Concept Paper

Forest Regeneration at WSL: Perspectives for Research and Implementation

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Summary

The purpose of this concept paper is to give an overview of tree regeneration research at WSL and to describe how it is organized. Regeneration includes all processes from seed production over seed dispersal, seed germination, seedling establishment to ingrowth to the tree layer. It encompasses both artificial and natural reproduction and genetic aspects. We found 43 WSL projects active in the period 2012-2021, most of them funded by FOEN or by Cantonal Forest Offices. The total third-party funds of these projects amounted to 10.0 million CHF. The projects were led by principal investigators (PIs) from eight Research Groups (RGs) in five Research Units (RUs). During this period, 195 publications with WSL authorship on regeneration topics appeared in scientific and technical journals, with 150 of them having been subjected to peer review. The annual number of publications tripled within 10 years.

WSL maintains hundreds of long-term experimental sites for investigating regeneration, which form an important infrastructure for future regeneration research. Undoubtedly, WSL is the leader of tree regeneration research in Switzerland. Yet, we found only few review papers on regeneration in the international literature. This lack creates opportunities for internal cooperation. Given the competence of its researchers and its large research infrastructure, WSL is in an excellent position to address future challenges in regeneration research. The regeneration topic is also well anchored in the WSL development plan for 2021-2024. We identified six topics of particular importance: demography in juvenile tree populations, environmental niches of juvenile trees, browsing effects on juvenile trees, improved simulation models, improved sampling designs and regeneration indicators, and silvicultural management for climate change adaptation. Interviews with forest practitioners conducted for this report showed that these topics are in line with practical needs. Practitioners expressed a clear and increasing demand for science-based guidance to improve their management.

The high number of organizational units (RGs and RUs) involved in regeneration research reflects different facets of regeneration, and the variety of methods used in regeneration research. The authors of this concept paper intend to increase their cooperation, by organizing regular meetings and more coordination with regard to, e.g., harmonization of methods, common proposals, publications and outreach activities.

Picture on title page: *Abies alba* seedlings, experimental area Visp, Mountain forest regeneration project. Photo Peter Brang

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Glossary

Artificial regeneration	Stand of young trees artificially established by planting or sowing
Assisted gene flow	Human-aided translocation of individuals ('genes') within the natural range of a species. It implies that the translocated individuals would introgress their genes into the native population ('gene flow').
Assisted migration	Human-aided translocation of individuals outside the natural range of a species
Natural regeneration	Regeneration resulting from natural seed dispersal or vegetative reproduction, unlike artificial regeneration
Regeneration	1) Population of juvenile trees; 2) the process of their establishment (i.e., the term can have both meanings). In this concept paper, the processes seed production and seed dispersal are also included.
Sapling	Juvenile tree of intermediate size, i.e. ≥ 1.3 m but with dbh < 12 cm. The height threshold of 1.3 m is used to differentiate a sapling from a seedling.
Seedling	Small juvenile tree older than one year but < 1.3 m. Here, a height threshold of 1.3 m is used to differentiate a seedling from a sapling.

1 Mandate and scope

Tree regeneration (called hereafter 'regeneration'), is the process of generation replacement in trees. It is an important sub-process of forest dynamics, during which the species composition of the future tree layer is to a large extent defined for the next tree generation, i.e. several decades to several centuries. Regeneration is thus crucial to forest adaptation to climate change, and - also because of that - has been a long-term topic in WSL research.

The WSL directorate has approved a third-party funded permanent position for a scientist in the field of 'Natural Forest Regeneration' in October 2021. In this context, the directorate has asked the leader of the Research Unit 'Forest Resources and Management' to submit a concept paper on regeneration research at WSL. The directorate wanted to get an overview on how the subject is organized at WSL regarding personnel and topics. In particular, it should be clarified which staff is involved and how it interacts, and what topics are covered.

The objective of this concept paper is to provide the requested information. Specifically, we show the relevance of the topic and how it is organized at WSL, and describe the perspectives for WSL research and outreach. Moreover, this concept paper is for us, the group of scientists working on different aspects of regeneration, a first step to foster institutional cooperation, e.g. by identifying synergies in research, or fostering future common publications or project proposals.

The geographical scope of this concept paper is Switzerland, but other countries in which WSL scientists are conducting regeneration research have also been included.

2 Procedure

Peter Brang, who was tasked by Marco Ferretti with coordinating the elaboration of this concept paper, organized a virtual workshop on 4 February 2022, to which all scientists potentially active in regeneration research were invited. During this workshop, the structure of the report was discussed and material for the concept paper gathered. After the workshop, the participants provided information on projects and publications on regeneration topics for the period 2012-2021, completing data derived from the WSL project database and the Dora publication repository (the query is in the Annex 9.3). In addition, P. Brang interviewed four scientists and three practitioners outside WSL (see Annex 9.4, including the questions asked) working in Switzerland on regeneration issues.

To show the relevance of the topic, we integrated information from selected review papers, instead of conducting a comprehensive literature review.

For this concept paper, a definition of regeneration is needed. Here, we decided to include all processes from seed production over seed dispersal, seed germination, seedling establishment to ingrowth to the tree layer (i.e. a dbh of about 12 cm). Artificial reproduction by planting or sowing and genetic aspects of regeneration were also included. In contrast, the many projects on ex-situ seedling physiology were excluded, because here seedlings are usually grown in pots and under controlled conditions, thus neglecting processes such as competition and/or facilitation, which are of primary importance for the ecology and dynamics of tree regeneration.

3 Status of research and outreach on forest regeneration at WSL

Projects: A search in the WSL project database revealed 43 projects active during the period 2012-2021 (Table 2 in Annex 9.1)[1]. The total funding for these projects amounts to 17.3 million CHF, but if components unrelated to regeneration are deducted (based on an estimated percentage per project), the third-party funding dedicated to regeneration amounts to 10.0 million CHF, i.e. about 1.0 million CHF annually. These projects were mostly funded by FOEN or the Cantonal Forest Offices, but four projects were funded by SNF, SCIEX or the European Commission. 17 WSL employees had a function as PIs in these projects.

The projects are distributed over eight Research Groups (RGs) in seven Research Units (RUs). Based on the affiliation of the PIs, the following organizational units are active in regeneration research:

- RU Forest Resources and Management
  - RG Stand Dynamics and Silviculture 22
  - RG Sustainable Forestry 1
  - RG Scientific Service NFI 1
- RU Forests Dynamics
  - RG Disturbance Ecology 7
- RU Community Ecology 4
- RU Alpine environment and natural hazards
  - RG Mountain Ecosystems 3
- RU Land Change Science
  - RG Dynamic Macroecology 2
- RU Forest Soils and Biogeochemistry
  - RG Rhizosphere Processes 2
- RU Biodiversity and Conservation Biology
  - RG Evolutionary Genetics 1

Publications: From 2012 to 2021, 195 publications with WSL authorship on regeneration appeared, 150 of which after peer review. Among the reviewed papers, 20 were published in non-ISI journals (15 of which in Schweizerische Zeitschrift für Forstwesen). The publication trend is clearly positive, with the total annual number having tripled within 10 years (Figure 1). Non-reviewed outreach papers amounted to about 40, but do not include about 10 additional papers in French professional journals.

[1] Three more projects were not yet active in 2022 (also listed in Annex 9.2). One of them has a PI in the RG Resource Analysis, thus a 9th RG doing regeneration research at WSL.

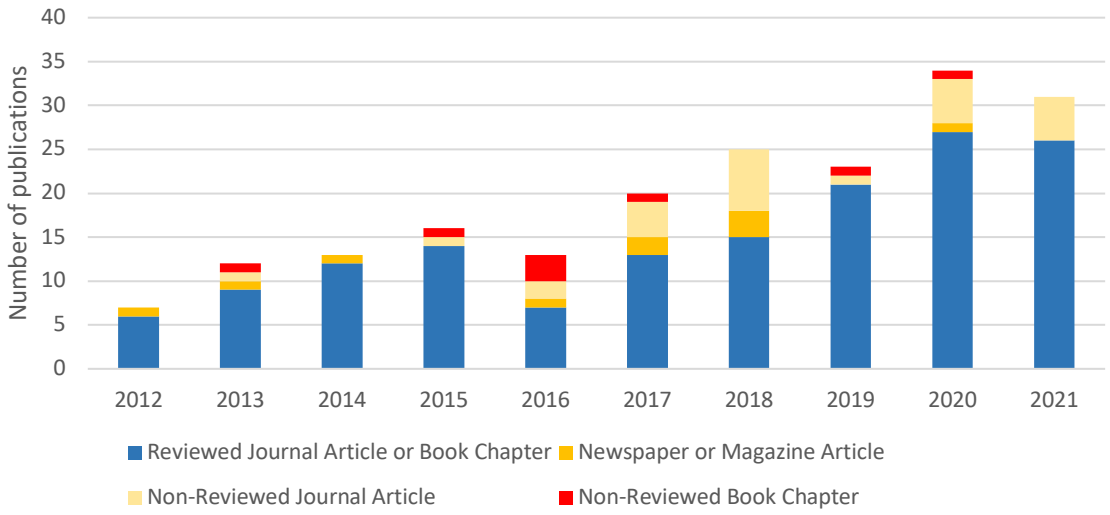

Figure 1. Number of publications on regeneration topics. There is only one reviewed book chapter in the category of 'Reviewed Journal Article or Book Chapter'. Newspaper or Magazine Articles include also Proceedings articles (N=1), PhD theses (N=1) and reports (N=4).

Topics: Regeneration research at WSL can be assigned to the following topics:

- Drivers of natural seedling establishment, including browsing, competing vegetation, microsites, light, soil properties and drought, with a focus on areas disturbed by windthrow, bark beetles or forest fires, and on species invasions
- Migration of tree species over long time periods including genetic aspects
- Frequency of reproductive success in tree species (masting)
- Demographic dynamics and competition in juvenile tree populations
- Performance of tree species, provenances and families in different environments
- Management effects on the composition and density of natural regeneration
- Methods and tools for assessing regeneration and for tree species selection

These topics are reflected in a wordle of the WSL publication titles (Figure 2). Figure 2 also shows that WSL research has focused on major species like Norway spruce, silver fir and European beech. However, there are also some studies on other species, including non-native tree species.

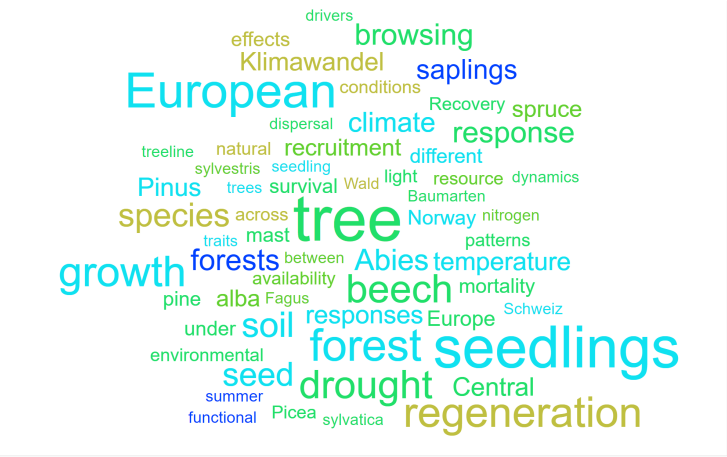

Figure 2. Wordle of the titles of the 195 publications with WSL authorship on regeneration in the period 2012-2021.

Field sites: WSL also maintains a large number of long-term field sites for investigating regeneration:

- > 60 sites with experimental plantations (most part of the Experimental Plantations Project, www.testpflanzungen.ch), with three sites having additional manipulative treatments (www.wsl.ch/de/projekte/polytunnel-greenhouse-experiment.html)
- Many sites where natural regeneration is studied with management manipulations, e.g. enclosures to test browsing effects (> 45 sites and > 140 pairs of fenced and unfenced sampling plots; www.wsl.ch/de/projekte/quantifizierung-von-totverbiss-an-verschiedenen-standorten.html) or silvicultural interventions (including > 70 sites with gap cutting in spruce mountain forests and 10 large sites in fir-spruce forests with > 500 sampling plots, www.wsl.ch/de/projekte/gebirgswaldverjuengung.html)
- > 500 sampling plots in > 20 windthrow and burnt areas
- > 200 stands across Switzerland in which seed production of trees has been monitored since the 1990s
- > 8000 plots where regeneration is assessed in the frame of large-scale inventories (NFI, www.lfi.ch) or inventories in forest reserves (www.waldreservate.ch)
- > 450 permanent plots in the Experimental Forest Management and Forest Reserve Research projects where saplings above the calipering threshold of 4 or 7 cm are assessed
- >500 'micro-gardens' to be established in the framework of MyGardenOfTrees (www.mygardenoftrees.eu) across Europe during 2022-2024 (25 have been already established).

Approaches: The approaches used include single and repeated sample surveys, often in combination with manipulative experiments, that alter the juvenile trees' environment (e.g. fencing, climate manipulation and silvicultural treatments), the exploitation of environmental gradients through plot networks, or dynamic forest simulation models at the plot (MASSIMO), landscape (TreeMig), and continental scale (LPJ-GM).

Outreach: Regeneration research is often motivated by management needs, and has therefore an important outreach component. This is demonstrated by the funding origin (see above), by tools like the Tree App (www.tree-app.ch) for species selection and the JuWaPfl tool for the estimation of tending costs, the regeneration sampling methods developed by WSL, cantonal browsing survey plots that were installed in collaboration with WSL, or the regeneration monitoring in disturbed areas in several cantons, and by outreach publications and events.

Education: Regeneration topics are also addressed in several lectures at universities (ETH, others), and are the focus of many theses at BSc and MSc and sometimes also PhD levels.

4 Current research on forest regeneration in Switzerland and in Europe

According to the interviews with scientists at ETH and HAFL, there is little and intermittent activity in regeneration research at institutes other than WSL. At ETH, there is one project on non-native species which could potentially replace native ash, which is severely threatened by ongoing ash dieback. Moreover, new activities have started on LWF plots to understand the ecological niche of tree seedlings. ETH is also active in integrating natural regeneration in simulation models, currently in an international consortium also including Heike Lischke from WSL. Master theses at ETH regularly deal with regeneration topics. At HAFL and ZVAW, theses (BSc, sometimes MSc) are often conducted in collaboration with WSL researchers.

At the international level, the topics addressed and the approaches used in regeneration research are similar to those at WSL. Several WSL researchers cooperate with international partners. Examples include co-operations with German researchers in the field of browsing impacts and experimental

tests of tree species for climate change adaptation, Oriental beech studies with German and French partners, and studies on the dynamics of natural regeneration in drought-damaged plantations in Bulgaria. The publications' landscape can be characterized by very few extensive review papers (apart from reviews dealing with regeneration in tropical forests). However, there are numerous case studies in selected forest types or dealing with particular tree species or particular disturbance or stress factors (e.g. windthrow, forest fire, ungulate browsing, drought), demographic dynamics of naturally regenerated and planted seedlings (often in disturbed areas), genetic aspects of reproduction and population dynamics in juvenile trees, and seed production and dispersal. Much of the literature on regeneration topics is also published in regional professional journals, often in local languages.

Review articles (WoS Core Collection) on regeneration topics are scarce and partly outdated. They covered native species regeneration in the process of restoring natural forests from mono-specific, even-aged tree plantations (Kremer & Bauhus 2020), direct seeding to restore oak forests (Löf et al. 2019), the influence of browsing on regeneration (Gill et al. 1992a-c, Hawkes & Sullivan 2001), also in the context of climate change adaptation (Champagne et al. 2021), assisted migration (Williams & Dumroese 2013), regeneration dynamics of North American boreal forest tree species (Greene et al. 1999), planting stock (Grossnickle & El Kassaby 2005), or modelling of specific aspects of regeneration, e.g. masting behavior (Vacchiano et al. 2018). The challenge for review papers is that the studies available differ in scope, spatial scale, classification of regeneration, and inclusion of drivers. However, the lack of recent review papers on regeneration means also there is an opportunity for WSL.

5 Research perspectives

5.1 Context: Environmental change, forest responses and technological innovation

Climate change will very likely result in more frequent and severe droughts, leading to increased mortality, biotic disturbance, and fire activity. Forests are expected to become, at least temporarily, more open, resulting in a higher amount of early stages. Shifts in tree species are likely, with an increased proportion of pioneer and broad-leaved species (including invasive alien species). Forest managers have started to respond by using assisted migration in order to shift the tree species composition towards mixed stands, with a higher share of drought-tolerant species, as key for higher stress tolerance, thus securing ecosystem services. Assisted gene flow is also increasingly applied as an adaptation tool, notably because it can assure the continued presence of species at critical sites by using, e.g., its more southern provenances. Ungulate browsing continues to be one of the main impediments for regeneration of climate-adapted tree species. While these general directions of forest dynamics and action seem clear, there is a high need for analyzing site-specific stress responses of forests (a widely ignored phenomenon in research), enabling site-specific guidance.

In the frame of technological innovation we expect, among others, even better and cheaper sensors to assess environmental and physiological variables, increased use of close-range remote sensing (aerial and terrestrial sensors) for measuring forest condition, and improved methods in genomics. It will hence become easier to assess forest growth conditions in finer temporal and spatial resolution, allowing for fine-tuned analyses of the fundamental niches of different tree species, and to assess the species' site-specific adaptability and phenotypic plasticity. These more detailed and reliable data will then serve as more detailed baseline data for improved forest models and allow for more precise forest projections in regard to climate change.

5.2 Opportunities for regeneration research

The changes described above offer ample opportunities for relevant and productive research on regeneration topics. Given the existing competence and the network of long-term experimental sites, WSL is perfectly positioned to address scientifically rewarding and relevant research questions regarding regeneration. The regeneration topic is also well anchored in the WSL development plan for 2021-2024 since it offers an important contribution to the topic forest dynamics in a changing environment and to the promotion of resilient forests.

The following list of research questions which could be addressed during the next five to ten years (e.g. until 2030) is not exhaustive. Most of these questions are to some extent already being addressed in ongoing research, or could be addressed by using synergies with ongoing activities.

1. Demography in juvenile tree populations: Which factors (e.g. climate including extremes, land-use history, stand structure and microclimate, seed trees, microsite variation, mycorrhiza, soil nutrients, pathogens) influence emergence and mortality in juvenile tree populations? How do these processes depend on site conditions, shape species interactions and finally alter the species composition of canopy trees? How do they shape switches of tree populations in response to climate change? How do juvenile tree populations develop on large areas affected by natural disturbances, and what is the role of disturbance type and size? How do these factors influence masting?

2. Niches of juvenile trees and genetic structure: What are the environmental limits of tree species and provenances across climatic and soil (i.e. site) gradients, and to which amount are these limits influenced by genetic variation? How can advanced airborne and terrestrial sensors be used to study this in the wild?

3. Browsing effects: How do juvenile tree populations respond to ungulate browsing, and what are the consequences for future forests? How can forest management contribute to reducing the impact of ungulates on the regeneration of climate-adapted tree species? Are there cascading effects of carnivores on regeneration? What effects on tree regeneration has the reintroduction of large herbivores like bison?

4. Improved simulation models: How can regeneration modules in simulation models be improved based on the findings of the questions 1-3, and how does this affect simulated long-term forest dynamics?

5. Sampling methods and regeneration indicators: How can sampling designs be improved to better monitor regeneration also in large-scale inventories? How can close-range imagery/ terrestrial laser scanning be used for this purpose? How can regeneration (in terms of quantity and quality) be easily assessed and judged at the stand scale? Which assessment methods have a large potential for application? How can data sampling inform regeneration models and vice versa?

6. Silvicultural management for climate change adaptation: How can natural regeneration of tree species adapted to future climates be promoted under different site conditions, taking ecological (e.g. species requirements) and operational (e.g. timber harvesting) constraints into account? How can site-specific tree species recommendations be improved for managing forests in a changing environment? What are the benefits and limits of artificial regeneration (including assisted gene flow/assisted migration) in comparison to natural regeneration? How can non-native and in particular invasive tree species be managed?

How can the silvicultural management of regeneration be optimized for specific ecosystem services?

5.3 Funding sources

Funding for regeneration research currently comes mainly from FOEN and Cantonal Forest Offices. We expect that these sources will continue to fund WSL regeneration research, but WSL will also need to clearly highlight the value and applicability of the results of its research. Other funding sources will also be considered for future research activities, such as the Swiss National Science Foundation SNF and the Velux Stiftung. In the field of experimental tests of tree species for climate change adaptation, a HORIZON proposal (OptForests) has just been approved.

6 Practical needs

Repeated discussions of WSL researchers with practitioners and the interviews conducted for this concept paper consistently show a high and increasing importance of the regeneration topic in forest management. The large amount of past funding from FOEN and Cantonal Forest Offices for regeneration projects demonstrates the need to continuously improve fundamentals and guidance from WSL. Regeneration is of particular concern in high-elevation mountain forests where it is often scarce, poor in species, heavily browsed, and grows only slowly. In most interventions in protection forests (50% of the forest area), regeneration is a key concern, which is reflected in the important place regeneration takes in the FOEN guidelines for protection forest management (Frehner et al. 2005/2009).

Regeneration is key for the adaptation of forests to climate change and therefore, for the future provision of ecosystem services. This is increasingly an issue in lowland forests where native tree species likely cannot keep pace with climate change impacts such as repeated drought, which raises the question on alternative future tree species. Practitioners need to know which tree species are adapted to future climate, to what degree and how (with which interventions) they can be regenerated naturally, and in which cases artificial regeneration (including assisted migration and/or assisted gene flow) should be used to enrich natural regeneration. In this context, the question of suitable species mixtures, i.e. the ‘tree species portfolio’, is also relevant.

The high importance of regeneration is also acknowledged by the KOK (Conference of the Heads of the Cantonal Forest Offices) which is interested in integrating regeneration as the 14th key indicator of sustainable forest management. Forest professionals need reference (target) values of regeneration (regarding quantity and quality) for practical decision-making, and associated assessment methods. Most cantons already monitor regeneration at least in selected areas for planning of wildlife management. However, this monitoring has so far often failed to deliver satisfactory results since in large forest areas highly palatable species, which are often rare and drought tolerant, continue to drop out at the seedling stage due to heavy browsing. An additional issue are species invasions, which are expected to increase in densely populated lowland regions, particularly in the case of management interventions and increased climate-induced disturbances.

7 Organization of regeneration research at WSL

The high number of organizational units involved is not a sign of overlap and duplication of activities, but of different facets and approaches to regeneration research, and partly of differences in spatial scales, altitude-dependent forest types and regions (Table 1).

The authors of this concept paper have, nevertheless, decided to increase their cooperation, from the current occasional exchange on their regeneration research to a more regular and organized functioning. Bi-annual meetings and more common proposals, publications and outreach activities are envisaged.

Table 1. Regeneration topics addressed in different WSL research groups with major activities (large projects), and activities in outreach as well as the regional focus. The topics 1-6 were taken from section 5.2. cc = climate change, JT = juvenile tree. Selected large ongoing projects (highlighted in green): BP = Browsing projects, EP = Experimental plantations, MFR = Mountain forest regeneration, NFI = National Forest Inventory, PE = Polytunnel Experiment, SP = Stillberg plantation.

Research Unit		Forest Resources and Management			Forest dynamics	Community ecology	Alpine Environment and Natural Hazards	Land Change Science	Forest Soils & Biogeochemistry	Biodiversity and Conservation Biology
Research Group		Stand dynamics & silviculture	Sustainable Forestry	Scientific Service NFI	Disturbance ecology	NA	Mountain ecosystems	Dynamic macroecology	Rhizosphere Processes	Evolutionary Genetics
Research Topics	1 Demography in JT populations including seed production	**MFR**			Masting	Invasive woody species, masting	Treeline		Genetic aspects	
	2 Niches of JT and genetic structure	Field experiments **EP**			Controlled experiments **PE** Statistical modelling	Invasive woody species	SP			Common garden & green house experiments hybridization
	3 Browsing effects	**BP, MFR**								Genetics of recovery from browsing
	4 Improved simulations models							Simulations of long-term forest dynamics		
	5 Sampling methods and regeneration indicators	Stand scale **BP, MFR**	Landscape scale **NFI**	Landscape scale **NFI**			Stand and landscape scale			
	6 Silvicultural management for cc adaptation	**MFR, EP**				Post-fire regeneration	Post-disturbance regeneration			Building prediction tools
Outreach (excluding publications)		Tree App, Regeneration indicators, browsing inventories, much oral outreach, mass media		lfi.ch	Mastweb, mass media	Mass media	Excursions			Participatory science
Regional focus		Switzerland and Europe	Switzerland	Switzerland	Lowlands	Southern Switzerland	Mountain forests	Switzerland and Europe	Lowlands	Europe

Only few WSL staff members are active in non-written outreach about regeneration topics.

In the coming decade, key players in regeneration research will retire, including Thomas Wohlgemuth, Peter Brang, Heike Lischke and Marco Conedera. Moreover, Andreas Rigling will leave WSL in 2022. Continuity in particular regarding large and long-term projects and outreach needs to be assured by special efforts.

8 Conclusions

Regeneration is already an important and productive topic in WSL research. It is highly relevant for forest management since juvenile trees are key for future forests and their ability to provide ecosystem services. Particularly important management challenges are climate-change adaptation and continued high browsing pressure.

WSL is in a very good position, at both the national and European level, to address the challenges in regeneration research. It has considerable (broad and deep) knowhow and excellent infrastructures including numerous field sites and networks with often long-term monitoring data. Moreover, the Swiss landscape offers the opportunity to exploit large environmental gradients, given its high topographical and climatic variability, e.g., with an altitudinal gradient of the forest area stretching from 200 to currently 2300 m a.s.l. Building on these assets, WSL should increase its visibility as an international key player in regeneration research, e.g., by writing more synthesis publications with high impact.

To realize the potential in the field of regeneration research, more cooperation and coordination is needed. Therefore, the authors of this concept paper have decided to organize regular meetings to discuss new findings and hot topics. The strive to actively foster co-operation and to identify opportunities for joint projects.

Increased coordination should also lead to joint outreach activities, including products like WSL leaflets (Merkblätter). Another option under consideration is to make WSL regeneration research more visible to professionals by creating a regeneration entry point on the WSL homepage.

9 Annex

9.1 References

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9.2 Project list

For this report, all WSL projects with a regeneration component have been compiled (Table 2).

Table 2. List of WSL projects with a regeneration component and an end after 2011. FA = Funding Agency, F% = Percentage of funding devoted to regeneration topics. Projects with ≥ 10 yr duration are in bold. Three projects starting in 2022, listed at the end of the table (No. 44-46), were excluded from the calculations of funding totals in chapter 3.

No.	Title	PI, WSL collaborators	Duration	Goal	FA	3rd party funding [kCHF]	F%
1.	**Landesforstinventar**	**Hägeli, Fischer**	**1983-**	**Objektive Grundlagen zum Zustand des Waldes und seinen Veränderungen hinsichtlich aller seiner Funktionen**	**FOEN**	*	*
2.	**Forschung und Wirkungskontrolle in Naturwaldreservaten**	**Brang, Hobi**	**2006-**	**To understand and quantify long-term forest succession in unmanaged forests in selected relevant forest types**	**FOEN**	**4795**	**5%**
3.	Trolifa und Trolifa-Plus - Trockenheit als limitierender Faktor für An- und Aufwuchs von Hauptbaumarten	Wohlgemuth, Moser	2009-2014	Während 3-5 Jahren werden Waldföhre, Buche, Fichte, Tanne und Traubeneiche an vier Standorten im Churer Rheintal untersucht	FOEN	267	100%
4.	**Gastbaumarten**	**Brang, Nikolova**	**2010 -**	**To test 6 non-native and 1 native tree species suitable in a +2 °C climate scenario**	**FOEN**	**186**	**100%**
5.	Auswirkung von Schalenwildverbiss auf Verjüngungsstrukturen	Kupferschmid, Brang	2011-2017	To examine whether or to what degree strong browsing leads to small sapling density, slow growth or loss of tree species.	WSL, FOEN	314	100%
6.	Defy drought: Combined effects of drought and raised CO_2 on early growth of conifers	Wohlgemuth, Moser	2011-2015	Seeds from coniferous tree species are collected, sown and exposed to different drought conditions and to increased CO2 pres-sure.	SCIEX	140	100%
7.	**Post-fire regeneration in beech forests**	**Conedera, Maringer, Wohlgemuth**	**2011-2024**	**Understanding the post-fire regeneration dynamic (including repeated fires) in beech forests**	**FOEN**		
8.	Wie regenerationsfähig sind Buchenwälder nach Waldbrand?	Conedera, Wohlgemuth	2012-2014	Untersuchung der Langzeitreaktion der Rotbuche auf Feuer und Prozesse der natürlichen Verjüngung	FOEN	80	100%
9.	Walddynamik Wallis (WaDyWa)	Wohlgemuth, Rigling	2013-2017	Erhebung der Vegetation und der Wirbellosen 10 Jahre nach dem Waldbrand Leuk sowie um eine 1. Erfassung der Baumverjüngung im Waldbrandgebiet von Visp (2010)	VS	240	30%
10.	Interactive effects of CO_2 and light conditions on drought resistance of conifer species during early growth	Wohlgemuth, Moser	2013-2014	To test the potential of autochthonous P. sylvestris (Leuk, Valais) to withstand aggravated drought under different environmental conditions (elevated CO2, light conditions)	SNF	277	100%
11.	Global Treeline Range Expansion Experiment (G-TREE)	Frei, Rixen, Bebi	2013 -	To assess abiotic and biotic drivers of germination, emergence and establishment of natural regeneration as well as experimentally added seeds in a treeline ecotone.	WSL	0	100%
12.	Eingriffsstärke und Holzzuwachs im Gebirgswald	Brang, Nikolova, Vitali, Zürcher, Gordon	2014-2017	Beurteilung der langfristigen Auswirkung grosser Verjüngungslücken auf die Verjüngung, auf die Mortalität in benachbarten ungenutzten Beständen und auf den Zuwachs der Randbäume.	WHFF, Cantons	160	80%
13.	Jungwaldpflegeverfahren auf der Lothar-Sturmfläche Diessenhofen TG	Brang, Bürgi, Nikolova, Ninove, Zell	2014-2015	To understand how large storm areas (after Lothar) with natural regeneration in the young forest phase can be efficiently managed	FOEN, TG	64	100%
14.	Vorprojekt zur Analyse des Effektes von Wölfen auf die Waldverjüngung	Kupferschmid	2014	Aufzeigen von möglichen Kaskadeneffekten von Wölfen auf die Baumverjüngung in der Schweiz	FOEN	18	100%
15.	Herleitung von Merkmalen zur Beurteilung des	Kupferschmid	2014-2018	Herleitung von Merkmalen zur Beurteilung des Wildeinflusses auf die Waldverjüngung	FOEN	300	100%

No.	Title	PI, WSL collaborators	Duration	Goal	FA	3rd party funding [kCHF]	F%
	Wildeinflusses auf die Waldverjüngung						
16.	Reaktionsvermögen auf Endtriebverlust von Schweizer Tannen, Fichten und Buchen je nach Genotyp	Kupferschmid	2015-2018	Unterscheidet sich das Reaktionsvermögen auf Endtriebverlust von Schweizer Tannen, Fichten und Buchen je nach Genotyp?	FOEN & WSL	100	100%
17.	**Waldverjüngung und Wildverbiss Misox**	**Bebi, Condera**	**2015-**	**Analyse der Faktoren, welche zu Verjüngungsproblemen der Tanne im Misox führen**	**GR, Parc Adula**	**20**	**100%**
18.	Methodischer Vergleich und Zeitreihenanalysen zu Verbiss im LFI	Kupferschmid, Huber	2016 - 2022	Zeitliche Entwicklung der Verbisshäufigkeit in der Schweiz	WSL & FOEN	320	100%
19.	CompMig: Extension and comparison of tree species migration models	Lischke, Lehsten	2016-2018	Modelling of large scale spatio-temporal forest dynamics (LPJ-GM)	SNF	191	100%
20.	Invasivitätspotenzial der Douglasie in Schweizer Wäldern und im Offenland	Wohlgemuth, Moser, Frei	2016-2019	Standortsbedingungen für die spontane Dou-Etablierung mittels Felderhebungen und anhand eines Sämlingsexperiments	WHFF	165	100%
21.	Carbon storage and water use efficiency in Abies alba as affected by simulated browsing and genetic heritability	Kupferschmid, Csilléry, Buchmann, Gessler	2017-2018	Carbon storage and water use efficiency in Abies alba as affected by simulated browsing and genetic heritability	WSL		100%
22.	ALLOSPRUCE: Allometric growth responses in Norway spruce	Nikolova, Gärtner, Zimmermann	2017-2018	To test the potential of a new method for root-shoot allometric analyses in order to quantify the effects of environmental changes on edge-tree growth dynamics	WSL	55	20%
23.	Forschungskooperation Ukraine	Brang, Hobi, Stillhard	2017-2020	Veränderungsinventur Buchenurwald, Naturverjüngung von Buche, Berg- und Spitzahorn	SBFI	880	30%
24.	Verjüngungskontrolle Pilot 2018	Kupferschmid	2018-2019	Verbisseinflussmonitoring	SG	30	100%
25.	Ungulate Monitoring in German National Parks	Storch, et al., Kupferschmid	2018-2022	Wildeinflussmonitoring	B'amt für Naturschutz	1900	100%
26.	LFI-Veg21	Wohlgemuth, Brändli, Scherrer	2018–2021	The project aims to plan the assessment of plant species diversity, tree regeneration and plant communities on the 4x4 km subset of the Swiss National Forest Inventory.	LFI	205	100%
27.	**Gebirgswaldverjüngung**	**Brang, Nikolova**	**2018-**	**To establish and monitor a long-term multi-site field experiment to investigate regeneration demography in silver fir-Norway spruce forests**	**WHFF, FOEN, Cantons**	**910**	**100%**
28.	**Testpflanzungen zukunftsfähiger Baumarten**	**Streit, Brang**	**2018-**	**Test the climatic niche of 18 tree species (and 7 provenances for each species) in Switzerland to explore the potential for assisted migration/gene flow**	**FOEN, Cantons**	**1112**	**100%**
29.	Koordination TreeApp	Brang, Nikolova	2019-2022	To develop an App for site-specific tree species recommendations for any location in Switzerland, for 2 climate projections	FOEN	300	100%
30.	Untersuchungen zur Orientbuche im Kanton TG	Sperisen, Brang, Csilléry	2019	Assess the extent of interspecific hybridization between European and Oriental beech at two sites	FOEN	24	100%
31.	BeechDrought - Oriental beech (*Fagus orientalis*) for assisted migration?	Sperisen, Csilléry	2019-2022	Building a database of Oriental beech stands in Western Europe, tracking their geographic origin, assessing the drought sensitivity of seedlings in a controlled greenhouse experiment, and assessing the growth patterns of adult trees	WSL	68	50%
32.	EXTRAS: Extending dynamic vegetation models to simulate non-tree species invasion	Lischke, Lehsten, Bolliger, Smith	2019-2023	Modelling of large scale spatio-temporal forest dynamics interacting with other species	SNF	443	50%

No.	Title	PI, WSL collaborators	Duration	Goal	FA	3rd party funding [kCHF]	F%
33.	Post-fire tree regeneration in a chestnut forest	Gehring, Conedera, Wohlgemuth	2019-2023	Understanding the post-fire regeneration dynamic (including repeated fires) in a chestnut coppice forest			
34.	Waldbauliche Entscheidungshilfe zum Umgang mit invasiven neophytenschen Gehölzen im Wald	Gehring, Conedera	2020-2022	Identifying the factors influencing the regeneration of neophytic invasive and native woody species in forest gaps in the deciduous forest belt of the southern Alps	FOEN	140	100%
35.	Quantifizierung von Totverbiss an verschiedenen Standorten	Kupferschmid	2020-2024	Schätzung der verbissbedingten Mortalität und der Reaktion von Bäumchen auf den Verbiss auf verschiedensten Standorten	FOEN & Cantons	280	100%
36.	MyGardenOfTrees: A range-wide transplant experiment using participatory science and genomic prediction to assess local adaptation in forest trees	Csilléry	2021-2026	Assessment of the regeneration capacity and early growth of silver fir and European beech, and their oriental sister species, using experimental gardens and genetic analysis across Europe	EC, ERC CoG	2000	60%
37.	Dokumentations-Tool Zukunftsbaumarten	Brang, Streit	2021-2024	Provide standards for documenting species trials by forest managers, and to develop a web-based application to assess and maintain existing and new plantations of locally remarkable tree species	WHFF, Cantons	22	100%
38.	CATReg: Combining aerial and terrestrial methods to assess the regeneration success in mountain forest stands	Nikolova, Brang, Hobi, Bast, Bebi, Marti	2021-2022	Tests the potential of UAV LiDAR based technologies in assessing key structural parameters of forest regeneration	WSL	59	100%
39.	MountEx (WP2): Management of spruce-dominated mountain forests under multiple risks	Nikolova; Brang, Temperli, Kalt	2021-2024	Trajectories of forest development before and after an extreme disturbance with pro-active and re-active management	Extremes	588	15%
40.	Comparaison IFN2-IFN4: Dégâts du gibier	Kupferschmid	2021-2022	Entwicklung des Verbisses in den letzten Jahrzehnten im Kanton Waadt	VD	40	100%
41.	**Polytunnel Greenhouse Experiment**	**Moser, Vitasse, Frey, Gossner, Grossiord, Hagedorn et al.**	**2021–2030**	**Assessing how rising temperatures and increasing drought ('hotter drought') will affect the growth of potential future tree species during the advanced regeneration stage (2–8 years-old plants)**	**WSL Grossinvestition**	**210**	**100%**
42.	FORISK (WP2): Changing forests and natural hazard risks in Davos	Bottero, Temperli, Bebi	2021-2024	Modelling of future forest and regeneration dynamics under a range of climate, forest management and disturbance scenarios in the region of Davos, Switzerland.	CCAMM	192	20%
43.	HeProMo	Schweier, Bont	2021-2024	Weiterentwicklung des Planungsinstruments HeProMo (2021-2024)	BAFU	216	14%
44.	Klimasensitive Modellierung des Einwuchs' im LFI-basierten Stichprobensimulator MASSIMO	Stadelmann, Zell, Portier, Scherrer, Thürig	2022-2023	Climate sensitive modelling of tree ingrowth (regeneration). Module for planting new / climatically better-suited species in MASSIMO.	LFI	157	100%
45.	Verbisseinfluss-Monitoring im Forstrevier Kirchberg im Herbst 2022	Kupferschmid	2022-2023	Verbisseinflussmonitoring unter Berücksichtigung des Sommerverbisses	Kanton SG	30	100%
46.	OptFORESTS	Fonti, Rellstab, Brang, Martinez-Sancho, Streit, Vitasse	2022-2027	OptFORESTS will evaluate adaptive and biomass traits in existing common gardens and newly-established next-generation ones, conserve and utilise unique tree lineages for ecosystem restoration and management, model future adaptation of trees at different life stages and conduct low-input breeding.	European Commission (HORIZON)	821	23%

* Regeneration is one component of the Swiss NFI, the Swiss NFI does not account for the exact number of hours on this topic. Thus, no reliable figures can be provided, neither for funding amount, nor for the percentage of funding devoted to regeneration topics.

9.3 Method of the publication query

The search in the Dora database (https://www.dora.lib4ri.ch/wsl/) was performed as follows. First, a query in the field “Anywhere” was conducted with the keywords “regenerat*” or “mast” or “seedling” or “sapling” or “recruitment” or “planting” or “seed” or “germinat*”, from 2012, all publication types, 1661 hits. The same was repeated with “Verjüng*” or “sämling*” or “nachwuchs” or “Pflanzung” or “pflanzen” or “samen*” oder “Keimung”, resulting in 56 hits. No search in French was conducted.

Then, inappropriate entries were manually removed. Moreover, each publication was assigned a publication type (Book Chapter, Dissertation, Journal Article, Newspaper or Magazine Article, Proceedings Paper, Report), a Review status (reviewed, not reviewed). Finally, the list was searched for Reviewed non-ISI Journal articles. The co-authors of this report were then given the opportunity to apply corrections to the resulting list. We did not perform a thorough cross-check of all entries since the purpose is only to depict the broad picture.

9.4 Interviews with external experts

The following experts were interviewed:

Practitioners:

- Robert Jenni, Division Forest, BAFU
- Micheline Meylan, DGE Vaud
- Samuel Zürcher, ibw / Fachstelle für Gebirgswaldpflege

Experts from science/education:

- Prof. Dr. Harald Bugmann, ETHZ
- Prof. Dr. Janneke Hille Ris Lambers, ETHZ
- Dr. Mathieu Lévesque, ETHZ
- Prof. Jean-Jacques Thormann, HAFL

The questions for practitioners were (interviews conducted in German or French):

1. Welche Bedeutung hat die Verjüngung in den Aktivitäten der befragten Institution und in dessen Strategie zu Forschung und Entwicklung? Welche Aspekte sind besonders wichtig? Wird die Bedeutung zunehmen, gleichbleiben oder abnehmen?
2. Welche Projekte (Forschung & Umsetzung) unterstützt die befragte Institution zurzeit? (Thema; Projektleitung/Institution; Dauer; evtl. Output)
3. Welche Projekte sind geplant?
4. Welche Forschungsfragen könnten oder sollten bis etwa 2030 neu bearbeitet werden
5. Welche Rolle beabsichtigt die befragte Institution in der Forschung und Entwicklung zu Waldverjüngung zu spielen?
6. Welche Rollen sollen verschiedene Akteure in der Forschung und Entwicklung zu Waldverjüngung spielen?

The questions for experts from science/education were:

1. Welche Forschungsaktivitäten laufen? (falls in Form von Projekten: Thema; PI; Dauer; Finanzierung; evtl. Output)
2. Welche Forschungsaktivitäten sind schon geplant?
3. Welche Forschungsfragen könnten oder sollten bis etwa 2030 neu bearbeitet werden?
4. Welche Rolle beabsichtigt die befragte Gruppe zu spielen?