing it? Why they are doing it or not? And so forth. For this line of research I am immensely indebted with the work of my former PhD student, Roxane Sansilvestri.

Hence, to summarize the role of public policies in my research, I can further refine my research question in the following terms:

- How can we minimize *the effects* of ecological and social uncertainty through new concepts and tools for understanding and implementing the long term adaptation of social ecological systems in a changing world?

Before I describe my work in more detail, I will very briefly address the need for an improved ethical perspective for the study of SES.

## 2.4 The need for an ethical perspective for the SES concept

So far, we have seen that both the popular definitions of SES as complex adaptive systems and my own definition, lack any explicit reference to an ethical framework. Should we simply accept that some SES will do better and secure more resources than other SES? Should we simply accept that the continued interaction of humans and the services they benefit from ecosystems will produce impoverished landscapes where only useful species are present? In other words, is a central working concept like SES desirable to be used for training students without any ethics regarding the **human-human interactions** or the interactions of **humans and other species**? Each of these questions has become a field in itself, addressed by currents like political ecology[14] and biodiversity ethics (Schroter et al., 2014; Ramp & Bekoff, 2015; Sarrazin & Lecomte, 2016). As noted earlier by Olsson et al. (2015), a neutral view of resilience and social-ecosystems as a systemic process can allow for political discourses that mainstream these ideas as political agendas without really addressing poverty issues for human societies. I do not intend to review any of these issues here, but just to mention that some of these aspects are dealt with through the concept of social-ecological restoration as discussed in Section 5. Having said that, our laboratory where I conduct my research with various colleagues is examining these questions, so any student that I will train at the PhD level will benefit from the insights they can give.

My own position is based on a strong interpretation of the precautionary principle, in which I consider that all species, known and unknown to science, are important and necessary for the maintenance of life on Earth, and that efforts should be done to minimize the impact of humans on ecosystems, including the reduction of human population growth and per-capita resource consumption in both developed and developing countries.

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[14] The study of the relationships between political, economic and social factors with environmental issues and changes. Definition adapted from http://environment-ecology.com/political-ecology/407-political-ecology.html

## 3. Summary of previous Doctoral training

My current doctoral training experience can be divided in two parts. The first part is related to PhD work that I closely supported for two students relating to the ecology and management of natural hybrid populations of ash. A big part of this tutoring occurred during my post-doctoral years. These collaborations led for the publication of various articles and one book chapter (Thomasset et al., 2011; Temunović et al., 2012; Temunovic et al., 2013; Thomasset et al., 2013; Thomasset et al., 2014). In these publications, I frequently appear as last author, something I had to negotiate with the 'in-house' tutors that were not very involved with these students. Finally, in 2008, I finished co-tutoring a colleague in Colombia, Rosalba Ruiz, for her PhD thesis on the genetic diversity of *Opuntia*, species (the *Cactus* family) from Northern Colombia.

My first intensive involvement in a PhD training resulted from the ANR financed project AMTools[15] that stands for: "*Outils écologiques et légaux pour la migration assistée des forêts*". This project, centered on the idea of "assisted migration" for forest trees because of climate change (see next section) required a series of partners and competences to be able to advance on all the different ecological and social unknowns. The ecological unknowns were clearly detected since the beginning: how can we estimate the adaptation to new climates for tree populations that are moved from a source population to a target place? The bulk of this work (Benito-Garzon et al., 2013a; Benito-Garzon et al., 2013b; Benito-Garzón & Fernandez-Manjarrés, 2015; Fernández-Manjarrés & Benito-Garzón, 2015) was carried out by the post-doctoral

[15] http://www.agence-nationale-recherche.fr/projet-anr/?tx_lwmsuivibilan_pi2%5BCODE%5D=ANR-11-AGRO-0005

researcher at that time, Marta Benito-Garzon, with whom I continue to collaborate (Benito-Garzón et al., 2018a; Benito-Garzón et al., 2018b).

Addressing the social-uncertainties in this context of the ANR were more complicated. For the ecological part, what really hold us up was the lack of sharing of what is called in the forestry world 'provenance tests'. These tests are common gardens of several tree populations that are planted along climatic gradients and allow to understand the correlation between climate, growth and survival that later can be used in models, as we did recently with the umbrella pine data, thanks to Bruno Fady from INRA-Avignon (Benito-Garzón et al., 2018a). The social uncertainties that were identified at the beginning of the project were: a) a weak legal framework that favored the local use of forest genetic resources, despite growing concerns that they might be maladapted; b) a strong misunderstanding of the role of the precautionary principle in the debate of assisted migration; c) the reasons why the concept of assisted migration is really being applied at different levels in North America and not so much in France; and d) the role of a heritage ('*patrimoine*') vision of the forest in France despite the long management tradition, as is the case in the Landes which is largely artificial, as barriers to adaption to climate change.

All the above issues (except the first that was addressed in a M2 by Louis Tschanz) were brilliantly handled by Roxane Sansilvestri during her PhD[16] . In her first article, she addresses the problems with the misinterpretation of the precautionary principle as a decision tool by conservation biologists, and provides a framework, that includes experimentation when possible

[16] http://www.theses.fr/2015SACLS257

for the translocation of populations (Sansilvestri et al., 2015). Second, the comparative analysis between North America (consisting of 4 provinces in Canada) and France provided a very interesting angle for understanding why certain policies seem to fail in one place and work in others (Sansilvestri et al., 2016) as it will be explained next. For doing her PhD, Roxane had to reach for help in the methodology of field work with faculty from the Sorbonne School on Geography, on the person of Laurent Simon, with whom I am very grateful.

# 4. Research program: from public policies to long term ecosystem management

As explained in the introduction, my research is constructed around an arbitrary choice of public policies that can have direct impact on ecosystems, and that is because of their long term implementation, involving both large ecological and social uncertainties.

## 4.1 Assisted migration in managed forests

Assisted Migration (also known as assisted colonization and managed relocation) has been one of the most illustrative recent management ideas that have 'escaped' the realm of applied ecology and conservation biology and reached the level of public policies. Because of harsh controversies within the conservation biology field and even within the forestry field that one would think are used to moving trees around, it constitutes an excellent 'boundary concept', that is itself related to concepts such as the precautionary principle. In this context the concepts of a 'biological population' and' local adaptation' from the field of conservation biology, became also boundary concepts as they require legal interpretations. In the case of forest genetic resources, a local population adapted to a given environment is considered a 'provenance', and it is in those terms that it appears in public policies, like for the European Union[17]. A visual summary of this line of research is presented in **Figure 3**.

[17] Council Directive 1999/105/EC of 22 December 1999 on the marketing of forest reproductive material

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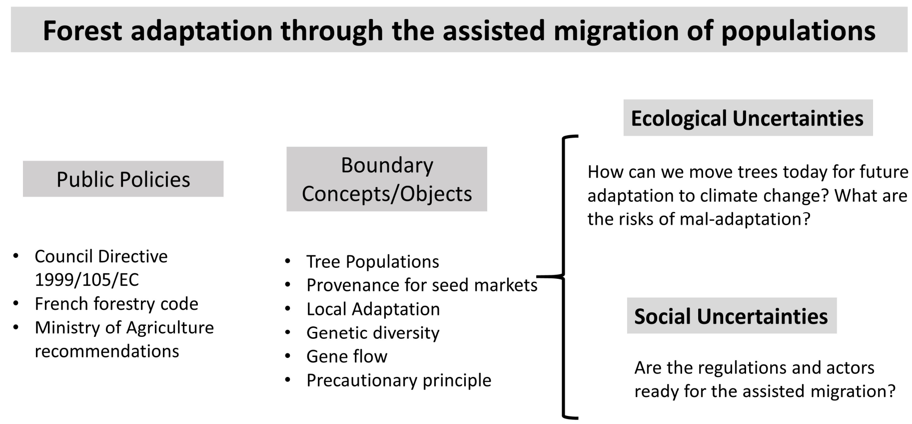


**Figure 4**. Summary of policies and boundary concepts and objects related to the assisted migration of trees.

When we started the assisted migration project in 2010, several issues remained unsolved, creating in the literature very long and sterile debates based on the known flaws of the use of the precautionary principle, the lack of any technique to use ecological data to create scenarios of assisted migration, the recognition of the limits of the idea of moving seeds and individuals even for commercial forests, and the lack of a framework for making decisions under uncertainty. It goes without saying that this work would have been impossible to do without Louise Tschanz (a master intern from the Sceaux School of Law), Roxane Sansilvestri (a PhD student co-tutored with Nathalie Frascaria-Lacoste) and Marta Benito-Garzón (now INRA based researcher), first as a post-doctoral researcher paid by the ANR and then as a Marie Curie fellow.

This work allowed for the first time a Canada/France comparison of how the application of a public policy imagined by ecologists has impacted, both positively and negatively the attitudes of the stakeholders towards managed forest adaptation to climate change. In this case, the 'applied public policy approach' of Rose (2005) was used. Rose uses "programs" as the unit to be studied, by asking questions of why, how, when a program started, was funded and if it was successful or not. In turn, the researcher has to detect the underlying mechanisms based on the first description of the program. In a way, this approach is similar to comparative studies in ecology. This practical approach (that to a large extent is inductive one goes there and see how a program works) is a first step for understanding the complicated processes that exist behind the implementation of public policies. In the context of interdisciplinary research, this inductive approach to examine programs is useful as it provides a framework in which an ecologist can evaluate wether a public policy is doing what is supposed to be doing (i.e., protecting diversity and ecosystem function) while giving a first glimpse into the politics behind these programs.

Many interesting results emerged from the comparison of different programs in Canada and in France: The "new world" vision of certain areas of Canada where complete forest removal is permitted, contrasted sharply with a conservative vision of forest adaptation in France where continuing current practices seem to reassure many actors (**Figure 4**). At the time of writing, assisted migration programs are arising very timidly in France, so it is too soon to evaluate if they have been successful or not. A very interesting experiment has been initiated for the trees of Verdun[18], but the experience was kept 'secret' from us for unknown reasons.

[18] http://www.lemonde.fr/planete/visuel/2016/07/29/derniere-chance-pour-la-biodiversite-les-arbres-de-verdun-premiers-deplaces-climatiques_4976100_3244.html

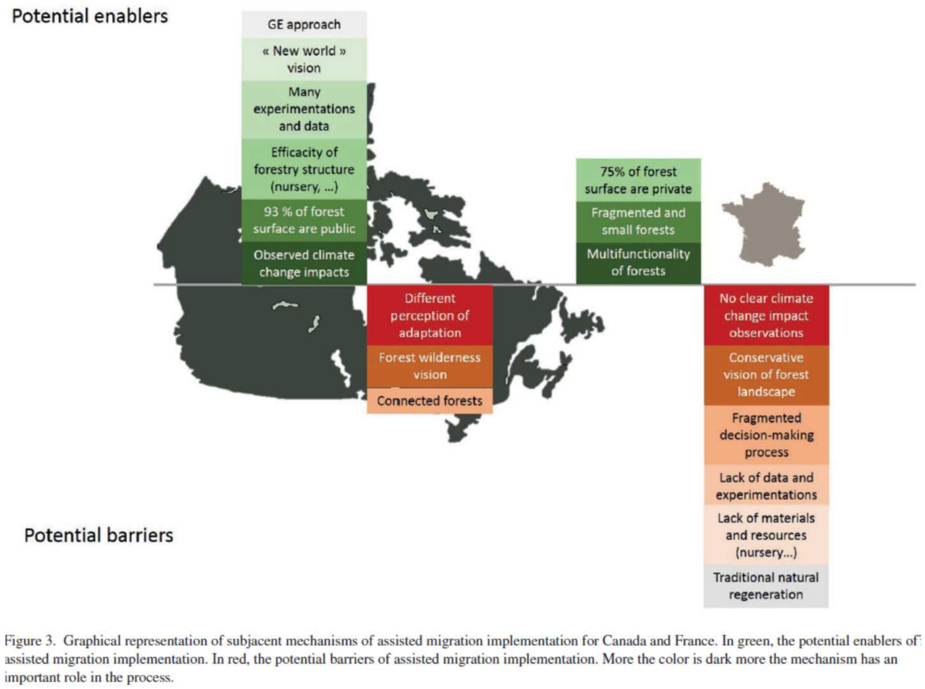


**Figure 4**. Summary of the differences between Canada and France regarding the context for the implementation or not of assisted migration in managed forests.

## 4.2 Mediterranean forests and biomass energy policies: a dysfunctional couple?

This line of research emerged from the main results of the thesis by Roxane Sansilvestri: more than climate change, certain regions in France can be potentially more affected by biomass policies than by climate change itself. Biomass policies to comply with international and European agreements and goals, distort the vision of multi-functionality of forests in France. For instance, the Directive 2009/28/CE (2009) of the European Union (EU) defined the common objective to reach 20% of renewable energies by 2020 for all EU countries. This means that in France these goals represent an increase of 13% of renewable energies production by 2020. In addition, France ranks first in Europe for wood energy consumption, both for household heating and the industrial electric power generation and heating (Sansilvestri et al., in preparation). **Figure 5** summarizes the framework of this work.

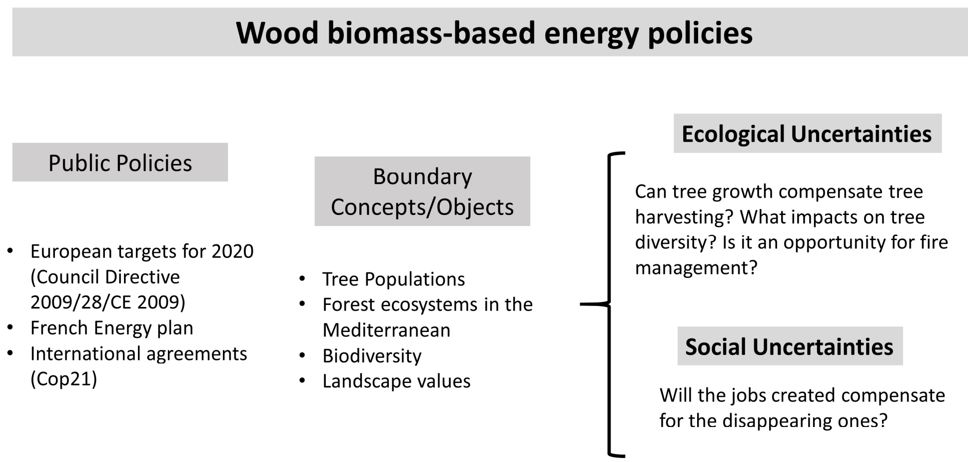


**Figure 5**. Summary of policies and boundary concepts and objects related to the use of forest wood as biomass for energy or heat production

It is not difficult to imagine that if biomass for boilers becomes the main use of the forests, this will lead to a simplification of ecosystems by planting only a few species of rapid growth and high caloric content like certain conifers, the closing of the different value chains that use forests for different wood products, a loss in landscape qualities, and probably a loss of true forest ecosystems, as wood energy requires more a kind of young tree rather than wood issued from a multilayer structure.

These issues are addressed in a multidisciplinary project with economists from the Observatoire from the UVSQ using the Provence-Alpes-Côte-D’Azur region (PACA) in Mediterranean France, where public policies related to diminishing dependency on oil products and for creating jobs are acting as a major perturbation of the system. In this research, I am ‘wearing my hat’ of ecologist, doing large scale estimates of different wood sourcing strategies over the region. For doing that, I basically use a database of more than 50000 trees that I use to estimate the position and abundance of species of interest for the boil industry and for which I simulate wood cuts for a short period of 10 to 20 years, using overall measures of forest growth and mortality for the area (**Figure 6**).

In this project, Roxane Sansilvestri is addressing all the social indeterminism present in the region through extensive interview of key actors of the chain of value. At the time of writing this document, we are just collating the results and preparing workshops with focus groups to better understand their points of view. Clearly, my role in this project is to minimize the ecological uncertainty around the sourcing of wood in a very diverse but low productive area.

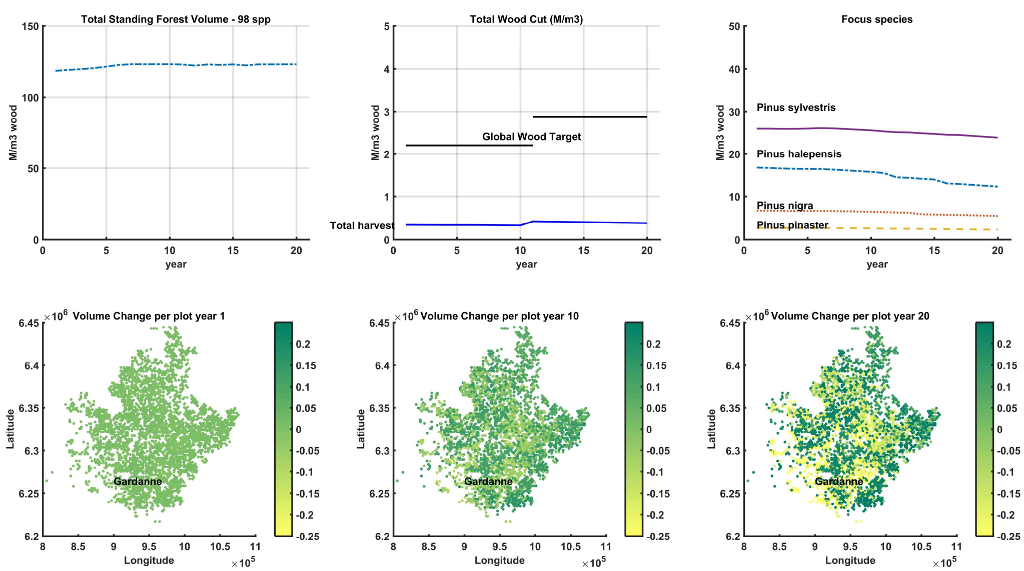


**Figure 6**. Example of the scenarios of wood sourcing simulations for the PACA region based on the expected demand on four foucs species (Fernandez-Manjarrés, in prep.) From left to right and from upper to lower panels: total forest wood is simulated as a stock for 20 years, the wood cut is subtracted, and the volumes of the most important species is recorded. Lower panels show the effect on total wood standing biomass considering the effect of random fires and wood sources.

### 4.3 Agroforestry policies as an adaptation option in Latin America

This line of research is both a continuation of my previous work, but it is also a relatively radical shift. It is a continuation because agroforestry both in Europe (see Hernandez-Morcillo et al., 2018 and references therein) and Latin America (for instance Murgueitio et al., 2011; Anderson & Zerriffi, 2012; Borner & Wunder, 2012; Montagnini et al., 2013; Holmes et al., 2017) is envisioned as an adaptation and mitigation option to climate change that can bring new opportunities to rural communities including indigenous people. And public policies like the Common Agricultural Pact is beginning to accept human-made ecosystems as a valid system to be considered for subsidies and other incentives[19].

It is a departure from my previous work as I have never worked in such systems. Although I have worked with managed forests and semi-natural ones, agroforestry is a big step regarding human management of forest ecosystems. I got interested in the question because as in the case of assisted migration that can be manipulated for political purposes, agroforestry seems caught between two extremes. On the one hand, many people argue for it from a cultural perspective and from a practical point of view: agroforestry systems can be used to control fire in the conditions that climate change seem to be imposing in the Mediterranean. On the other hand, agroforestry seems a public policy that can be easily manipulated to convince the public that the right way of using tropical ecosystems is this kind of management, opening the door to absurd practices as African palm monoculture with the known pernicious consequences: replacing highly diverse forests with homogenous landscapes and displacement of people and large animals, among others.

[19] European Commission A new EU Forest Strategy: for forests and the forest-based sector. Brussels, 20.9.2013 COM(2013) 659 final

Latin America has been traditionally a producer of coffee (*Coffea arabica* in the mountains and *C. robusta* in the Brazilian lowlands), that is known been portrayed as agroforestry too, and, with the current boom of chocolate demand for emerging economies, cocoa trees (*Theobroma cacao* and related species), are filling a new gap in warmer areas where coffee usually does not grow. Moreover, cocoa trees are being regarded also as alternatives to adapt to climate change in areas where coffee plantations are decaying because of droughts and warmer temperatures. In particular, there is an aggressive program of agroforestry in Colombia, where replacing coca plantations (*Erythroxylon coca*) is a main public policy of the country, and where the most likely candidate is cocoa production. As an ecologist working in interdisciplinary research, my approach is different from those of the CIRAD and IRD institutes that have a more agronomic based research programs. As explained before, I am interested in how this kind of agroforestry programs can be managed for the long term allowing for a true adaptation to climate change while securing income for rural people (Figure 7).

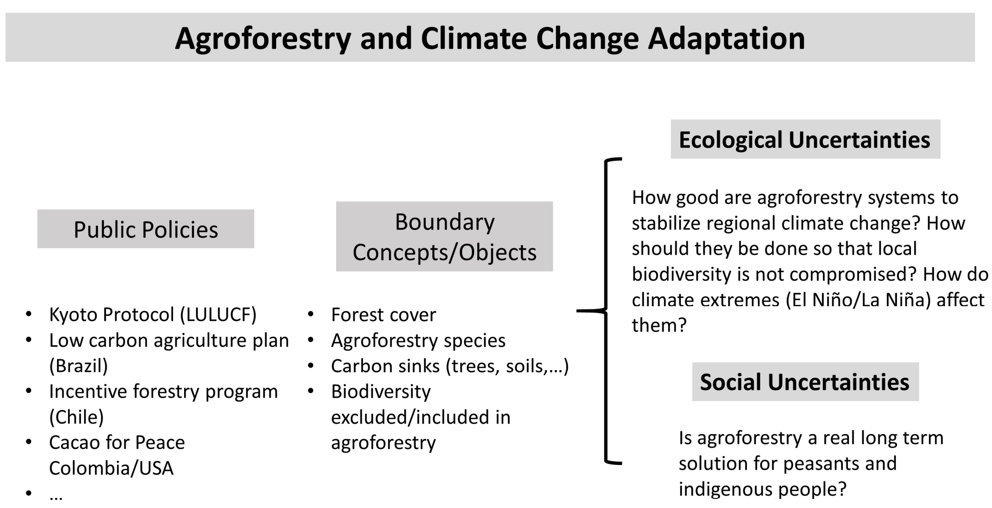


**Figure 7**. Summary of policies and boundary concepts and objects related to programs of climate change adaptation through forestry in Latin America

My research on agroforestry-based systems centered on cocoa has just begun in 2017 in collaboration with Anne-Gaeil Bilhaut, ethnologist, researcher associated to the Institut francais des études Andines in Quito, Armelle Maze, economist (INRA sAdapt)  Isabelle Goldringer geneticist and specialist in participatory plant breeding (INRA-Moulon), and Stéphane Dupas, , genetics of diseases in tropical crops at the IRD Giff. This line of work already produced a Master's thesis by Jilmar Castañeda that visited 4 communities in the upper lands of the Amazon in Ecuador. We are preparing a manuscript to submit later this year regarding how poor organization in these communities does not let them handle climate risks and most importantly, allow them to make a living out of cacao agroforestry.

As explained next, my goal is to start a program around agroforestry as an adaptation option to climate change in Equatorial America, (Colombia, Ecuador and Peru), using as a conceptual framework the ideas I will explain in the next section.

# 5. Future research program: Social-ecological restoration as a unifying concept

In this last section of the document, I present my general approach for future research. This approach is both a continuation of things I have worked on (i.e., adaptation of tree populations to climate change through management) and the starting point for new research venues. Frequently during my career (since I started working in Colombia), there has been instances when the need of ecosystem restoration was in contradiction with solving human needs. And I am not referring to people making money out of ecosystems, but barely surviving and with almost no decent living standards. The ecosystem-centered approach to nature has always bothered me because it involves "cherry picking" (to use a popular expression nowadays) the preferred species in a given ecosystem at the expense of many others, both known and unknown. In addition, it seems, from a probably uneducated perspective, as another way of favoring the creation of economic business for large private groups. For all these reasons, I have been reluctant to conduct active research in aspects involving the concept of ecosystem service as a goal in itself. What I will present next, provides to a large extent a research framework that I have been struggling for many years, and that I hope can aid reconciling ecological restoration programs with people.

In Fernandez et al. (2008, full article provided in the Annex), we argued that there is room for a social-ecological restoration (SoER) concept considered as a problem-solving approach to jointly restore the interdependent social and ecological processes in a social-ecological system. We also argued that this concept and practice are probably more adapted to areas in which the historically strong presence of humans has shaped landscapes and in which present-day human populations struggle to have a sustainable society. The full article, that is short (~3000 words) is provided in the Annex 1 so I will only highlight some key aspects.

First, the term social-ecological restoration was first coined in 2014 by Takeuchi and colleagues in an article from Japan, wrote after the restoration of coastal forests north of Fukushima after the tsunami. In this extreme case, it is clearly exposed how the symbolic values of forests, forest-land, and land sea interfaces (that receive specific names in Japanese, *Satoyama* and *Satoumi*) are as important as the revenues they expect from the supporting ecosystems. In fact, the restoration of the ecosystem is seen as part of a healing process for human populations that have undergone a major disaster. In this paper, we tried to formalize the idea of SoER to make a clear distinction from other restoration initiatives (even if differences can be fuzzy, see **Figure 8**), and argued that the same context applies for human populations that have undergone long and difficult social pressures.

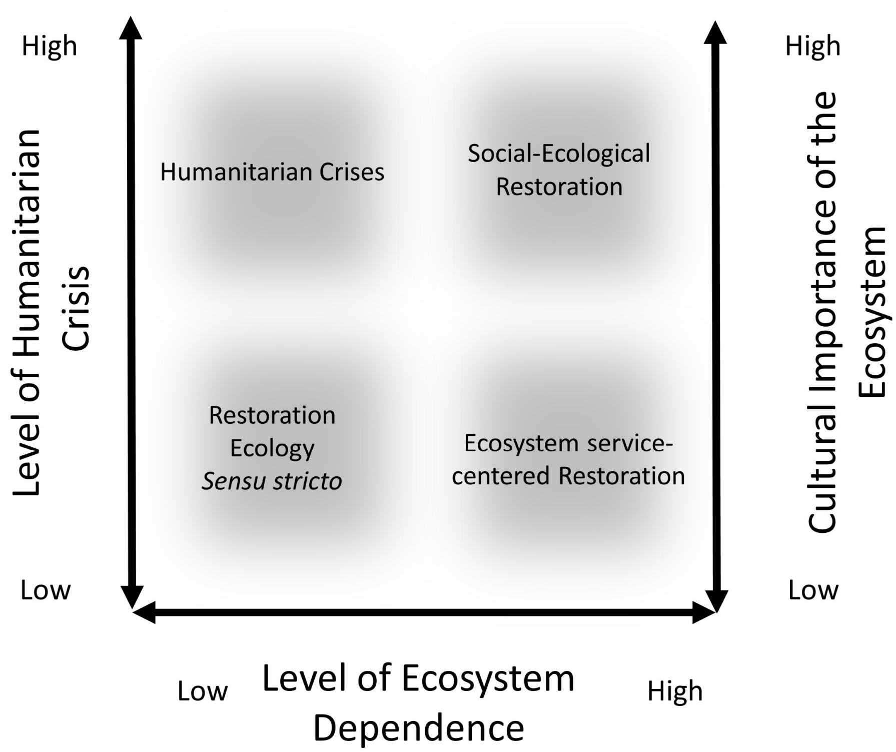


**Figure 8**. Typology of different types of restoration and the placement of social-ecological restoration as a specific activity.

The work that we have started in the Ecuadorian Amazon highlands with indigenous cacao producers (Master's thesis by Jilmar Castañeda, 2017) made us make the connection between ecological restoration and social problems. These indigenous people are struggling to get back a cultural identity while trying to integrate modern Western economies that push them to grow different "cash trees". For the Shuar people in particular, cacao was part of a garden they cultivated within the forest, but was never the key-stone species. Nowadays, they are trapped in public policies that prone forest protection on the one hand and that seek to promote agroforestry as a solution for rural unemployment on the other hand. Hence, we thought that there were clear parallels between the examples of Takeushi in Japan and many people that struggle to have decent living standards and for which ecosystem restoration represents a common goal.

I intend to focus my research program around this concept, identifying different communities in Colombia, Ecuador and Peru, which are three countries that share the same biomes (lowland forests, low-mountain forests and cloud forests). As stated in the previous section, agroforestry is heavily inscribed in public policies in Latin America, with an enthusiasm that seem to ignore many potential pitfalls. In this sense, many questions remain open. I cite here some of them:

- At what **scales (spatial and temporal)** can agroforestry provide the climate change adaptation and biodiversity protection it is supposed to produce?
- What **types** of agroforestry provide the climate change adaptation and biodiversity protection it is supposed to produce?
- How can programs of **social-ecological restoration** be implemented, taking into account the **opportunities/restrictions** from agroforestry policies in this moment to achieve the ambitious climate, biodiversity and social goals?

This work clearly requires the involvement of Aid agencies in these countries and an approach more centered in rural areas, which is difficult from a pure research perspective. At the time of writing I am contacting *the* Agence Française pour le Development and different universities in Colombia and Ecuador, as well as the *Institut Français des Etudes Andines*. My firsts steps in this new open program is to map areas in which agroforestry programs are being created (or already exist), look into the potential biodiversity that these programs may be impacting, and assess the socio-economic status through indicators for Colombia, Ecuador and Peru. Once priority areas have been identified, specific contacts towards those areas will be carried. Then, as explained in our article (Fernandez et al. 2018), extensive and intensive evaluation of the state of the people and of the ecosystems is needed before any actual program (or restoration cycle) of social-ecological restoration may start. For the case of Colombia, much of the research is intended to be carried in the South, where many cacao (*Theobroma* spp.) plantations exist since Colonial times, and they represent a "leading edge" of cacao distribution as it is the one that grows in high altitude (Figure 9).

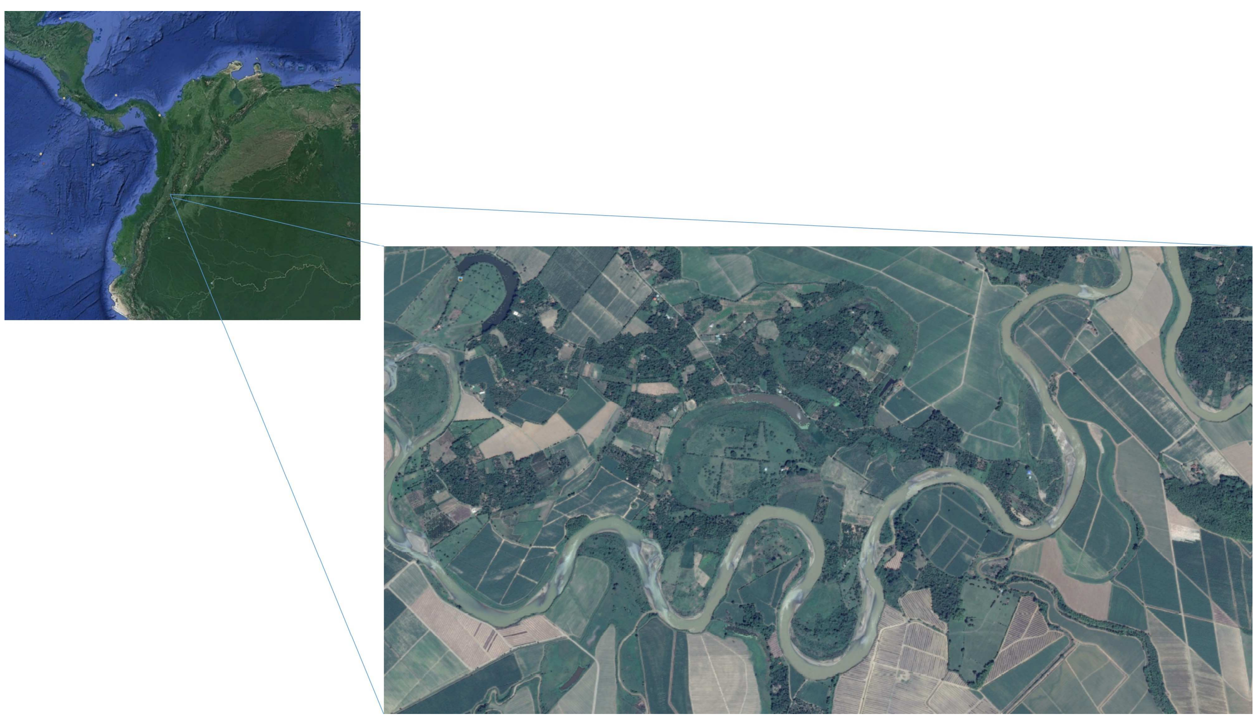

**Figure 9**. Example of area of high altitude relict cocoa plantations in the middle altitude Andean valley of the Cauca River. Many of these small plantations occur on periodically flooded areas and are managed by African-descendent people. In this parcels, low-altitude coffee (*Coffea arabica* L.) coexists with native cocoa trees.

These populations also offer a very interesting case of climate change adaptation, as this high altitude cocoa is currently replacing low coffee plantations that are already suffering from climate change. Please note that even though the current emphasis is given to cacao, it all depends on what people interpret as agroforestry in these countries so other species may be found as 'boundary objects'.

## 6. Grant and Funding strategy

My funding strategy is simple. As working in a new area requires starting money, I will address the 'Masion des Sciences de l'Homme' of Saclay University as it has a continuous call up to 25000 € for starting new projects. A draft is being written for the next July call in collaboration with the economist Armelle Maze. At the same time, I am working with colleagues from the Universidad de Alcala de Henares (Economics department) and Gent University (Faculty of Bioengineering), to propose a COST action this fall. The idea of this COST action is to create a solid network between producing countries, exporters and manufacturers of chocolate in Europe. The name of this COST action we are writing is "*Adapting to Climate, Adapting to Markets: Opitimizing the value chain in Cocoa production*". This networking step is seen as preparatory for a H2020 call "**SFS-01-2018-2019-2020: Biodiversity in action: across farmland and the value chain".** Note that there will be a recycling of several parts of a previous proposal that I submitted to the H2020 in 2016 that passed the first round but finally was not funded.

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Restoration Ecology
THE JOURNAL OF THE SOCIETY FOR ECOLOGICAL RESTORATION

OPINION ARTICLE

# The emergence of the social-ecological restoration concept

Juan F. Fernández-Manjarrés[1,2], Samuel Roturier[1], Anne-Gaël Bilhaut[3]

**Many ecosystems in the world are the result of a close interaction between local people and their environment, which are currently recognized as social-ecological systems (SoES). Natural catastrophes or long-standing social and political turmoil can degrade these SoES to a point where human societies are no longer autonomous and their supporting ecosystems are highly degraded. Here, we focus on the special case of the restoration of SoES that we call social-ecological restoration (SoER), which is characterized as a restoration process that cannot avoid simultaneously dealing with ecological and social issues. In practice, SoER is analogous in many ways to the general principles of ecological restoration, but it differs in three key aspects: (1) the first actions may be initially intended for human groups that need to recover minimum living standards; (2) the SoER process would often be part of a healing process for local people where cultural values of ecosystems play an essential role; and (3) there is a strong dependency on external economic inputs, as the people belonging to the SoES may be incapable of reorganizing themselves on their own and supporting ecosystems can no longer self-recover. Although it might not be desirable or necessary to call all restoration projects with a social component an SoER, the use of this concept may help in defining early restoration targets that may prevent conflicts among users in the long term. From the perspective of other disciplines, SoER would be more appropriately perceived as programs of "social-ecological recovery" in the long term.**

**Key words:** ecosystem restoration, humanitarian crisis, natural catastrophes

### Implications for Practice

- Social-ecological restoration (SoER) cycles may involve several very difficult decisions between human well-being and ecosystem recovery for which many managers may feel overwhelmed. Hence, managers should reach for extended collaboration beyond their usual disciplines and institutions.
- Natural catastrophes may set ecosystems in trajectories with which people dependent on them may not be able to cope. Open minds and a dynamic view of ecosystems are therefore needed for a successful SoER.
- Resources need to be wisely allocated in SoER as social dynamics can be very fast while ecosystem dynamics may be beyond human generation times.

## Introduction

Reconciling ecological restoration goals with human well-being objectives is a restoration approach that needs no further presentation in the ecological sciences. The link between the two has been actively tackled through the ecosystem services concept, with various review articles suggesting the links between restored diversity and ecosystem function on the one hand, and the availability of ecosystem services on the other (Benayas et al. 2009; Alexander et al. 2016). The underlying hypothesis is that if restoration reenables ecosystems services while maintaining and promoting biodiversity, human needs are met in a "win–win" scenario and may even help to alleviate poverty (Cao et al. 2009; Aronson et al. 2010 and references therein; Cao 2011; Yin & Zhao 2012). A related approach used to address the relation between ecological and social issues in restoration has been to include traditional ecological knowledge in restoration programs (e.g. Uprety et al. 2012). However, an ecosystem service-centered approach to restoration and conservation goals has been also criticized on the grounds that it can lead to a loss of biodiversity and ecosystem functions in the long term without really solving the social issues they were supposed to (Blignaut & Aronson 2008; Vira & Adams 2009; Schroter et al. 2014; Batavia & Nelson 2017). Hence, there is a need to maintain a diversity of worldviews, including cultural values of ecosystems, when social and economic concerns are pressing.

Here, we argue that under certain circumstances, a common goal of social and ecological reparative measures can be

Author contributions: JFM conceived and designed the study; AGB contributed the study case with Amazonian Ecuador communities; all authors wrote and edited the manuscript.

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doi: 10.1111/rec.12685
Supporting information at:
http://onlinelibrary.wiley.com/doi/10.1111/rec.12685/suppinfo

explicitly named "social-ecological restoration" (SoER) provided that the goal is to restore a "social-ecological system" (SoES). By SoES, we understand a complex system that has emerged through a series of people's close interactions with their supporting ecosystems and species, creating structures and processes that would otherwise not exist. Only until recently has the scientific literature begun to explicitly address the concept of SoER as both a practice and a conceptual field in itself. To the best of our knowledge, the term was coined recently by Takeuchi and collaborators in an article addressing the need for a comprehensive approach to reconstruct the areas devastated by the 2011 earthquake, ensuing tsunami, and radioactive pollution in northeastern Japan (Takeuchi et al. 2014).

In contrast to the ecological sciences, the social sciences and organizations that deal with humanitarian crises do not use the word restoration. Instead, the term "recovery" is more commonly used, but mostly as part of a "recovery plan" for countries torn down by war or natural catastrophes (UNDG 2007). The expression "social restoration" is not used in the social sciences, because it would be a controversial concept for obvious reasons, including undesirable political interpretations. Societies and cultures are not restored as no one would intend to return exactly to past cultural values or practices. It is well accepted that cultures change and that each epoch has its own set of shared values that will evolve over time. Nevertheless, the expression "social restoration" has been used sporadically by urban planners in the context of how ecological restoration should be socially acceptable and not lead to conflicts with users (Eden & Tunstall 2006; Nagendra & Ostrom 2014). Thus, it would appear that Takeuchi and colleagues' use of SoER is the first attempt to clearly interlink social and ecological goals in the reconstruction of societies and their supporting ecosystems.

Here, we propose that SoER is a problem-solving approach in which the main goal is to *jointly* restore the interdependent social and ecological processes in an SoES. We believe that this concept and practice are probably more adapted to areas in which the historically strong presence of humans has shaped the terrestrial landscapes, wetlands, and coastal areas and in which the present-day human populations struggle to have a sustainable society. We discuss throughout the text how this approach differs from ecosystem-service centered restoration, present some practical issues related to the emergence of the SoER concept by presenting a parallel with humanitarian crises, and include a case study from the Shuar communities in Ecuador to illustrate the concept applied to ecosystems that have been degraded for a long time.

## Do We Need a New Concept?

The short answer, in our opinion, is yes. Many readers will argue that they have already been working in SoER and that the lack of a term has not prevented them from using both ecological and social approaches to deal with specific restoration cases, which we agree with. Yet the need to use a specific term, as with Takeuchi and collaborators, stems from at least three key points: (1) it permits an up-front dismantling of any animosity or ambiguity in a restoration program by setting clear goals from the onset that are well accepted by a majority of people; (2) it helps to identify quickly objects and processes that link the natural system and human societies at the proper geographical and temporal scales; and, most importantly, (3) it is a concept appropriate for societies that have suffered from natural disasters or long-term armed conflicts in which people have lost everything and supporting ecosystems are presently fragile.

Conflicts and animosity against restoration programs are not new, and it is one of the most recurrent issues (Geist & Galatowitsch 1999; Buckley & Crone 2008; Palamar 2010; Halme et al. 2013; Winkel 2014; Druschke & Hychka 2015; Fox et al. 2016; Alves-Pinto et al. 2017). As stated previously by Geist and Galatowitsch (1999), there is a need to show and implement reciprocity in restoration programs so that people's contributions to the restoration of ecosystems are inversely compensated by the contributions of ecological restoration to people, which proves extremely challenging. In areas where there are close links between human societies and plant or animal populations, which represent the main resources of livelihood, programs framed as SoER may be better accepted by stakeholders. Humanitarian, postconflict, or postcatastrophe management agencies and organizations will be obliged to look into ecosystem recovery, something that is frequently overlooked because of the dimensions of the crisis (Abrahams 2014). Evidently, the open use of the SoER concept does not prevent all conflicts, as unforeseen tensions may emerge at any time.

The SoER approach helps to identify early keystone objects and processes that would otherwise be pondered differently or in later steps if only ecological or social analysis were conducted. After a crisis, chances are that the affected society will very quickly point out what essential components of the ecosystem are lacking and what processes have been disrupted that they deem necessary to return back to their normal lives that frequently include practices and species with high cultural value. In the case of the post-tsunami actions in Japan, coastal forests (object 1) were identified as natural way to stabilize dunes (process 1) in stark opposition to concrete barriers, which would destroy the landscape. Likewise, inner riparian broadleaf forests (object 2) were identified as a means to maintain good-quality water (process 2) for oyster culture in the sea, which is an essential part of the human activities in the area (Takeuchi et al. 2014), and so forth. This object process-based approach will also help to identify the disciplines and expertise required to tackle problems at the social-ecological level in an interdisciplinary way as this cannot be anticipated in advance. Whether forestry, aquaculture, agronomical, and even mining expertise is needed during the implementation of a humanitarian program depend much of how people see themselves after crises (see next).

In our view, the use of SoER as a driving concept can prove particularly useful after natural or human-induced disasters, because almost all natural and social processes and structures have been disrupted. Moreover, as shown by Takeuchi and collaborators (2014) and in the example of the recovery after Hurricane Katrina in the southeastern United States (for a review see Day et al. 2007), reconstructing the links between people and natural processes can help in the healing processes for the human populations. For instance, reconstructing the natural structure of the Mississippi Delta will require new paradigms of development if the same catastrophes are to be avoided in the future, and if a human environment that is culturally identified with living within the wetlands is to be maintained. However, the SoER concept may be useful not only for regions affected by large natural catastrophes but also in places where long-standing conflicts and social turmoil have erased people's capacity to manage and conserve their ecosystems (see example with Amazonian communities in the last section). For example, international organizations have been increasingly working with the restoration of degraded ecosystems due to overpopulation, poverty, and war (see http://www.unep.org/disastersandconflicts/what-we-do/recovery/environmental-cooperation-peacebuilding). Although the expression of SoER has not been used in these programs, the arguments are similar to what we propose here. In fact, the subjacent idea that the good governance of resources is an essential way to prevent conflicts strengthens the concept of SoER.

## What Is the Scale of SoER?

If the research or restoration object of SoER is the SoES, then its spatial and temporal scale corresponds to the SoES. As seen above, the general definition of SoES is open to discussion regarding the relevant spatial scale, because it is difficult to trace limits in a globalized economy. One response from institutional economics can help us to limit the scope of SoER. In particular, the works of Elinor Ostrom and colleagues define the scale (or SoES itself) as the scale at which people self-organize to use a given resource (Ostrom 2009). In the context of Ostrom's works, "resource" refers to provisioning ecosystem services such as irrigation water, timber, fisheries, and so on. This approach baffles the majority of ecologists who, for obvious reasons, would argue that the spatial scale of the supporting ecosystem as the scale to consider. Hence, SoER would need explicitly a step of negotiation between ecologists and social workers and between the ecologists and funding agencies for the need to include a larger geographical area for the implementation of restorative ecosystem measures. Again, this was clearly shown by Takeuchi and collaborators when they addressed the need to work together on the mountain–plain interface (*satoyama*) and on the shore–sea interface (*satoumi*) as integrated spatial units that represent essential landmarks of their cultural heritage.

## People Recovery, Reference Systems, and External Inputs

Solving humanitarian crises (EuropeAid 2004) and ecological restoration (Mcdonald et al. 2016) share management principles of cycles of diagnostics, implementation, and evaluation (Fig. 1; Table S1, Supporting Information). Restoration cycles, either ecological or humanitarian, are necessarily sequential, incremental, and each step has a duration that cannot be predicted. Humanitarian aid is highly coded by international institutions and is defined at the scale of a country even if the actions are local. Nevertheless, despite overall similarities between restoration cycles and humanitarian aid cycles, key differences exist between ecological restoration and SoER (Table 1). The first main difference is that in SoER the majority of resources would be used in the initial stages of the restoration process to recover the minimum living standards for the people concerned. This can be viewed as a social bias in the restoration process, but aside from the humanitarian reasons, it actually may be a useful thing to relieve the pressures placed on the supporting ecosystems before a complete SoER plan is being designed.

Although the cultural values of ecosystems is of primary importance in SoER as people can regain self-confidence through their cultural and natural landmarks, it is difficult to anticipate how much of the previous ecosystem will be actually desired by the people. The second and perhaps greatest challenge in SoER, at least from the perspective of the ecological sciences, is agreeing on the reference system to be used for restoration. In countries in the recent aftermath of civil wars or natural catastrophes, people who may have lost everything may simply ask for ways to escape the traps of poverty and violence. Whatever comes first with the promise of a better future will quickly be accepted by people, even if it entails new ways of interacting with the natural systems. At this point, conservative views of what restoration is will collide with what people are demanding. For instance, illicit growing of coca (*Erythroxylon coca*) in South America for the last 40 years has caused degradation of many areas of tropical rain forest in Bolivia, Peru, and Colombia, creating social conflicts and violence among peasants that have reduced their quality of life. Because of the difficult climatic conditions and low fertility of tropical forests, agroforestry propositions to replace illegal coca monoculture plantations with a handful of useful native plants are often proposed as an alternative (Corradi et al. 2013). However, local tree diversity can easily exceed 100 tree species per hectare in the western Amazon (Ter Steege et al. 2003), a species richness that will never be attained with agroforestry programs. According to Society for Ecological Restoration standards, this type of restoration would be considered closer to rehabilitation than to ecological restoration (Mcdonald et al. 2016). Still, using a handful of legal tree crop species may be better than a single, highly polluting crop such as coca plants. If the idea of SoER helps local people and external organizations to coconstruct a viable future in a respectful manner for both people and natural systems, it may be worthwhile using the concept early in the recovery programs as better biodiversity and social objectives may be attained in the long term.

The third and probably most striking difference with more ecologically centered restoration programs is the level of external inputs, especially economic inputs (Table S1). Current approaches in ecological restoration seek to assist the recovery process of the relevant ecosystem by allowing for the internal reorganization and adjustments of the system (Mcdonald et al. 2016). By contrast, highly degraded ecosystems and societies that are a consequence of long-term conflicts or natural catastrophes require immense amounts of external economic input, sometimes for decades. In this regard, the budget allocated

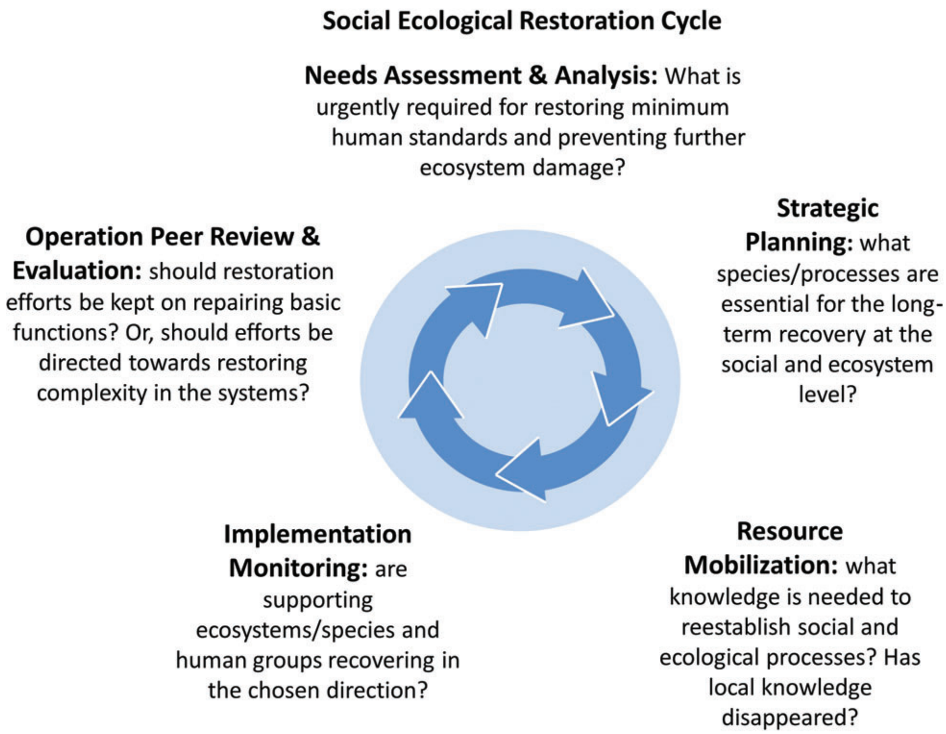


Figure 1. General social-ecological restoration cycle with a nonexhaustive list of questions addressed at each step. Within each step, many more precise questions need to be answered in order to advance to the next level (see Table S1).

to most restoration programs is insignificant compared to the resources committed for recreating stable and self-sustainable human populations. Hence, joining inextricably both social and ecological restoration processes, albeit more difficult and costly, may help in the achievement of long-term goals, and hopefully in many cases to ensure sooner the sustainability of human groups in a respectful manner with their environments.

A second external input that may be needed disproportionally in SoER is expertise to recover the traditional ecological knowledge (i.e. knowledge people have of their environment) that may be endangered or even lost. Community leaders or vulnerable population categories may have fled, lost their leadership, or died in areas where social turmoil has been chronic. In this regard, universities, museums, and scholars may go along with local communities and participate in SoER programs for recovering disappearing local knowledge.

SoER efforts do not need to start from scratch but can learn from experiences developed and accumulated in programs of community restoration. For instance, if the key biodiversity object for restoration identified in the first steps of the SoER cycle is a "commons" (i.e. resources accessible to everyone and clearly affected by the subtractions of units like trees in a forest or fishes in waterbodies), there is a clear need to acknowledge the complexity associated with governing the commons and avoid top-down out-of-the-box solutions (Ostrom 2009; Frey & Berkes 2014). As with community-based conservation principles (Berkes 2004), SoER would benefit of building the capacity to deal with multiple objectives and use of deliberative processes (concertation) to allow for a multilayered governance for the various institutions that would get involved in ecosystem restoration (Berkes 2007; Frey & Berkes 2014) and humanitarian crises. This means that deliberation processes to account for the multiple layers of governance and actors will probably be permanent in SoER cycles.

## Social-Ecological Restoration After Long-Term Ecological and Social Degradation

As stated earlier, not all SoER programs would be intended for the aftermath of disasters. Until recently, the hunter and horticulturist Shuar people from southern Amazonian Ecuador and northern Peru were a seminomadic population. Since the late nineteenth century, Christianization led them to become sedentary, drastically changing their social and political organization as well as their economic life. At present, a large part of their traditional territory is cleared of the original highland Amazonian forest vegetation because of cattle breeding or timber trade, which they adopted to secure titles to their ancestral land to comply with government requirements in the 1960s.

Some Shuar communities have initiated family-level restoration programs based on their traditional agroforestry system, the *aja* (Fig. 2) with a focus on native trees as keystone restoration species (sensu Garibaldi & Turner 2004). The goal of the *aja* is to reproduce the high biodiversity of the forest, viewed as the domesticated garden of the master spirit *Nunkui* where women have the leading role (Descola 1994). Present-day *ajas* are less diverse than their traditional counterparts and increasingly include *Theobroma* spp. and *Herrania* spp. (domesticated

**Table 1.** Main differences between ecological restoration and social-ecological restoration based on six principles of ecological restoration (Mcdonald et al. 2016).

| *Key Concept* | *Ecological Restoration* | *SoER* |
|---|---|---|
| 1 | Practice is based on an appropriate local native reference ecosystem, taking environmental change into account. | The target system can be a highly reinterpreted reference system; the new system typically builds resilience to floods, fires, etc., and could be seen as rehabilitation or even as ecological engineering. External market opportunities may cause local people to switch to new ways of interacting with their ecosystems and the species that they collect or gather. |
| 2 | Identifying the target ecosystem's key attributes (threats, physical conditions, species composition, structural diversity, and ecosystem functions and flows with other ecosystems) is required prior to developing longer-term goals and shorter-term objectives. | In addition to identifying the ecosystem's attributes, *SoER* programs may need to address the level of people's vulnerability and their access to food, shelter, and basic goods, as well as security, political participation, and the end of violence, among others. |
| 3 | The most reliable way to achieve recovery is to assist natural recovery processes, while supplementing them to the extent that natural recovery potential is impaired. | In contrast to letting the system self-organize, massive external economic inputs may influence the trajectory of the system in very short periods of time, which is common in humanitarian crises. |
| 4 | Restoration seeks the "highest and best effort" toward full recovery; the recovery can be quantified for each of the key attributes (see principle 2). | Full recovery is rarely known for *SoER* in countries with civil wars, as they may be recurrent crises because of poverty and violence traps. |
| 5 | Successful restoration draws on all relevant knowledge. | Relevant knowledge may have been lost if key actors have died or fled from the target regions. |
| 6 | The early, genuine, and active engagement with all stakeholders underpins long-term restoration success. | Long periods of time may be needed until all actors are actively engaged, thus making the *SoER* process probably longer than equivalent ecological restoration programs. |

Figure 2. Not all social-ecological restoration programs are intended for the aftermath of natural disasters. Poor and remote populations of many indigenous peoples and peasants worldwide struggle to maintain their cultures and make a living in a globalized economy. The picture shows a Shuar member in the Zamora-Chinchipe region, Ecuador, entering a traditional *aja* agroforestry plot that is considered by them as a way of maintaining important cultural traditions and restoring the Amazon forest in accord with their view of what constitutes an upland Amazonian ecosystem (Photo by student J. Castañeda, 2017; used with permission).

and wild cocoa) because of pressures by exporters looking for rare organic cacao beans that they buy at very low price. This fragile context makes it very easy for some communities to allow mining into their lands or tree felling to make charcoal, as the cash flow is greater and steadier than the difficult market of organic produce for international markets for which they are not prepared. Sadly, the Shuar ignore that cacao trees were domesticated there 5,500 years BP (Valdez et al. 2013) and have no means to increase their produce value despite its importance.

Even a superficial needs and assessment analysis (first step of the SoER cycle in Fig. 1) would promptly identify that their

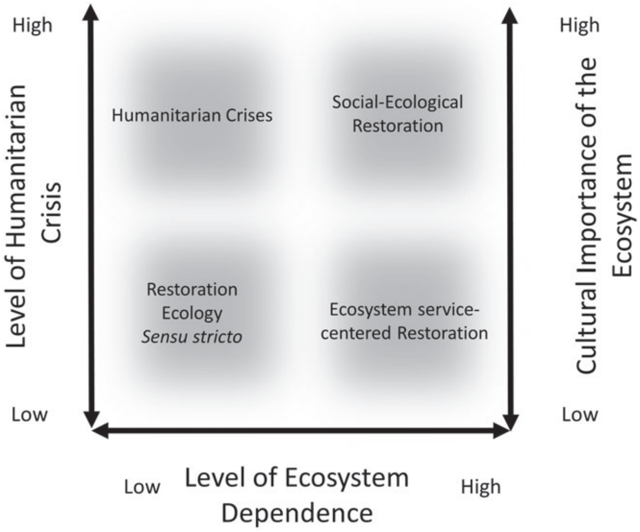


Figure 3. Different types of restoration programs can be thought of as a continuum defined by the level of humanitarian crises, the level of ecosystem dependence of local people, and the collective cultural value of the supporting ecosystem. In this context "restoration ecology sensu stricto" means classical restoration ecology with only ecological goals and refers to a well-defined reference state.

rich ecosystem has been degraded to a point where natural regeneration will hardly bring back the biological diversity associated with extirpated late successional trees without external intervention. It is also obvious that living standards are low and that local knowledge is disappearing fast. People live precariously without running water or sewage and have no one trained at the university level in agronomy or marketing to deal with external markets that appear as the only source of income. Our hypothesis is that engaging the Shuar in an SoER restoration cycle would increase ecosystem health and the Shuar's well-being. For instance, a careful zoning to intermix organic cacao plantations, regeneration plots for late successional tree species, and enriched *aja* gardens for their medicinal and food needs could be a viable option to discuss with them. Such actions would require leadership and local community commitment that is currently wanting, making the dependence on external aid unavoidable. Unfortunately, examples like the Shuar abound worldwide in developing countries and it is difficult to imagine a successful ecological restoration without restoring the links between people and their surrounding nature, even if they include new ways of human-nature interactions.

## Conclusions

In sum, we define the emergent concept of SoER *as cycles of reparative processes in which restoring ecosystem function is inextricably linked to repairing cultural ecological landmarks for human populations that struggle to regain their normal lives*. In general, SoER would be placed in a gradient where humanitarian crises are strong, the dependence on key processes or species within an ecosystem is essential for the local communities, and where the cultural values of the ecosystems and their components are essential for the people's identity (Fig. 3). In that respect, the cultural value of ecosystems can help people in a social healing process as much as the direct or indirect income they may eventually get from a restored ecosystem.

We do not argue here in this short essay that all restoration ecology projects should be envisioned as an SoER process. In fact, speaking of SoER might even be counter-productive in cases where the links between human welfare and biodiversity are not straightforward. The SoER concept can constitute an alternative path in the debate that traditionally opposes the development of human populations and ecological conservation, especially in developing countries where substandard conditions of life are the norm and many cultural practices have disappeared.

As explained earlier, it will be very unlikely that the term "restoration" would be used outside of fields related to the ecological sciences because it is awkward when applied to social issues. A more general term including short- and long-term reparative actions for both social and ecological components could be "social-ecological recovery." It is impossible to anticipate which expression will generalize, but any of them could help raising awareness within the humanitarian aid community for calling early on the expertise of ecologists and ecosystem managers when handling humanitarian crises.

## Acknowledgments

Parts of this research were financed by the LabEX BASC (https://www6.inra.fr/basc), which is a French inter-laboratory initiative for interdisciplinary research on biodiversity, agrosystems, society, and climate. We also thank J. Castañeda for providing the photograph included here.

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## Supporting Information

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

**Table S1**. Synopsis of humanitarian cycle programs and their similarities with restoration ecology programs as currently conceptualized by leading institutions in the area.

*Received: 6 October, 2017; First decision: 9 November, 2017; Revised: 25 January, 2018; Accepted: 27 January, 2018*

ENVIRONMENTAL SCIENCE & POLICY 51 (2015) 192–201

Available online at www.sciencedirect.com

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# Reconstructing a deconstructed concept: Policy tools for implementing assisted migration for species and ecosystem management

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ARTICLE INFO

*Keywords:*
Environmental policy
Precautionary principle
Prevention principle
Species translocations
Ecosystem reinforcement
Climate change
Management

ABSTRACT

Assisted migration (AM) is increasingly proposed to limit the impacts of climate change on vulnerable plant and animal populations. However, interpretations of AM as a purely precautionary action along with multiple definitions have hampered the development of precise policy frameworks. Here, our main objective is to identify what type of policy tools are needed for implementing AM programs as part of broader environmental policies. First, we argue that policy frameworks for translocations of endangered species that are subject to climatic stress are fundamentally different from translocations to reinforce climatically exposed ecosystems because the former are risky and stranded in strict regulations while the latter are open to merges with general landscape management. AM implementation can be based on a series of phases where policies should provide appropriate grounds closely related to extant environmental principles. During a ''Triggering phase'', AM is clearly a prevention approach as considered by the Rio Declaration, if unambiguously based on evidence that population decline is mainly caused by climate change. During an ''Operational phase'', we suggest that policies should enforce experimentation and be explicit on transparent coordination approaches for collating all available knowledge and ensure multi-actor participation prior to any large scale AM program. In addition, precautionary approaches are needed to minimize risks of translocation failures (maladaptation) that can be reduced through redundancy of multiple target sites. Lastly, monitoring and learning policies during an ''Adaptive phase'' would promote using flexible management rules to react and adjust to any early alerts, positive or negative, as hybridization with local individuals may represent an evolutionary chance. Our analysis of study cases indicates that except for two programs of productive forests in Canada, current AM programs are predominantly small-scale, experimental and applied to endangered species isolated from general environmental management. As the effects of climate change accumulate, policies could include AM as part of larger environmental programs like habitat restoration with common species seeking to provide stable ecosystems in the future.



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http://dx.doi.org/10.1016/j.envsci.2015.04.005
1462-9011/

## 1. Introduction

The impact of climate change on biodiversity and ecosystems presents new challenges for the scientific community, managers and policymakers, obliging them to adapt research agendas, conservation practices and regulations to these changes. Among the many conservation strategies developed to lessen the impacts of climate change on plant and animals assisted migration (AM) is one of the options receiving increased attention. The rationale behind is a compensation for the dispersal limitations and potential lack of adaptive capacity of a given species resulting from the speed of current climate change. This concept encompasses several overlapping definitions (Ste-Marie et al., 2011) generating a great deal of debate (Hunter, 2007; McLachlan et al., 2007). Most of the time, AM refers to the movement within or outside the natural species range to mitigate the impacts of climate change (Aitken and Whitlock, 2013). In addition to this general notion, we find two other closely related concepts: assisted colonization (AC) which describes a movement beyond the range of species to limit human-induced threats (Seddon, 2010), and recently, assisted gene flow (AGF) which describes a movement of individuals (genes) inside the range of species to facilitate adaptation to anticipated local conditions (Aitken and Whitlock, 2013). Here, we consider AM to be a general technique corresponding to a human-assisted movement of biological entities (seeds, other propagules, individuals or populations) from a region where their survival is mostly threatened by climate change to a region where they could survive and maintain ecosystem services under current and expected future climates. On a more general perspective, AM would belong to actions seeking to repair the environment and ecosystems like in restoration or ecological engineering programs that have been recently dubbed ''manipulative ecology'' (Hobbs et al., 2011).

Despite the fierce debate that AM has recently produced between opposing actors who see more risks than benefits in AM initiatives and those seeking to act in the face of climate change threats (see Neff and Larson, 2014 and references therein), AM could be nevertheless seen simply as an extension of the practices of translocation and reintroduction of endangered species. In fact, the distinction between translocations and AM is becoming increasingly artificial because climate change makes parts of the historic ranges of many species unsuitable as reintroduction recipient sites (Dalrymple et al., 2011). Critics of AM invoke the high failure rate of translocation programs (Fischer and Lindenmayer, 2000) as a counter-argument. Translocations can fail for many reasons including when supposedly 'core habitat' is in fact marginal for the translocated population (Dalrymple and Broome, 2010) suggesting that lack of ecological knowledge and not the fact of translocating individuals itself is a frequent limiting factor. Nevertheless, AM is developing gradually in public policies of various institutions and countries more as a general objective than as structured programs with precise policies, methods and funding. For instance, preliminary AM considerations have recently been included carefully by the International Union for Conservation and Nature (IUCN) in its latest translocation guidelines for endangered species (IUCN & SSC [Species Survival Commission] 2013). Likewise, the Scottish government (Brooker et al., 2011), the Australian authorities (NCCARF National Climate Change Adaptation Research Facility, 1990), the European Union LIFE program (Silva et al., 2011) and Canadian forest seed planting regulations in Ontario (Eskelin et al., 2011), among others, have all included some sort of AM in their texts.

If AM is deemed necessary by a panel of experts its application requires not only sound ecological knowledge but also clearly identified policy frameworks (Schwartz et al., 2012; Shirey and Lamberti, 2010) that still need to be fully developed. AM policies do not need to start from scratch but can be built upon major principles of environmental law or ecosystem management. Here, our goal is to answer the main question of what kind of policy frameworks are needed for implementing AM programs. Our specific questions are: (1) what are the definitions, scale and risk issues related to AM actions that need to be clearly identified in environmental policies? (2) If AM is an extension of environmental management and translocation programs, what pre-existing regulations and policies can help its implementation? And (3) what can be learned from known cases of AM? To conclude, we provide some recommendations for policymakers when AM is implemented as an option within larger biodiversity and ecosystem management programs in response to climate change.

## 2. Definitions, scale and risks issues in assisted migration policies

At least three main factors are essential to consider before designing any policy framework for AM: establishing a clear definition of the main objective of the action, assessing as precisely as possible the scale of the proposed action, and assessing the risks related to the action (Fazey and Fischer, 2009; Hewitt et al., 2011; McLachlan et al., 2007; Richardson et al., 2009).

AM has been used as a generic concept describing multiple related actions that can be placed along a continuum (Aubin et al., 2011; Ste-Marie et al., 2011) each requiring different policy frameworks. At the extremes of this continuum, however, two contrasting ideas emerge: whether the migration is to protect by translocation a target population from climate related risks, or to maintain or restore the ecosystem function of a target site. The first case corresponds to what Pedlar et al. (2012) termed 'species rescue AM' where the unit moved is the same to be protected. Here we call this type of AM as 'species-centered AM'. In the latter case, migrations are made *into* a target ecosystem to reinforce ecosystem processes with local, neighboring or even exotic species. Thus, an ecosystem that we want to protect will not be moved obviously, but other genetic units supposed more robust are brought in. We call this process 'ecosystem-centered AM'. Species-centered AM could be implemented where endangered species represent have a low invasion risk, have few migration possibilities in low-connectivity landscapes, low migration rates, low adaptation potential, low population size and well documented life history traits (Loss et al., 2011; Vitt et al., 2010). In contrast, ecosystem-centered AM would be appropriate for managed ecosystems such as productive forests (Pedlar et al., 2012), urban parks, water basins (Kreyling et al., 2011), managed prairies and other semi-natural landscapes, which consist mostly of a few common species without endangered status that have already been managed for many years.

Once the objective of the translocation has been identified, choosing the scale of action (biological, geographical and institutional) conditions the policies needed for AM, many of which already exist, in principle, in the regulations of most countries. The biological scale of the unit to be moved (seed, juveniles, individuals, population, etc.) must be determined first because the movement of propagules, for example, does not require the same sanitary controls as those required for adult plants or animals, and probably not the same economic resources either. Next, the geographical scale of the action needs to be identified, i.e., within, to the margin of, or beyond the current and historical range of the target species, because the risk of invasion is considered lower for sites closer to the historical range. The institutional scale (local, regional, national, bi-national, etc.) at which the AM action would be performed also needs to be determined because the authorizations involved in moving individuals within a reserve network are very different from those involved between countries.

On the contrary, handling the major risks associated with AM may require new suitably structured policies. First, the introduction of potentially invasive species in target ecosystems when the scale of the action is beyond the current and historical range of the species concerned (Aubin et al., 2011; Mueller and Hellmann, 2008; Ricciardi and Simberloff, 2009a; Winder et al., 2011) would be minimized if policies allow small scale experimental introductions to test for invasiveness prior to any large scale migration program; second, the risk of genetic pollution of native populations already present in the recipient ecosystem if species are moved into an area where there might be closely related taxa (Aubin et al., 2011; Frascaria-Lacoste and Fernández-Manjarrés, 2012; Minteer and Collins, 2010; Ricciardi and Simberloff, 2009b; Vitt et al., 2010) could be evaluated at experimental sites provided that molecular markers are available for a first monitoring, for example. In stark contrast, some researchers propose that AM could represent an "evolutionary opportunity" in the context of climate change, if bringing new genetic material into threatened areas (Aitken and Whitlock, 2013). AM can create artificial gene flow to maintain and increase genetic diversity of species by using genetically diverse populations potentially with genes pre-adapted to new conditions. The potential hybridization (genetic introgression) that may result from AM could be an opportunity for future rapid adaptations in changing environmental conditions (Scriber, 2014). These ideas are developed further in the section where we discuss the operational and management aspects of AM.

## 3. Specific policy frameworks for different types of AM

In the species-centered case, target species predominantly have endangered status (see examples in Table 2), so the application of AM programs is *de facto* difficult. In general, the more critical the status of a population, the more it will be regulated. Furthermore, the greater the translocation distance the more difficult the application of AM programs will be. In the USA, the Endangered Species Act (ESA) includes the 'experimental population' status to translocate populations beyond their range provided that local authorities see no risk for the recipient ecosystem (Shirey and Lamberti, 2010). Likewise, the relatively recent 'Habitats Directive' (92/43/CEE) regulation of the European Union provides a framework close to the ESA of North America. This directive and the programs derived from it are highly constraining and conservationist making many regions in Europe restrictive for AM. As with ESA, however, the Habitats Directive and the French Environmental Code (articles L411-1, 2, 3, 4 and 5) for instance, allow to eventually obtain derogations for small-scale experimentation for the movement of endangered species, as would be the case for other European countries.

On the other hand, new policy frameworks for ecosystem-centered AM should include awareness on the current and future potential ecological interactions (positive and negative) considering the connectivity of the landscapes. Here, the focus is on common biodiversity translocated to reinforce ecosystems so there are a priori small or no legal constraints for this kind of action. Ecosystem-centered AM implies a wider set of actions because of the multiplicity of species and interactions at the landscape level. However, risks exist related to permanent changes in the landscapes because of productivity arguments (Fernández-Manjarrés and Tschanz, 2010). Highly managed ecosystems (e.g., urban parks, productive forests, managed water sheds, etc.) benefit from several characteristics such as regular monitoring of good quality, management plans, and economic significance, making them very good candidates for this type of AM. Bearing in mind these two types of AM and their specific features, we examine next what extant environmental principles and tools could provide a basis for managing natural systems through AM through a series of steps.

## 4. Policy foundations for assisted migration: extant tools and their timing

### 4.1. *The triggering phase*

In our opinion, the biggest source of disagreement surrounding the debate of AM is the notion that such actions pertain solely to the realm of anticipation. In addition, the uncertainty about climate change and their impacts on biodiversity led scholars to reach first for principles focusing on uncertainty issues which are extremely difficult to implement in real situations. In this section, we argue that the innovative combination of two founding international environmental principles can provide policy grounds for a triggering phase of AM not substantially different from other environmental practices.

In the literature discussing the convenience of AM, the "precautionary principle" (PP) (Table 1) or "precautionary approach" appears as the main legal tool used to justify or argue against AM programs responding to climate change

**Table 1 – Definitions and interpretations of the precautionary and prevention principles.**

| | Rio principle | Type of risks | Type of action | Interpretation/utilization |
|---|---|---|---|---|
| The Precautionary Principle (PP) | 15 | Hypothetical | Anticipation | Extension of the PvP. Most common approach is the identification of minimum risk. |
| The Prevention Principle (PvP) | 17 | Proven | Remedial | Originally proposed for environmental assessment now present in most environmental legislations. Never cited in the AM debate, it is overshadowed by the most ambitious PP. |

(Camacho, 2010; Lurman Joly and Fuller, 2009; Ricciardi and Simberloff, 2009a,b; Sax et al., 2009; Schwartz et al., 2009; Shirey and Lamberti, 2010). However, it is well known in the legal literature that the PP is not an effective decision-making tool and was never intended as such (Cooney, 2004; Hahn and Sunstein, 2005; IUCN (International Union for Conservation and Nature) Council, 2007; Peterson, 2007; Weier and Loke, 2007). Because most definitions of the PP remain vague its application is not straightforward allowing different actors to appropriate the PP to their own ends. It is therefore not surprising that the PP is invoked legitimately both to justify the application of AM to avoid biodiversity loss (Sax et al., 2009; Schwartz et al., 2009), and at the same time to oppose to AM because of uncertainties regarding the possible introduction of invasive species (Ricciardi and Simberloff, 2009b) or the manipulation of already weakened populations in their source site (Kreyling et al., 2011). Like all principles, the PP states only a general truth (Sands and Peel, 2012; Tridimas, 2007) and does not prescribe any specific actions. Besides, its legally non-binding character does not imply any implementation or regulation strategy. So, even if a degree of uncertainty is inherent in the PP, in reality too many uncertainties block its interpretation and therefore its application, as observed currently with the AM debate. In sum, the PP role is not to be used as an initial decision-making tool, but as a means of raising awareness for future risks and their management implications.

So, if precautionary approaches are not necessarily at the crux of AM, what principles would provide the necessary grounds for triggering it? In AM decision-making frameworks (Hoegh-Guldberg et al., 2008; Winder et al., 2011) the initial stage always questions whether the population considered for translocation is clearly declining because of climate change (climate vulnerability) and not if there are potential negative effects of climate change on a population. So, the presence of clear proof of population decline and/or its exacerbation by climate change fits the purpose of another international environmental principle, often overlooked, namely the ''prevention principle'' (PvP) (Table 1). By definition, the PvP addresses environmental issues where there is relatively little uncertainty on damages but clear evidence that environmental risk has been proved (soil pollution, habitat fragmentation, resource overuse, and so on). In the ecological disciplines, the PvP is akin to the concepts of ecological remediation or ecological restoration.

The PP differs in a subtle but fundamental way from the PvP and the difference lies in the characterization of environmental risk. In the case of prevention approaches, risk has been proved unequivocally and the uncertainty only involves the magnitude of the risk. For precautionary approaches, however, risk is hypothetical but plausible, so uncertainty not only relates to magnitude, but also to the occurrence of the risk in question. The PvP applies in the case of the existence of proven risks, i.e., population decay or ecosystem function decay caused by current climate change, and the PP applies to supposed risks, i.e., the likelihood of negative future climate impacts. In action planning, the PvP triggers the action at time $t$ and the PP allows integrating the future uncertainty to act today for conditions at time $t + 1$.

If we have proof of population decline or ecosystem malfunction because of climate change in biodiversity management, the next question is whether we have enough knowledge about the species ecology to decide upon the appropriate remedial action: to preserve in situ, ex situ, or to move and compensate for current and expected climate change (i.e., AM). For the case of ecosystem-centered AM, it will be necessary to decide if we have good enough knowledge about the history and function of the ecosystem concerned and to identify translocation candidates of well-known keystones species. In traditional biodiversity management, evidence of population decay or ecosystem dysfunction calls for ecological remediation or restoration (Fig. 1, upper left). When ecological modeling suggest high climatic vulnerability for a population, species or ecosystem, awareness of risk based on the PP calls for population and ecosystem monitoring to be able to react rapidly and preliminary research to accumulate knowledge (Fig. 1, lower right). In the context of AM implementation for species-centered AM or ecosystem-centered AM, the PP and the PvP will necessarily overlap (Fig. 1, upper right). The PvP provides grounds to start an action where there is proven vulnerability (population decline or ecosystem dysfunction) and the PP converges with the PvP to anticipate the uncertainty of climate change when vulnerability is supposed (Fig. 1, upper right).

### 4.2. *The operational phase*

We have seen that precautionary and preventive approaches play primary roles in the implementation of AM and as such should be clearly identified in policies regarding translocations. Whereas the ''triggering phase'' relies on a certain degree of political commitment, this phase relies on ecological knowledge and past empirical experience of translocation programs. Translocation practices have been conducted for many years generating a wealth of methods and recommendations and the most well-known are probably those of the IUCN. These guidelines are permanently updated and provided as reports that support the implementation of translocations by giving step-by-step guidance on feasibility, risk assessment and monitoring (IUCN and SSC, 2013). However, 'traditional' translocations based on a principle of 'equivalent

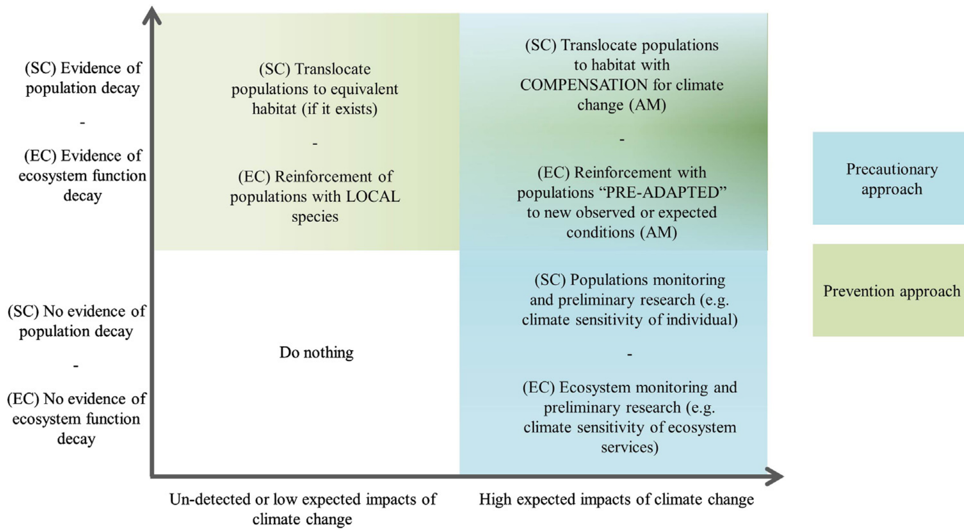


**Fig. 1 – Conceptual approach depicting how AM action accounts for both the precautionary and prevention approaches for Species-Centered AM (SC) and Ecosystem-Centered AM (EC).**

habitat availability' will be more difficult to apply with ongoing global changes and innovations in translocations practices are needed to increase the probability of success of translocated populations.

The notions of multilevel collaboration and consultation are central to the operational phase of translocations, and by extension, to AM. These notions are well-known in international environmental legislation as the ''coordination principle'' in the United Nations Declarations (The United Nations, 2002, 1992, 1972), the Convention on Biological Diversity (CBD) ecosystem management guidelines and widely acknowledged by the scientific community (Heller and Zavaleta, 2009; Hulme, 2005; McLachlan et al., 2007; Mueller and Hellmann, 2008). In the same way, the IUCN/SSC guidelines (IUCN and SSC, 2013) introduced the notion of multi-disciplinary and multi-scale set of skills alongside biological, ecological, social, economic or technical expertise with a wide approach to limit biodiversity management risks including those related to translocating species (IUCN (International Union for Conservation and Nature) and SSC (Species Survival Commission), 2013; Secretariat of the Convention on Biological Diversity, 2004). This approach will help bridging the gap between current translocations practices and the approach needed for complex programs as AM. In the case of AM, coordination and consultation are particularly important for two main reasons. First, isolated experimental cases of AM as currently implemented (see Table 2) may be forgotten if the short-term grants that financed the action are not renewed, as is often the case. Second, consultation and coordination in AM programs increases their transparency and in consequence, their acceptance by social and expert audiences. Lessons from past translocations show often that social acceptance play an important role in the implementation of these programs (Michaels and Tyre, 2012). For instance, coordination has played an essential role in the AM program for *Abies nebrodensis* in Sicily, Italy, a mountain species threatened by increased drought and fires with less than 50 trees left in the wild. This program has been realized with the participation of the agricultural ministry, university, conservationists, national park and local organizations, thus facilitating its social acceptance and allowing the implementation of continual monitoring of populations at the target site and at the introduction orchards in the main land (F. Ducci, pers. comm).

Finally, risks of failure during the operational phase could be minimized by spreading risks with redundancy approaches. This step is different from experiments to assess the climatic niche of a target species, like provenance tests which provide very valuable information about adaptation, invasions or pest resistance. Redundancy follows any experimental stage and provides the maximum of chances for translocated species in the face of uncertain climate change. The idea of ''bet-hedging'' or spreading the same population across different climates has been suggested to preserve the variety of forest genetic resources under changing climates and in ecological restoration (Lawler, 2009; Millar et al., 2007; Society for Ecological Restoration International, 2009). The choice of future habitat for populations in AM is usually based on statistical models (species distributions or niche models) but the real suitability of the habitat for the translocated population remains uncertain until tested. One way of dealing with this inherent uncertainty is to include redundancy in translocation practices. Redundancy is a well-established principle in safety design in which different components perform the same task providing robustness to a system. Here, redundancy is understood in two ways: for species-centered AM, by placing translocated populations on multiple sites selected along and across a climatic gradient instead of concentrating them in one habitat that may have been predicted to be the most suitable; and for ecosystem-centered AM, by bringing multiple species with different climatic tolerances. The use of redundancy can be understood as a way of implementing precautionary approaches in the field (Fig. 1, upper right) and it merits explicit inclusion in any new regulation concerning AM.

**Table 2 – Comparative analysis of known assisted migration study cases.**

| Project references | Species | Species status (IUCN) | Localization | Climate vulnerability (low/medium/high) | Demographic vulnerability (low/medium/high) | Main threat | Distance between source site and target site | Location of target site (inside or outside actual distribution of species) | Policy context | PP/PvP |
|---|---|---|---|---|---|---|---|---|---|---|
| **Conservation (Species-centered assisted migration)** | | | | | | | | | | |
| (McLane and Aitken, 2012) | *Pinus albicaulis* | Endangered | Canada (British Columbia/USA | High | High | Beetle (linked to climate change) | Between 700 and 1800 km | Inside for the most southerly population and outside for most northerly population | Experimental population | PvP and PP |
| (Willis et al., 2009) | *Melanargia galathea* and *Thymelicus sylvestris* | Endangered | United Kingdom | High | High | Combination of habitat fragmentation and climate change | Between 50 and 100 km | Beyond the northern border | Experimental population | PvP and PP |
| (Ducci, 2011) | *Abies nebrodensis* | Endangered | Italy | High | High | Climate change/ habitat destruction | ~750 km (Sicilia to Italy) | Outside | Experimental population. In collaboration with ministry, local organization, natural park, conservatories, and university | PvP and PP |
| (Shirey and Lamberti, 2010) | *Neonympha mitchellii* | Endangered | USA | Medium | High | Combination of habitat fragmentation and climate change | Hypothetically ~200 km | Outside | Theoretical analysis of AM programs in ESA. Use of experimental population status. | PvP and PP |
| (Pedersen et al., 2014) | *Liatris ligulistylis* and *Houstonia longifolia* | Regionally vulnerable | Canada (Alberta) | Unknown | High | Small population size/climate change (?) | 450 km south and 500 km north | Outside | Experimental populations | PP |
| (Liu et al., 2012) | Several Asiatic orchids | Endangered | China | Unknown | High | Destruction of habitat | Less than 30 km | Outside | Experimental populations – ecological compensation | PvP and PP |
| Torreya Guardians (www.torreyaguardians.org) | *Torreya taxifolia* | Endangered | USA | Unknown | High | Weakness in reproductive success | ~1600 km | Outside the actual distribution but inside the paleo-ecologic distribution | Independent social movement | PvP |
| **Integrity of ecosystems (Ecosystem-centered assisted migration)** | | | | | | | | | | |
| (O'Neill et al., 2008) | 15 common tree species of Canadian forest | Least concern | Canada (British Columbia)/USA | Medium | Low | Climate change | ~1000 km | Outside | Experimental trials in agreement with provincial and federal ministry. | PP |
| Beardmore team (www.rncan.gc.ca/forests/climate-change/13121) | 6 hardwood tree species | Least concern | Canada (New Brunswick and Ontario)/USA | Medium | Low | Climate change | Between 500 and 1400 km | Outside | Experimental trials in agreement with provincial and federal ministry | PP |

### 4.3. *The adaptive phase*

The adaptive phase is based on monitoring, learning and adapting management that should be reflected in any new AM policies. This last phase does not mark the end of AM actions because it is essential to see translocations and introductions as an iterative process of species and landscape management. Monitoring is essential in all biodiversity and ecosystem management programs, but even more so when a certain degree of risk is involved, as in AM where monitoring has multiple advantages. First, it allows the collection of data to understand how well suited recipient habitats are in compensating for climate change and it is therefore helpful in the design of future translocation programs (Dalrymple et al., 2011; Godefroid et al., 2011; Heller and Zavaleta, 2009; Piazza et al., 2011). For instance, *Abies nebrodensis* seedlings are followed every year in Italy and in the translocated populations using paternity analysis to monitor the reproductive success of different grafted individuals (F. Ducci, pers. comm.).

More importantly, detailed monitoring allows a rapid response in case of early warnings of maladaptation at the early stages of population establishment (Benito-Garzón et al., 2013; IUCN, 2013). In fact, we should always expect some level of maladaptation in AM because latitudinal and altitudinal changes cannot compensate exactly for climate change and also because expected climates cannot be compared with either 20th century conditions (Williams et al., 2007) or other climates in the recent geological past (Benito-Garzón et al., 2014). The question remains open of what level of maladaptation would be acceptable for the translocation to be considered acceptable.

## 5. From theory to practice: analysis of study cases

In this section, we analyzed a subset of cases from the scientific literature and from non-published sources that clearly state the use of the concept of AM. Several ecological interventions can be assimilated to one type of AM, but we selected cases where the AM terms are clearly mentioned to avoid confusion with ecological restoration programs or reanalysis of already existing tree provenance tests. For each case we considered the status of the focus species, the main threat and the main motivation for the AM program (Table 2). Two cases were in Europe, six in North America, and one in Asia. Translocation distances vary from as little as 30 km to as much as 1800 km.

From current projects explicitly stating AM or AC, we can observe more species-oriented AM cases (cases 1–7 in Table 2) than ecosystem-centered AM (cases 8 and 9 in Table 2) despite the very strict legal context of endangered species. In fact, proofs of demographic decline seem to be an essential step to start AM programs and the application of PvP approaches appears as a common sense decision for managers. Consciously or unconsciously, managers in the field follow the procedure described in the Section 4.1, highlighting the adequacy of our proposed implementation framework (Fig. 1). In general, to override constraints on endangered species manipulations, actors used a variation of the 'experimental populations' status to conduct their AM programs. Thus, this experimental population status found in many current regulations appears to represent an adequate solution, albeit a temporary one.

In contrast, for the last study cases (cases 8 and 9 in Table 2), the motivations are clearly different from conservation of a particular endangered species. These cases with common Canadian trees species closely match the first steps of an ecosystem-centered AM. In fact, these are mixed cases of AM experimental research and forestry improvement with common and commercially important North American species. Their motivation is based on economical concerns to find the best provenances and to maintain the productivity of forests despite climate change. These cases with common species potentially vulnerable to climate change correspond to the lower right box in Fig. 1 or strict precautionary approach. They are not yet a complete ecosystem-centered AM as we defined it previously, but they do represent the first research steps for future ecosystem-centered AM in the field. These programs involve the selection of the best genetic material for reinforcing ecosystems through extreme testing of populations for a ten-year or so period in order to understand the functional climatic limits of the species and obtain rules for population translocation distances.

Surprisingly, climate vulnerability does not seem to be a condition to implement AM programs. We found three cases with clear evidence of population threat or decline but where climate vulnerability has not been explicitly shown to be the cause of the current decline and even as a potential future threat of the species (cases 5, 6 and 7 in Table 2). For these three cases the motivations are context-specific. First, the AM program in Alberta represents a case where researchers test simultaneously the climate vulnerability of two regionally endangered species and conduct an AM program in a typical proactive and purely precautionary management. Second, the justification of the Chinese case was the threat of direct habitat destruction by urban expansion. In fact, this action is closer to an ecological compensation program to avoid biodiversity loss. Lastly, the well-known case of the Torreya guardians that have translocated seedlings of *Torreya taxifolia* to more northerly latitudes in North America represents an independent citizen action of very involved and proactive people. These three cases highlight that in different contexts, proofs of population decline or habitat destruction threat are sufficient to start AM programs even without climatic vulnerability evidence. We do not know if the number of such cases will increase or remain anecdotic in the future.

All these cases show that proven demographic decline is a powerful incentive to promote AM programs, whether climatically justified or not. Even if we have few and preliminary AM cases, the pragmatic approach seen here when dealing with clearly climatically endangered species points out that policies based on PvP approaches (demographic vulnerability) are probably more easily accepted than those based only on precautionary thinking that nevertheless is needed for the correct implementation of AM.

## 6. Implications for policymakers

Our study cases analysis highlight that current actions self-claimed as AM are mainly small-scale programs for endangered species, mostly adapting the 'experimental status' option, making them isolated from general environmental management policies. The inclusion of AM as an explicit climate adaptation option in environmental policies will involve integrating clearly climate change constrains in regulations and by consequence allowing for increased flexibility (Camacho, 2010), while improving at the same time the management of associated risks. This means that the risks of invasiveness, for example, would be considered not more important than the risks of extinction, so regulations could open windows to experimental translocations under controlled semi-natural environments. Here, the complexity is that policy-makers should implement regulations for two-fold precautionary actions, for extinction risks and AM risks. Probable extinctions could be avoided by facilitating appropriate management actions even if risky, and management risks should be decreased by a responsible, reactive and reasonable biodiversity management. Thus, experimentation must remain a first essential step to be able to measure the real extent of the risks involved. Concerning the risk of genetic pollution, management guidelines must consider integrating new ecological and genetic interactions because of the translocations. Even if genetic pollution could damage ecosystems it could also represent an opportunity for adaptation. Policy-makers and managers must accept that some degree of maladaptation could be the first step before natural selection adjusts populations to the new environmental conditions (Aitken and Whitlock, 2013).

Current policies for ecosystem management focus in providing and promoting adaptability, survival, resources provision, ecosystem services, and encouraging biodiversity conservation and recreational aspects. However, this multi-dimensional component may be more and more difficult to achieve in a changing environment. One option is to reconsider management goals and prioritize according to wider land use planning objectives with potential trade-offs between robustness (seen as the global perpetuation of a healthy ecosystem) and optimality (seen as the maximization of *certain* ecosystem services) of ecosystems. For example, degraded forests could be used as an experimental opportunity for AM by bringing new genetic material from lower latitudes and/or altitudes to reinforce local populations. This type of forest restored through AM would be managed for optimality in biomass production or carbon sequestration while other better conserved areas would be managed for biodiversity conservation. In turn, people using plants for restoring different habitats can follow the experimental approach example from the forestry community and set up seed certification schemes based on networks of reciprocal transplant tests to understand the functional limits of common species used in restoration.

Regulations should clearly address a transparent cross-sectorial coordination between science (researchers), local and national authorities (policymakers and implementation agencies) and technical support (managers and communications officers) where each have a key role in programs that manage living entities and ecosystems. Cooperative research initiatives like the "Ouranos" program created in 2001 in Québec (www.ouranos.ca) involving more than 450 researchers from different disciplines can bridge the gap between research policy and management. This type of program could serve as an example to conceive the implementation of AM, as they are capable of providing stakeholders with data, knowledge and a set of realistic options compatible with what is required in the field.

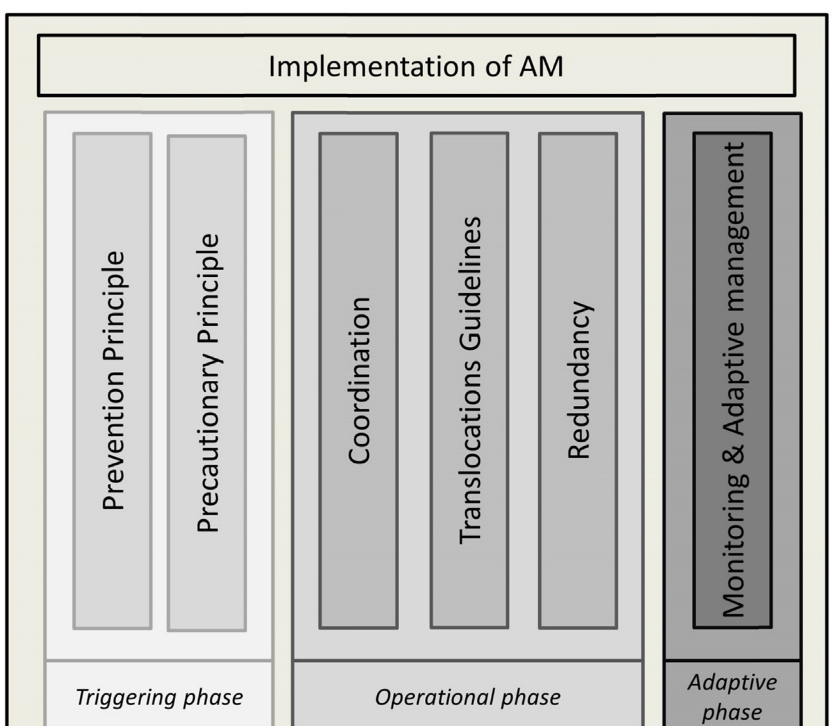


**Fig. 2 – Conceptual framework for the implementation of AM programs showing the three action phases.**

## 7. Concluding remarks

Today, AM is still barely used in environmental management because its associated risks have hampered its implementation. Nevertheless, we have seen that there are already legal norms and environmental principles (Fig. 2) providing grounds for its implementation as a climate change adaptation strategy. In any case, both types of AM as defined here should have an experimental stage before engaging in larger scale programs including redundancy and coordination approaches since the offset, as exemplified by the forestry sector. Besides, during this experimental stage, invasiveness, genetic pollution and enhanced evolutionary potential can be strictly monitored. Due to the costs involved, this sort of experimentation can only be done by large networks probably involving both the private and the public sector, and as mentioned earlier, should focus on familiar managed species.

It is essential that policymakers write regulations that provide a clear distinction between the PP and the PvP and interpret them for local applications (Cooney, 2004). Of course, implementing precautionary measures engenders higher political and economic costs than preventive actions and AM is no exception to this. As the legal context for 'classic' translocations depends on endangered species regulations – that we doubt will be relaxed soon – species-centered AM will remain inextricably attached to endangered species restrictions. Hence, it is likely that we will see in the future more cases of AM similar to that of the *Pinus albicaullis*, *Abies nebrodensis*, *Melanargia galathea* and *Thymelicus sylvestris*. These cases merged prevention approaches from factual evidence and precautionary approaches to anticipate for increased climatic risks in the future providing legitimacy and reassuring justifications to act. For other species for which few studies exist, or those that we simply do not realize are endangered due to climate change, managing and preserving local habitats and their interconnectivity may be the sole remaining option.

## Acknowledgements

We are grateful for funding obtained from the National Research Agency (ANR) which provided supported for the doctoral position of R. Sansilvestri through the AMTools French ANR project (ANR-11-AGRO-0005). We would also like to thank B. Colas for fruitful discussions about translocation practices, G. O'Neill for his invaluable insights in the subject and F. Ducci for details on the Sicilian fir program.

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Restoration Ecology
THE JOURNAL OF THE SOCIETY FOR ECOLOGICAL RESTORATION

RESEARCH ARTICLE

# One option, two countries, several strategies: subjacent mechanisms of assisted migration implementation in Canada and France

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**Climate change obliges societies to develop adaptive strategies in order to maintain sustainable management of resources and landscapes. However, the development and implementation of these strategies require dialogue between researchers and policy-makers about what they understand for adaptation. This dialogue can be hindered by language differences, the hidden agendas, and conflicting concerns of those involved. In this research study, we explored the mechanisms that underlie the implementation process of assisted migration (AM), an adaptation strategy that aims to limit the impact of climate change. We conducted a comparative analysis of 80 semistructured interviews with actors in the forestry sectors in Canada and France. In Canada, our results show a division between the provinces strategies, causing a debate about AM because researchers are wary of the geoengineering and economic arguments that frame AM in areas where the effects of climate change remain unclear. In contrast, we found that the observation of climate impacts is a strong trigger for the application of AM despite an awareness of its associated risks. In France, we explained the absence of AM implementation by a lack of information flow between research and foresters regarding the concept of AM, a cultural attachment of French foresters to their forest landscapes and that climate change effects are not clear yet. Clarity on what implies a true ecological engineering approach in ecological restoration can help maintaining adaptive actions like AM within the general scope of ecosystem management and minimize simplistic applications of adaptation strategies because of climate change.**

**Key words:** adaptation strategies, assisted migration, climate change, ecological engineering, geoengineering, implementation barriers, proactive restoration

### Implications for Practice

- Adaptation is an ambiguous concept with two different approaches, geoengineering and ecological engineering.
- Defining assisted migration (AM) as a totally new concept hampers its implementation.
- In Canada, AM raises debate because of a lack of distinction between the economic and conservation goals of AM.
- In France, despite AM being accepted by forest actors, the desire to preserve forest legacy blocks the application of AM.
- The observation of climate change impacts and the local forest culture seems to be the subjacent mechanisms of the AM implementation.

## Introduction

Climate change poses very real challenges to policy-makers and managers. These challenges are difficult to assess and predict, but they include the implementation of strategies to maintain ecosystem services. Faced with the environmental impacts of climate change, societies have two main strategies: mitigation and adaptation. Mitigation (essentially reducing $CO_2$ emissions) is a generally accepted concept that is both understandable and has clear guidelines for application. Mitigation is limited only by the success and scope of international negotiations and agreements that are often blocked by arguments regarding the uncertainty of climate change outcomes (Barrett & Dannenberg 2012). On the other hand, adaptation is a more national or local strategy whose methods of application are rather less clear. In contrast to mitigation, strategies for adaptation to climate change depend not only on human choice but also on ecosystem functioning, that is, the implementation of a relevant adaptation strategy must benefit both the well-being of and resource provision for humans, as well as the preservation of biodiversity and ecosystems. Compliance with this compromise almost always requires dialogue between policy-makers, scientific actors, and managers. Such dialogues are often complex and entail discrepancies between the concepts, language, and agendas of each actor.

Author contributions: RS realized all of the interviews, analyzed the answers, edited figures and tables, wrote and edited the manuscript; NFL contributed for the thinking about the ecological engineering and geoengineering; JFM is the project supervisor and participated to the analysis of interview answers and the edition of the tables.

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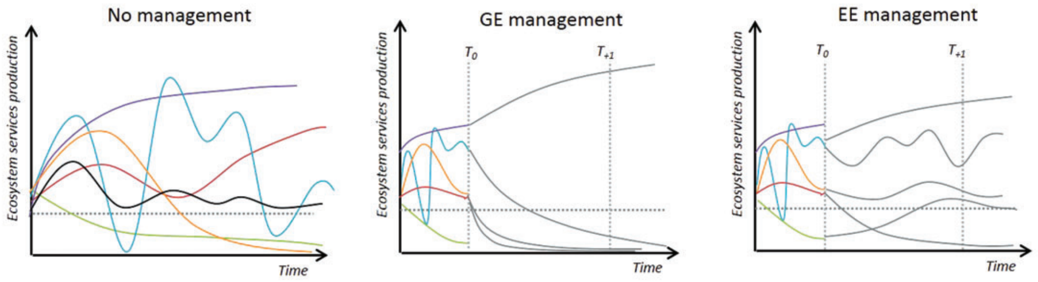
doi: 10.1111/rec.12343




| | | |
|---|---|---|
| The system, with known properties and functions, produces services. With no management the system evolves randomly to another unknown state with a possible decrease in service production or the production of different services. | <u>GE strategy :</u> Geoengineering management involves precise goals to avoid perturbations and change to the properties and functions of the system to maintain and increase the production of a specific service. <u>T0:</u> start of the GE management practices <u>T+1:</u> GE management maintains one trajectory of the system forcing to increase productivity. <u>Examples:</u> conventionnal agricultural system or mono-specific forest with inputs | <u>EE strategy:</u> Ecological engineering management guides the system to a new state of functioning, preferably one with a good production of ecosystem services, but services could be different from the currents. <u>T0:</u> start of the EE management practices <u>T+1:</u> EE management maintains several potential trajectories of the system attempting to preserve system integrity and eventually increase productivity. <u>Examples:</u> biological agroforestery or multifonctionnal forests |

Figure 1. Theoretical graphic representation of the effects of the no-management, geoengineering (GE), and ecological engineering (EE) management approaches to a system.

Even when stakeholders share the same goals, they diverge frequently on how to approach an adaptation strategy. Originally, in biological sciences, the term adaptation referred to Darwin's evolutionary theory of the nineteenth century, and could be used as either a verb ("to adapt") or as a noun. The verb describes the *process* of how natural selection preserves characteristics that permit organisms to survive and evolve in a given environment but with no precise ultimate goal. The noun refers to the *result* of the process as a particular organ or physiology has changed in response to environmental selection. However, in a climate change context, the concept of adaptation has evolved to place more emphasis on the ultimate goal of the process. In the report of working group II of IPCC (2007), adaptation is referred to as an "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effect, which moderates harm or exploits beneficial opportunities." Hence, in the public sphere, adaptation is commonly used to refer to a strategy that involves detailed processes and specific expected goals and is designed to cope with change and manage potential risks. Nevertheless, the strategy remains vague about what "adjustment" or "response" is required from society. Today, strategies to limit risks and cope with change in social-ecological systems fit into the development of "adaptive strategies," which could be described in two main ways, geoengineering (GE) and ecological engineering (EE) approaches. Adaptation strategy in this context should not be equated to adaptive management as the first refers to a set of objectives to cope with perturbation and the second with how any management decision should be monitored, evaluated, and reformulated periodically.

In the face of climate change, political actors are more likely to understand adaptation strategies in terms of the GE approach. The GE approach considers the strategy process to involve the accommodation of perturbations through a process of blocking or avoiding the impact of the perturbation (Keith 2000) (Fig. 1, center panel). The GE approach differs from traditional engineering because it addresses the threat to the global climate and develops strategies to cope with climate change. The most famous example is the deployment of aerosols of $SO_2$ into the atmosphere to limit solar radiation. With this type of adaptation approach, managers want to keep the existing functioning of the productive system from the impacts of climate perturbation, supposedly without changing the intrinsic system characteristics or functioning of the system. This type of strategy generates a rapid response of the system, but it implies regular interventions to maintain the sustainability of the system. Obviously, there is an uncertainty on the intervention and its consequences on the system evolution, and on the success of the management action.

At the same time, most researchers in the biological sciences think of the EE approach when invoking adaptation strategies. The EE approach considers adaptation as an intrinsic change of the system, that is, a perturbation such as climate change is accepted as a new element of the environmental condition. In this type of adaptive approach, the system has to change its characteristics, functioning, and thinking, perhaps in an unexpected manner, in order to remain sustainable (Mitsch 2012) (Fig. 1, right panel). It consists to maintain a process rather than a state and requires, in theory, one intervention at the beginning of the management. Moreover, one of the key characteristics of the EE approach is that the final system could be radically different from the previous system and there is a big time offset between the intervention and the adaptation of the system. Once again, there is uncertainty with this adaptation strategy concerning the success of the management action, and the rebalancing of the system after the intervention. This contrasts with the GE approach in which the goal is to maintain the same system. In both the GE and EE approaches, adaptation strategies require a dialogue between scientists and policy-makers to make the best choice for ecosystems and societies. This means that barriers to implementation can arise during discussions between stakeholders as a result of differing views of adaptation.

In recent years, a new adaptation strategy of assisted migration (AM) has been developed in order to limit the impact of climate change on biodiversity. AM is frequently defined as the human voluntary movement of individuals or populations from a site where they are threatened by climate change to another site where they are not currently present but where we suppose they could survive under future climate predictions. However, in an ecosystem restoration context, AM has also been defined as the integration in a target ecosystem of individuals or populations supposed more robust face to changing conditions in order to reinforce the local ecosystem (Kreyling et al. 2011; Sansilvestri et al. 2015*a*).

The proposition of AM has not been greeted with unanimous enthusiasm in the scientific community. Between 2005 and 2011, AM caused a fierce debate about the associated risks, with conservatives concerned about the biologic and genetic risks of AM opposing interventionists who wanted to act proactively against the climate threat (McLachlan et al. 2007; Neff & Larson 2014). Many researchers have attempted to use scientific arguments to settle the debate but with little success, in part because of the ethical, political, ecological, and economic issues (Schwartz et al. 2012) that complicate decision-making processes regarding the artificial movement of individuals or species in the face of climate change.

The view of AM as a completely new management practice mainly for species conservation has inscribed it de facto as a forceful manipulation of nature and made it more likely to be embraced by those with political agendas that entail a need to show results in combating the effects of climate change. However, AM is not in fact a new concept. Gardeners and foresters have been moving plants and trees for millennia (Pardé 1924) without causing much debate. The novelty of the proposition is only in the use of intentional movement as an adaptation strategy in a climate change context. Most definitions and applications of AM are at the scale of species, which means that they take a GE approach to AM that involves the movement of threatened species from one unsuitable site to another in order to recreate the same system without changing the practices used to manage that system. Even if the GE approach supposes a robustness of the intrinsic functioning of the system, there is always a risk to change the target ecosystem with the movement of species. Yet, as Seddon (2010) has proposed, AM can also be applied from an EE perspective at the scale of community, which implies a holistic and adaptive approach. In this case, AM could be thought as a restoration practice for communities impacted by climate change. This type of management represents a proactive restoration with the aim to build new ecological communities that create new suitable habitats for future environmental conditions with a concomitant change in management practices (Fig. 1, right panel) (Sansilvestri et al. 2015*b*). Hence, the shift from a GE to an EE approach implies an extension of AM to the natural communities and landscape management, rather than a sole focus on species or population management. Today, AM is mainly envisaged as a type of management for forest ecosystems on a species-by-species scale, but it could take different forms in the future according to the scientific view, political and social considerations.

Considering the slow migration rate of trees, forest ecosystems represent a good candidate for AM. However, forest characteristics also exacerbate the complexity involved in the implementation of climate adaptive strategies. With very large temporal scales in their development, there are crucial issues in the sustainable management of forests in the uncertain context of climate change. The selection and planting of trees must be suitable not only for today and the next 30 years, but must also remain appropriate for the following 60 or 100 years and beyond. A key challenge in restoration of forests and forestry is therefore to maintain the evolutionary potential of tree species and/or populations (Williams & Dumroese 2013) while maintaining productivity.

In this article, we offer an analysis of data collected from semistructured interviews with French and Canadian forest actors who have considered, or who are actively involved in, the implementation processes of AM in forest ecosystems. These two countries represent good candidates for the application of AM programs because of their steep climatic gradients, their potential vulnerability to climate change, and the important position of the forestry sector within the two countries as a whole. The goal of this analysis is to determine the factors that influence decision-making in relation to the implementation of a complex adaptation strategy such as AM, and the potential barriers to its implementation. Our specific questions are (1) what are the subjacent mechanisms in Canada and France that facilitate or constrain AM implementation processes? And (2) what are the lessons that can be learnt from Canadian and French examples of the implementation of AM in forest ecosystems?

## Methods

Our study was conducted in Canada and France. For the Canada, interviews were conducted during the spring of 2014 in four provinces: Quebec, Ontario, New Brunswick, and British Columbia (Fig. 2B). These provinces were chosen because they currently have AM programs. In Québec, Ontario, and New Brunswick, programs are, for the time being, experimental. In British Columbia, programs include species conservation, experimental research, and official large-scale initiatives. In France, interviews were conducted between August 2014 and February 2015 in five French forest regions: one mountain Alpine forest, one Mediterranean forest, two temperate forests, and one Atlantic forest (Fig. 2A). These regions were chosen in view of their ecological, economic, and climatic vulnerabilities, which mean that AM could be a relevant management option in these areas. Here, we present a comparative analysis of AM in France and Canada on the basis of semistructured interviews that form part of another study on forest social-ecological vulnerability, which we discuss in details elsewhere. In total, 80 semistructured interviews were performed in the four provinces

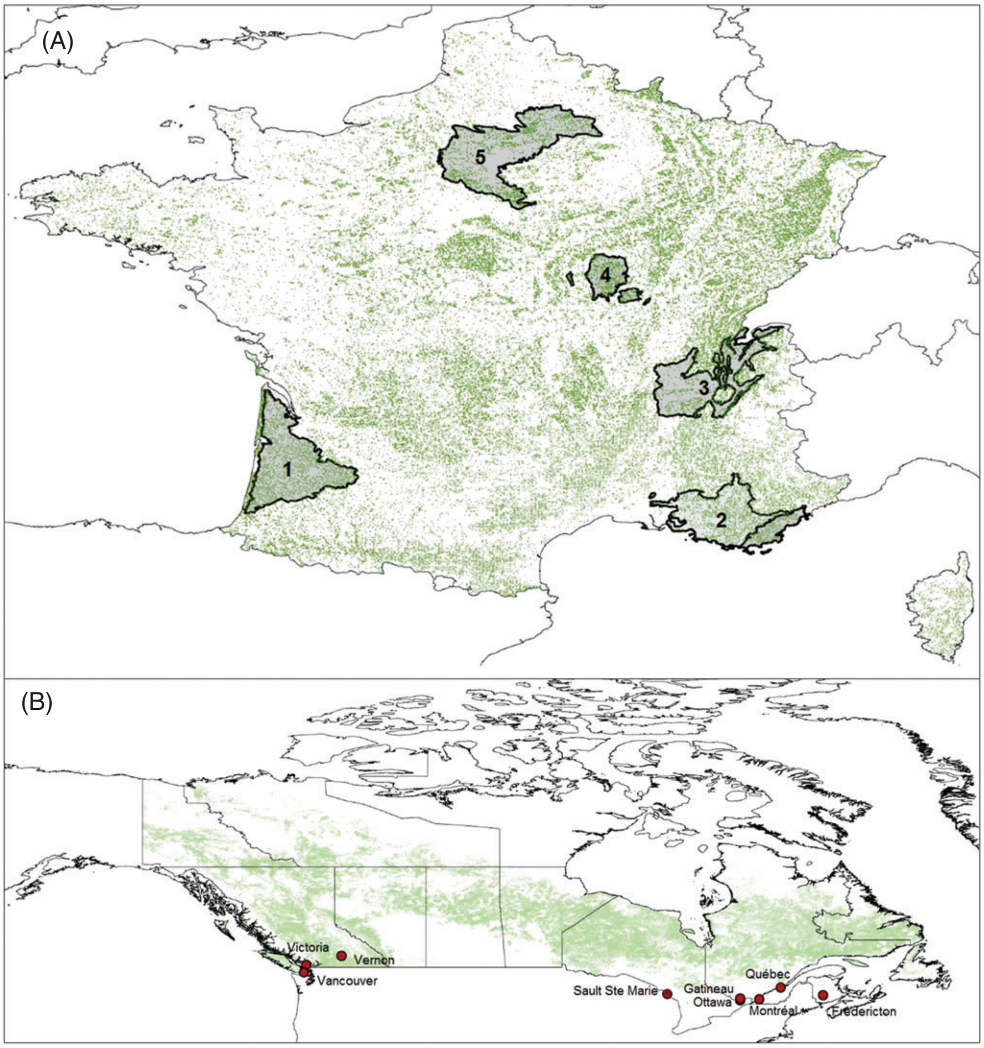



Figure 2. (A) Map of France with the location of the five selected forest regions 1: Atlantic region; 2: Mediterranean region; 3: Alpine region; 4 and 5: Temperate regions; (B) Map of Canada with the different sites visited.

of Canada and in the five regions of France. In Canada and France, interviewees were researchers, institutional officers of the respective national forest offices, members of the forest/natural resources ministry, technical field managers, and industry people. Three types of interviews were designed, one for the private forest owner, one for the forest policy-makers, and one for the forest members company. The semistructured interviews are characterized by the absence of proposed answers, the interviewees are free in their answers, and the text is analyzed using as much as possible the interviewees' point of view. The lists of questions are available by request to the first author.

## Results

In this section, we proceed to a comparative analysis between Canada and France, and we attempt to understand why it seems to be easier to move trees in Canada than in France (Fig. 3).

### AM in Canada: Contrasting Visions Across Provinces

Even though AM programs have already been implemented in Canada, there are opposing views and complex debates separating the reactive eastern provinces (Quebec, Ontario, and New Brunswick) "*AM is an interesting idea but there are still too many uncertainties*" (*Forest researcher 1, Ontario*); and the proactive province of British Columbia (BC) "*AM represents a good tool to diminish the stress caused by pests, insects, and climate*" (*Forest genetic institute member 1*, *BC*).

For the eastern provinces, the biggest barrier to AM is the differences between the approaches of scientists and decision-makers. The former take an ecosystem approach to AM, akin to the EE approach, whereas the latter take a species-centered economic approach (assimilated to GE approach). For many actors, AM is seen as a lure of the attractive to governments as a way to avoid the implementation of mitigation policies. "*AM was proposed as THE solution to maintain good healthy forests in the face of climate change, but in reality*

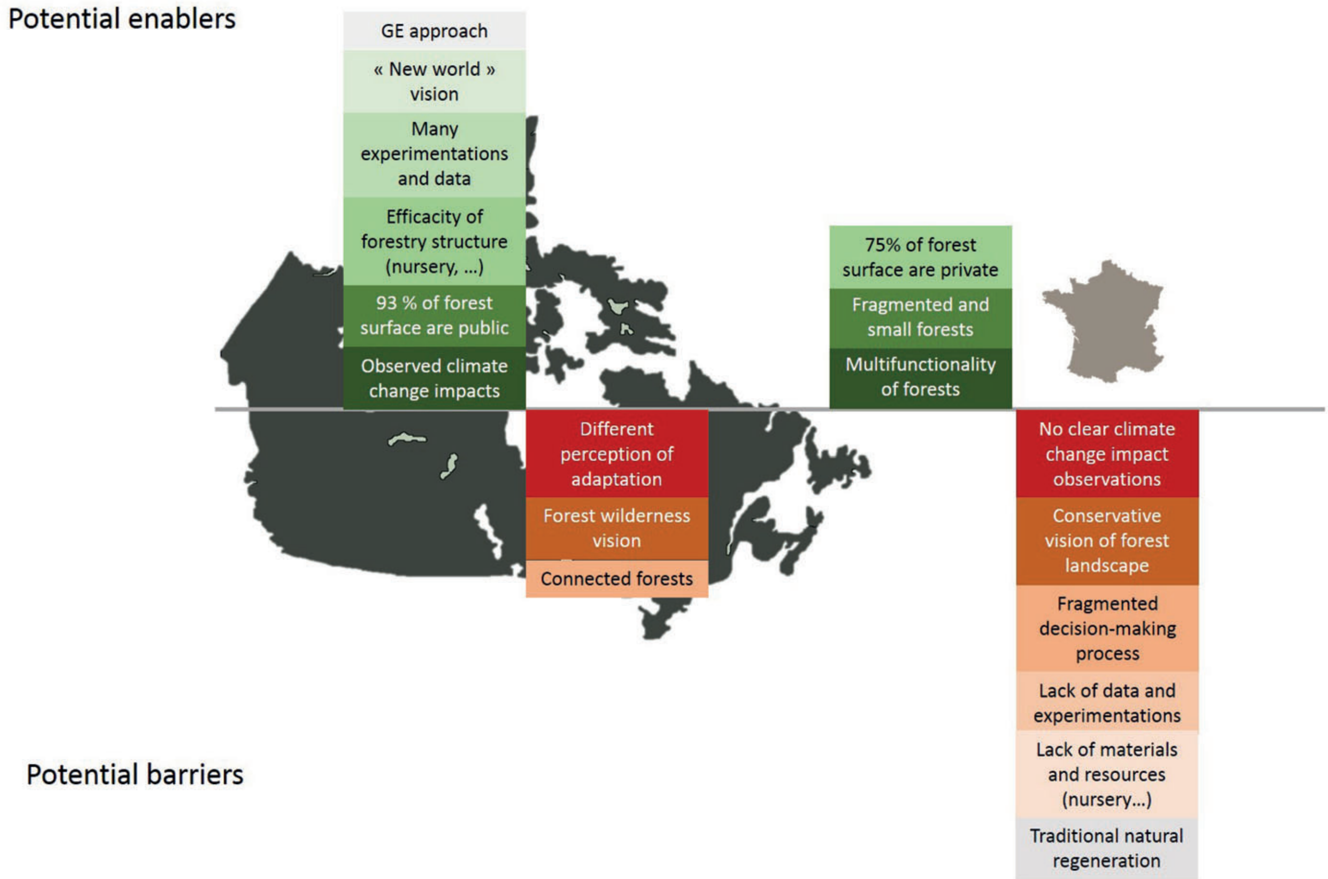



Figure 3. Graphical representation of subjacent mechanisms of assisted migration implementation for Canada and France. In green, the potential enablers of assisted migration implementation. In red, the potential barriers of assisted migration implementation. More the color is dark more the mechanism has an important role in the process.

*AM is mainly developed to maintain and increase the productivity of forests*" (*Forest researcher 2, Ontario*)/"*AM is a tool, is not the only tool that exists but it is the only tool that politicians want to use. Government uses smoke and mirror with AM implementation to avoid involvement in a mitigation strategy*" (*Forest researcher 3, Ontario*). The Natural Resources Ministry funds a large spectrum of research on AM to develop knowledge (http://www.nrcan.gc.ca/forests/climate-change/13121) at the provincial level. Currently in the eastern provinces, AM programs are experimental or in the initial stages of conception; researchers use provenance tests and forest data (Table 1) to review seed guidelines for forest management within the provinces. For example, the Ontario Forest Research Institute supervised a project to assess AM as a climate change adaptation (Eskelin et al. 2011). AM programs exist mainly for tree species with economic value. Yet, as Hewitt et al. (2011) have pointed out, AM programs conducted for economic rather than for conservation benefits represent a barrier to the social acceptance of AM. Hence, scientists in these provinces feel cheated by government policies and forestry management choices, and believe that economic issues are considered more important than ecological issues. Researchers interpret government actions as "green-washing." "*Today, lobbyists divert government and research money from mitigating the impact of climate change to a focus on adaptation in order to maintain business as usual and bet on adaptation like geo-engineering*" (*Forest researcher 2, Ontario*)/"*AM is not helpful, except for some endangered species. For the rest it is just an economic issue*" (*Forest researcher 4, New Brunswick*).

Within the multiple definitions, the species-focused definition of AM allows decision-makers to interpret the adaptive action of AM only from a GE approach. In addition to the debate about the risks of AM, we witnessed specific discussions inside the Canadian scientific community about its definition. Many papers have been published that describe differing types of AM (Seddon 2010; Ste-marie et al. 2011; Aitken & Whitlock 2013), and discuss whether the movement of a species should be *beyond* the existing distribution, *inside* the existing distribution, or *at the limit* of the existing distribution of the concerned species (Table 1). Yet, all of these definitions focus on species or populations as the unit that is moved during AM, suggesting that the existing system can be maintained but moved to limit the impact of climate change and supporting the "business as usual" view of decisions-makers regarding forest management. Sadly, no definition conceptualizes AM at the scale of community or ecosystem management (but see Pedlar et al. 2012; Sansilvestri

**Table 1.** Differences between Canada and France with regard to the concept and implementation of AM.

| | *Canada* | *France* |
|---|---|---|
| Forest property | Stated owned, given by concession to companies | Private ownership mostly (75%), but the state exploits forests as well |
| Forest goals | Either production or conservation | Multidimensional objectives including management of heritage sites |
| Extant AM debate | Yes | No |
| Widespread definition | The movement of species or populations with some debate about whether movement takes place within or outside of the current range of the species | The movement of species or populations beyond the existing range of species |
| Knowledge of the AM concept | Well known to all forest actors | Known to scientific and policy forest actors but unknown to forest managers and owners in the field |
| Type of species considered | Local and in some extreme cases nonlocal species but from the same continent | Nonlocal species (same continent) but also exotic species |
| Implemented in official programs | Changes in regulations for *Western larch pine* plantation in British Columbia | No |
| Policy development | Advanced thinking in Ontario and Québec concerning changes in seed provenance regulations | Some hesitancy about seed provenance recommendations |
| Experimental programs (nonexhaustive list) | Yes. Optisource (Québec, Beaulieu 2010); SeedWhere (Ontario, McKenney et al. 1999); the *eastern white pine* study (New Brunswick, Major 2012) AMAT Trial (British Columbia (O'Neill et al. 2008); *Whitebark pine* case (British Columbia, McLane & Aitken (2012)) | Unofficial and in early stages, anecdotal |
| Main policy goal | Contradictory issues in Quebec, Ontario, and New Brunswick. Productivity and conservation issues in British Columbia | Mainly to maintain forest productivity and genetic conservation |

et al. 2015*a*, 2015*b*). This limits the possibility of the evolution of a more ecosystem-centered approach to AM, which in our opinion is a better approach in a climate change context to restore and reinforce the integrity and the functioning of ecosystems for current and supposed impacts.

In BC, like in most Canadian provinces, there is recognition of the risks of AM, and there are some actors who are against it. However, despite this, the BC forest administration has implemented a new seed regulation for one species, the Western larch pine, which makes changes to the regulations governing altitude planting (O'Neill et al. 2008; Klenk & Larson 2015; Natural Resources Canada, http://www.nrcan.gc.ca/forests/climate-change/adaptation/13121). With this modification, the Western larch pine can now be planted 100 m higher in altitude to compensate for observed climate change impacts and preserve productivity. Because of the importance of the forestry sector in BC, AM management has been accepted rapidly as a means to maintain both wood productivity and the integrity of forest ecosystems, and for genetic conservation (Table 1) "*AM is a good tool for resilience and to respond to a threat like climate change where we do not know the exact nature of change*" (*Provincial forest officer 2, BC*). In recent years, the provincial natural resources ministry and the Forest Genetic Council of BC have funded many research programs (Table 1) to develop knowledge about genetic issues and wood productivity "*We need more knowledge of species and ecological indicators, AM outside of ecological range needs a genetic assessment. It is a tool to develop*" (*Forest researcher 5, BC*).

Currently, AM policy in BC is proactive and involves the implementation of large experiments and new regulations. These initiatives are implemented by decision-makers despite the existence of some debate. Because the discourse surrounding them is characterized by strong arguments about forest management, they succeed to go through the conservatory debate (Klenk & Larson 2015). The proactive policies of BC can be explained by three suppositions. First, BC is characterized by a steep and complex climatic gradient, which makes this province a good, and perhaps involuntary, candidate for AM. This complex climatic gradient allows the presence of many specialist tree species within specific distribution areas. Moreover, a report by Hamman and Wang (2006) demonstrated that big changes in BC ecosystem climates are expected, which represented an additional argument to consider AM as an interesting option to maintain the integrity and productivity of forests. Second, BC has already been affected by climate change, with waves of mortality caused by epidemics of the "mountain pine beetle" and large fires caused by heat and drought. Government scientists and decision-makers used these events as an opportunity to garner support for proactive management. To avoid a sharp politic or scientific u-turn, the new regulations have been implemented as a "range expansion" of the species and not as an introduction: "*People think that AM means that we lose the* *existing distribution of species with a shift of distribution, but in reality, it is an expansion of species distribution*" (*Provincial forest officer 1, BC*). Third, BC benefits from a very organized and efficient forest management structure with a Tree Seed Center that centralizes all the tree seeds in BC, and a Seed Planning Registry for the selection of seed lot. Hence, each year BC has the capacity to plant more than 250 million tree seeds for future harvesting, which facilitates the application of AM programs. Furthermore, there is a developed and supported genetic conservation policy within the Forest Genetic Council. For researchers, the recent move toward AM in BC represents a "*transition from tree improvement to genetic management*" (*Forest researcher 6, BC*). However, even though AM seems to be more accepted in BC, its application is still at the scale of species (for conservation e.g. *Whitebark pine*, and for productivity e.g. Assisted Migration Adaptation Trial or *western larch pine*). This raises the question of whether this discourse will lead to the implementation of more extensive and far-reaching AM programs, such as the introduction of exotic species and larger scales of operation in BC or in other provinces, or form the basis for a future EE approach to AM.

For the time being in Canada, we could observe that policy-makers have appropriated a concept of AM that is constrained to the movement of a particular species. This situation could be explained, *inter alia*, by the existing administration of forest landscapes, which separates forests by their functions. In Canada, forests are either a conservation area (national parks) or a productive area (forest with exploitation license). This means that the potential of AM management practices to increase the adaptive capacity of forests is not a high priority, and AM is instead used for the strict management of one species, for either economic or conservation purposes.

### AM in France: Some Hesitancy and Big Forest Legacy

Historically, forests and forestry have been very important in France, with its influential forest culture and a long tradition of *savoir-faire*. We selected five forest regions with economic, historical, social, climatic, and ecological issues, which suggest that AM could be a management option for these regions. This allowed us to analyze possible implementation processes of AM in France (see Fig. 2).

With a steep climate gradient from Mediterranean to Alpine areas including the Atlantic climate, French forest researchers and ministry members recognize that France represents a good candidate for AM programs (*Forest officer 1, French forest ministry*). However, there are currently no official AM programs in France, even at the experimental level (Table 1). Contrary to Canada, the proposition of AM in France has not created a debate "*The idea of species movement is accepted but we are still thinking about it*" (*Forest researcher 1, Forest National Office*). Scientists in France, as in Canada, have raised the question of the risks involved in AM and the uncertainty of climate change outcomes (Benito-Garzón et al. 2013), but they will consider implementing AM in future forest management if adequate evidence of the benefits exists (Benito-Garzón & Fernández-Manjarrés 2015). In general, forest researchers and the forest ministry are publicly in agreement in forums and workshops about the development of new forest regulations; AM has always been considered as an interesting option for both parties. This consensus can be explained by the historic profile of forest management and the relationship between forest and foresters in France.

French foresters (in both public and private forests) probably identify more with their forests than Canadian foresters, and in consequence feel these forests as their own living spaces. This may be because French forests are mainly small and accessible. On the contrary, the Canadian unexploited forests, with their large and wild characteristics, create a "wilderness" vision of forests even if the forestry practices are harder than in France. Moreover, today there are few natural or primary forests in France; forests have been highly managed either in the past or presently and their characteristics are now the result of earlier human management choices. For instance, since the seventeenth century, French forests have mainly been managed in order to produce wood for economic and military interests (Polge 1990). Hence, the economic importance of forests is largely accepted in France "*The management of forest is an act of optimization, we are very proud of our tree production*" (*Forest manager 2, French temperate region*). The biodiversity aspect came later, at the end of the twentieth century with the "green" movement. This movement initiated a multidimensional vision of forest management in France, which means that economic, social, and biodiversity aspects must be taken into account in management choices, at least at the level of regulation even if not in the minds of all stakeholders. This multidimensional vision potentially helps to avoid a narrow focus on the AM of species only, as is the case in Canada. Hence, we could assume that in France AM could be applied at the scale of the ecosystem in line with the EE approach.

Despite this consensus and willingness to apply AM in managed forests, there are currently no AM programs in the field, not even for single tree species. This could be explained by three assertions. First, AM is regularly discussed and proposed in ministry and research meetings. Yet, managers and owners in the field are not usually aware of this type of management. The impact of climate change has not yet been considered widely in forest management in France. "*Even if we've talked about climate change for a long time, for the moment, we do not observe climatic impacts in our forests. So it is not tomorrow that we will begin to act*" (*Forest private owner 1, French Atlantic region*). The extent of this gap in knowledge between institutions and managers may derive from the fragmentation and breakdown of French forest governance. The long history of mainly private ownership of forest in France has generated an accumulation of stakeholders who interact at different levels of forest management. These complex frameworks of actors make the transmission of information between stakeholders difficult. Forest owners do not know who to talk to and forest operators are too busy with industrial competition to take on the role of providing a bridge for information "*We hear lot of things; we do not know whom to believe*" (*Forest private owner 20, French Mediterranean region*). At present, French forest

**Table 2.** Forest characteristics and main barriers to tree species change in different regions of France.

| *Region* | *Species* | *Climate Vulnerability* | *Barriers to Species Change* |
|---|---|---|---|
| Atlantic region: South West of France | Maritime pine (*Pinus pinaster*) | Storms, droughts, and pests | Emotional and cultural attachment. Strong industrial attachment |
| Temperate region: East of France | Douglas fir (*Pseudotsuga menziessi*) | Not yet, but models suggest high risk because of heat | Industrial development |
| Temperate region: North East of France | Common beech (*Fagus sylvatica*) | Droughts | Strong emotional attachment |
| Mediterranean region: South East of France | Atlantic cedar (*Cedrus atlantica*) | Droughts | Cultural attachment and landscape conservation |

governance is undergoing reform as a result of changes to the recommendations on provenance made to managers and forest owners. However, rather than using this reform to implement a new strategy or new recommendations for AM, the ministry remains cautious probably because they fear the failure of AM. For the moment, the committee in charge of changing the 5-year report of recommendations on the provenance of tree seeds (two forest officers from the forest ministry, two forest engineers from the Environmental and Agronomic Research and Technological Institute, four forest researchers from different research laboratories, one forest PhD student, one forest industrialist, and one forest manager from a private forest management institute) have limited their output to recommending the use of seeds from the southern adjacent area of the previously recommended area and only for a few species (Sansilvestri R, 2014, Université Paris-Sud, Paris, personal observation). In practice, there is a real will to change the regulations on provenance but the committee has few resources for the implementation of these new regulations. Moreover, they are afraid of a possible backlash against them by forest actors (Sansilvestri R, 2014, personal observation) if AM involves relocations that are too far removed from the present locale of forests. "*Regarding the question of whether to act or not, people are torn. Hence, we remain cautious about recommendations*" (*Forest officer 2, French forest ministry*). So, unlike Canada, the barrier to AM implementation does not come from a divergence in opinion about forest management between researchers and ministry officers, but from extreme caution due the potential of AM to create thousands of disconnected private forest owners.

Second, the history of forest management creates a strong forest culture and a conservative vision of forest landscapes. Managers are rather conservative concerning landscape management and the choice of tree species. Surprisingly, many species in France have been imported (e.g. *Pseudotsuga menziessi*, *Picea sitchensis*, *Acacia* … ), but many managers and forest owners now consider them to be "native" because they have naturalized over the course of the last century or two. Climate change in France is exacerbating the marginal condition of some species and is highlighting the negative management choices of the past: "*[Climate change] reveals our past mistakes*" (*Forest manager 2, French temperate region/Forest manager 11, French Mediterranean region*). This is the case for *Abies alba* in the low Alps or *Fagus sylvatica* marginal populations in Eastern France (Frascaria-Lacoste N, 2015, AgroParisTech, Paris, personal observation) for instance. Despite these early warnings of climate change effects, foresters are not willing to change species because of emotional or economical attachments (see Table 2), but also because of an interest in keeping the current landscape features of their forests.

Contrary to the intensive use of seeds in Canada, particularly in BC, the species composition of forests in France is controlled mainly through selection during the natural regeneration of trees. French foresters have a rather technical vision of forest management. Hence, even though there is a possibility of natural reorganization of forests through natural regeneration, the proposition to artificially change the distribution of species through AM is very difficult to implement in the field: "*The social acceptance of new forest landscapes is the main barrier to adaptation policies*" (*Forest manager 9, French temperate region*).

Lastly, French forest research currently involves few experimental programs and the collection of data from provenance tests is not on the level and to the extent that would be required to make decisions for climate change adaptation. All researchers agree that there is a need to increase knowledge about the ecological characteristics of tree species, genetic issues, and provenance tests: "*There are few resources allocated to forest research, so there is a big lack of knowledge, especially for species distributions*" (*Forest Researcher 2, French Mediterranean region*). This problem of lack of resources is clearly understood by forest managers: "*There is no budget. We see the research institutions coming with research programs but after a few years everything is abandoned. There is lots of data there if we bothered to collect it*" (*Forest Manager 8, French temperate region*)/"*We need resources to implement experiments in the field to show concrete results to foresters*" (*Forest Manager 10, French Alpine region*). For example, it can be noted that there are no provenance tests being set up between France and other countries further south such as Spain, Italy, Morocco, or Tunisia, which could anticipate the effects of a potentially warmer climate in the south of France in future. France remains a little reticent about experimental programs compared with Canada or even other European countries. This can be explained by fragmented forest management in France and lower investment in any kind of forest research that does not focus on genetics and genomics.

## Discussion

Adaptation and AM are complex concepts that need to be precise and context-specific. In this article, we have examined the impact of the ambiguous definition of AM, caused by the differences between GE and EE approaches to AM. The GE approach is often better understood and more accepted by decision-makers because it allows the development of specific tools with precise goals, such as the movement of a specific tree species from one area to another to maintain its productivity, as we saw in Canada. Moreover, the GE approach is more accepted because in theory, it does supposedly not change the system intrinsically. But, the GE management, despite its simplicity, implies also risks and uncertainty concerning the success of the management and the reaction of the ecosystem to the intervention, as genetic pollution, biological invasion, or unforeseen effects on ecosystem functioning. An AM application with GE approach, that is, maintaining a productive tree species with a simple relocation, promotes the risk of ecosystem collapse because of the focus on only one dimension of the system. On the contrary, the EE approach to AM is more daunting because of the uncertainty caused by changes to the system and because it is difficult for nonscientists to understand its application in the field. The EE approach to AM involves allowing the system to change freely according to its own dynamics. Again, there is a risk of failure and uncertainty on the ecosystem evolution. However, this ecosystem approach allowing biological mechanisms to compensate each other, diminish the risk of collapse with the possibility of a natural evolution of the system. The desire for complete control of the forest system could explain the slow implementation of AM in France, despite the fact that a multidimensional vision of the forest exists there. Moreover, French foresters are afraid to lose the control on forests. To promote the evolution of forest management in a climate change context, it is very important for researchers to advance complex notions case-by-case to avoid misunderstandings occurring in dialogues between scientists and decision-makers. For France and Canada, definitions should include precise goals, risks, issues, and guidelines.

We believe that it is essential to take an ecosystem vision to define AM with an EE application. This approach could allow a less controlled vision of ecosystems which is important in an uncertainty context like climate change to let the possibility of both management and ecosystems to evolve. The application of AM in a mono-directional manner appears easier technically and economically than a more ecosystem-centered approach, but there is a substantial risk during manipulations of ecosystems of a consequent loss of biodiversity and function diversity. The EE version of AM is very recent, so its conception and implementation will take many years. Meanwhile, foresters should move beyond a technical approach to forestry and consider managed forests as living systems with their own independent evolution. In other words, we must support ecosystems rather than try to dominate them.

The comparative analysis between France and Canada demonstrates that the introduction of new species to forests is a social barrier to the implementation of AM in both continents, but not for the same reasons. The differentiation between productive and protected forests limits the likelihood of AM being approached from an EE perspective in Canada. In a protected forest, it is difficult to implement AM programs beyond those that aim to protect and conserve specific endangered trees (e.g. *Whitebark pine*), which means that the application of AM is reduced to the monitoring of one species. In a productive forest, management is influenced by what could be called a "new world" culture involving a vision of limitless and controllable resources, which facilitates the implementation of AM programs only for economic goals with a "hard" GE approach. In all cases, forest management is limited to the strict management of one species, for the fulfillment of either economical or conservation goals. This limits the potential of AM to increase the adaptive capacity of forests. In France, foresters (in both public and private forests) are attached to the forest landscape and wish to conserve the forest legacy even if it includes non-native naturalized species, while in Canada most foresters wish to conserve the wilderness of the forest. A new integrated version of forest management that would include both French and Canadian visions could introduce more flexibility to managed forests and provide more space for wilderness as in Canada, as well as meeting explicit economical goals, as in France.

In sum, this comparative analysis highlights that evidence of the impact of climate change on trees is a powerful trigger for the implementation of AM programs in forest management, and we are certain that this will be the case when other cases with endangered species or ecosystems appear. Perhaps, if the resource in question is private that do not necessarily accept a top down approach, like foresters in France, adaptation strategies can undergo a long scrutiny that may highlight their advantages and disadvantages before they are implemented. Only time will tell if when climate change effects become more apparent in France, AM would be applied at the ecosystem level respecting local biodiversity, or if productivity approaches will dominate.

## Acknowledgments

We are grateful for funding from the National Research Agency (ANR), which provided support for the doctoral position of R. S. through the AMTools French ANR project (ANR-11-AGRO-0005). We thank G. O'Neill for his invaluable help on the subject and the many informative discussions. Finally, we thank sincerely all the actors who participated in the interviews and who offered their time to the project.

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*Coordinating Editor: Vicky Temperton*

*Received: 4 September, 2015; First decision: 10 November, 2015; Revised: 14 December, 2015; Accepted: 6 January, 2016*