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Major
Forests and their Environment

Forest management for climate adaptation: Effect of three management scenarios on the landscape disturbances and responses to climate change

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Abstract
Because climate change will alter forest functioning, it is necessary to apply management that will allow the forest to adapt and to continue to provide ecosystem services. I focused on the Klamath region, situated at the North-West of California, an area experiencing rapid climate and forest changes. There is disagreement, however, as to the best management approach for this region. Therefore, I tested two management scenarios: an Adaptability scenario, that consists in avoiding obstacles to natural adaptation (increase connectivity, promote natural regeneration…) and a Pro-active scenario that consists in a human management of forest adaptation (assisted migration, economical resilience scenario on suitable sites…). I compared these management scenarios to a Business as usual scenario. To compare the management scenarios, I parametrized the mechanistic landscape model LANDIS-II and forecast forest change over 100 years. The management scenarios are compared regarding carbon sequestration, vulnerability to disturbances, forest sustainability and forest biodiversity. For these categories, a classification of the scenarios regarding their suitability is realised.

Résumé
Du fait des perturbations liées au changement climatique, il apparaît nécessaire d'appliquer une gestion permettant aux forêts de s'adapter tout en continuant de rendre des services écosystémiques. Le présent travail se concentre sur la région Klamath du Nord-Ouest californien, une zone connaissant de rapides changements climatiques et forestiers. Il existe cependant des désaccords concernant la meilleure approche afin de gérer la région. Deux scénarios de gestion ont par conséquent été testé : le scénario « Adaptabilité », qui consiste à éviter les obstacles à une adaptation naturelle (augmentation de la connectivité, favorisation de la régénération naturelle…) et un scénario « Pro-actif », qui consiste en une prise en charge humaine de l'adaptation (migration assistée, résilience économique appliquée dans les sites favorables…). Ces scénarios ont été comparés à une gestion en *Statu Quo*. Afin de réaliser la comparaison, Le modèle mécaniste LANDIS-II à été paramétrisé et a permis une simulation du paysage sur 100 ans. Les scénarios de gestion ont été comparés en prenant en compte la séquestration du carbone, la vulnérabilité face aux perturbations ainsi que la pérennité et la biodiversité de la forêt. A partir de ces catégories, une classification des scénarios concernant leur pertinence a été réalisé.

Summary

Acknowledgments

First of all, I want to thank Dr. Robert Scheller for the trust he showed in giving me this interesting internship directly linked to research, and also for the valuable advice that helped me to complete it. I also thank all the Dynamic Ecosystems & Landscape Lab, for all these interesting meetings and for having integrated me as part of the team since the beginning. I received valuable advice and scripts from Zachary Robbins each time I struggled with GIS computation on R. I thank him for this help.

I thank the members of the meetings "LANDIS in California" for having shared valuable experiences, knowledge, and reflections, and having taken time at the meetings to discuss my technical or conceptual wanderings. I especially thank Dr. Charles Maxwell for having shared data and having always answered my (sometimes quite numerous) questions.

I also want to acknowledge Célia Bresson for her support concerning IT and material issues, as well as for her ongoing help concerning the supplementary models needed for the paper. I thank Josep-Maria Serra Diaz for having prepared the best conditions to realise this internship, as well as for his regular checks on the advancement of the project, always with enthusiasm and benevolence.

Finally, I thank all the workers at the Rameau building for the good atmosphere that prevails, making working in it enjoyable.

List of abbreviations

BAU: Business as usual

CanSM: Canadian Earth System

DE&L: Dynamic Ecosystems & Landscape Lab

IR: InsectRisck prescription

IUCN: International Union for Conservation of Nature

MIROC5: Model for Interdisciplinary Research On Climate

NCSU: North Carolina State University

UNC System: University of North Carolina

USA: United States of America

I) Introduction

I.1. Presentation of the Dynamic Ecosystems & Landscape Lab

The internship was initially scheduled to take place in the United States of America (USA) at the North Carolina State University (NCSU) in the city of Raleigh. Because of the global pandemic (due to COVID-19), the internship was done on remote working at Nancy.

The NCSU is part of the University of North Carolina, commonly referred to as the UNC System (Figure 1). The UNC System is a multi-campus public university system of North Carolina.

The NCSU is a public research university founded in 1887 as a land-grant college (meaning it's a public agricultural and technical educational institution) for study in Agriculture and Engineering (NC State University 2021). The internship took place in the Dynamic Ecosystems & Landscape Lab (DE&L, Figure 1).

The mission of DE&L is to understand landscapes, their functioning and interaction with human society. The lab studies the future evolution of the landscapes in the aim to improve the policies of landscape management and to respond to social demands in an uncertain climatic context. To do so, concepts and theories from landscape ecology, ecosystem ecology and landscape management are used. Social science also contributes to the research when it concerns local knowledge, actions, and networks (DE&L 2021).

Dr. Robert Scheller is the Lab director and was the tutor of my internship. He is a professor in landscape ecology and in management of forest and environmental resources.

I.2. Context of the internship

Among the studies that the DE&L published, a series concerns the interaction between forest management and disturbances, in particular fire regimes (Maxwell *et al.* 2020) and insect outbreaks (Olson *et al.* 2021).
This expertise on the domain created an inspiring environment for the internship; and was shared during the weekly meetings of the laboratory. Other regular meetings, with the Discussion Group (people working in the same region and with the same tool) or only with Dr. Robert Scheller, the internship tutor, were also realised (Figure 1).
These meetings were crucial for the realisation of the internship whether for the information and methods shared or the constructive discussion that helps to contextualise the study.

The internship physically took place in the school of AgroParisTech (site of Nancy), which provided all the materials and technical support needed, alongside crucial social interactions during a period of remote working.

The landscape in which the management scenarios will be tested is the Klamath region. It is a mountainous zone situated alongside the west coast, inside Oregon and California. For this study, only the area inside California was considered (Figure 2). As presented below, the relevance of using this region lies in its diversity of landscapes, in the importance of disturbances in its ecosystems and in the ongoing literature on the topic.

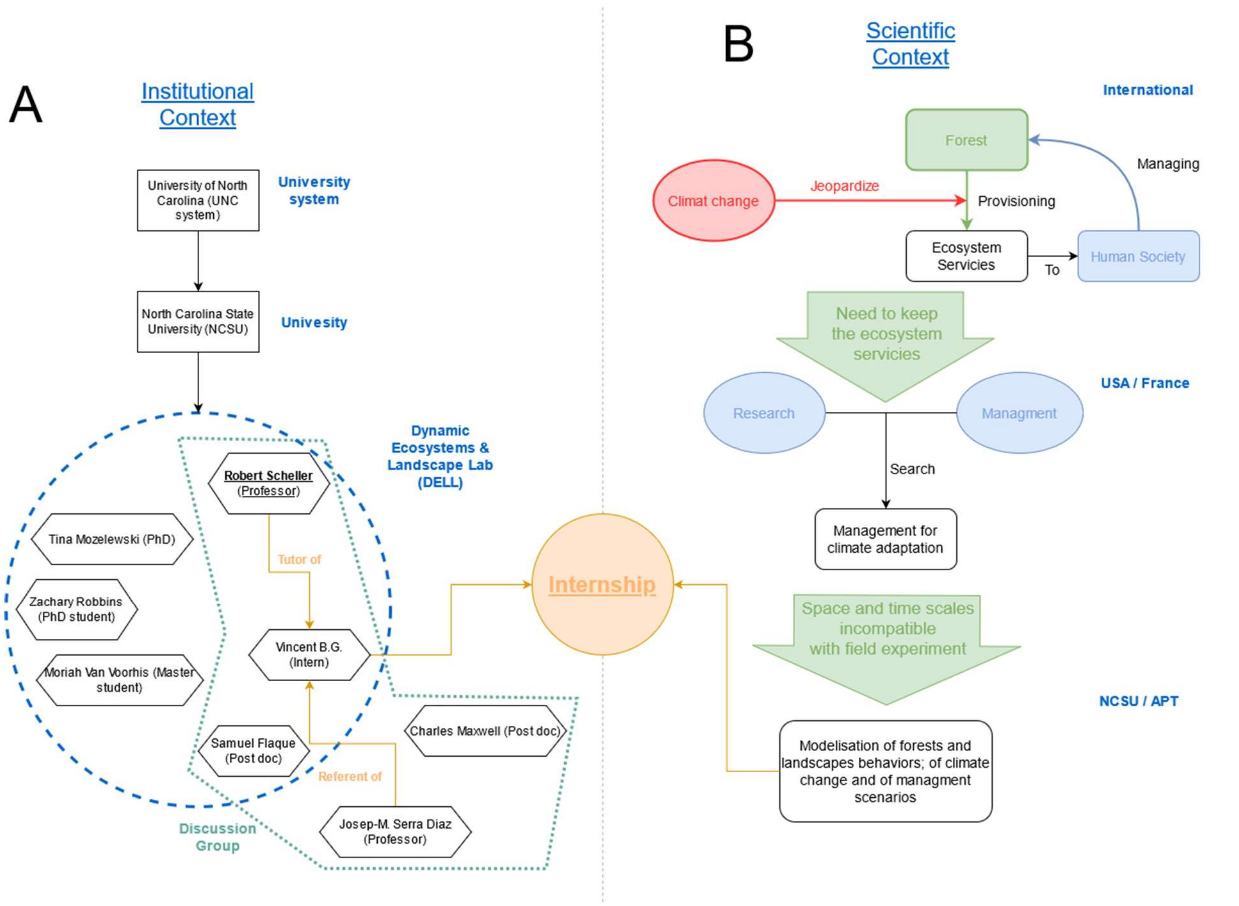


Figure 1: Description of the social context (A): institutions organisation and work groups (DELL and Discussion Group). Description of the Scientific context (B): global problematics that leads to the interest of the study.

I.3. Context of the study

I.3.1. Presentation of the study site: the Klamath region

I.3.1.1. A heterogeneous region of the North-East of California

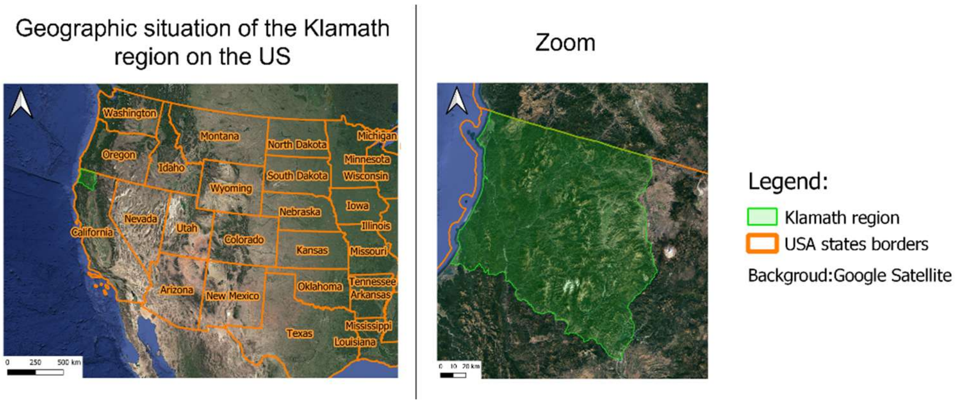


Figure 2: Geographical situation of the Klamath region

The study site represents a surface of more than 3 million ha, with an altitude that ranges from 0 - 2600 m and containing 3 different ecoregions, the Klamath Mountains, the Coast Range and the Southern and Central California Chaparral and Oak Woodlands (National Health and Environmental Effects Research Laboratory and U.S. Environmental Protection Agency 2000).

The Klamath Mountains are subject to lengthy summer droughts, these being the principal limiting factor for the vegetation. The complex topography and geology of this mountainous landscape offers a variety of microclimates. Because of that, this ecoregion has microrefugia where tree species can persist since the last glaciation until a favourable climate return (Whittaker 1960). Thus, the ecoregion is rich in endemic and relic tree species, including the Brewer spruce *Picea breweriana*, an endemic species and one of the rarest in the USA, part of the IUCN Red List (Maxwell and Scheller 2020).

The Coast Range is fog-shrouded and covered by productive coniferous forests. This ecoregion has been changed by intensive logging, being today dominated by Douglas fir plantations. Finally, the Chaparral and Oak Woodland is characterised by a Mediterranean climate (hot dry summers and cool moist winters), less exploitation by human activity and, as indicated by his name, a vegetative cover comprising mainly chaparral and oak woodlands (Griffith *et al.* 2016).

I.3.1.2. A forest changing in response to climate change

It is well known now that the greenhouse gases emissions modify the climate system (Houghton, Jenkins, and Ephraums 1990; Stott 2016; IPCC 2021). In California, anthropogenic warming (0.001 to 0.1 °C per year from 1992 to 2008, Hansen *et al.* 2006) create droughts, in particular in the period 2012-2014 (Diffenbaugh, Swain, and Touma 2015; AghaKouchak *et al.* 2014) resulting in increased insect activity (Raza *et al.* 2015) and leading to more frequent and severe outbreaks. But the increasing disturbance most widely known and covered by media are the fires regimes (Williams *et al.* 2019) having this year again endangered forests, houses and people (Chappell 2021).

These disturbances alter vegetation, changing the ecosystems through both long term (global warming) and short term (extreme weather events) mechanisms. A first effect of these changes on forest ecosystems is a shift on species composition. Because a large part of the Klamath region is drought limited, it is expected that the warming of temperatures will decrease soil moisture and increase evaporation, resulting in drought-induced mortality and regeneration failure for more mesic species (Millar *et al.* 2012; Andrus *et al.* 2018). For the montane conifers surviving within microrefugia, like the Brewer spruce, it is predictable that with warming temperatures and no place to go, only the adults will likely persist and only until disturbance removes them (Maxwell and Scheller 2020). More generally, observations and models predict that landscapes dominated by temperate forest will evolve towards temperate shrubland and grassland, being on a global scale (Gonzalez *et al.* 2010), or specifically at the Southwest of the USA (Keyser *et al.* 2020).

These changes in species composition are already observed in the Klamath region, whether showing a woody encroachment (Norman and Taylor 2005) or in most cases a shift towards shrub and chaparral dominated landscape (Serra-Diaz *et al.* 2018a), with a declining of mountain tree species (DeSiervo *et al.* 2018).

I.3.2. An urgent need of management for climate adaptation

By modifying the functioning of the forest ecosystems, climate change jeopardises the provisioning of ecosystem services (Montoya and Raffaelli 2010; Chiabai *et al.* 2018), figure 1). "Ecosystem services are the aspects of ecosystems utilized (actively or passively) to produce human well-being" (Fisher, Turner, and Morling 2009). To sustainably benefit from the forests through these ecosystem services, the society has historically managed forests for this purpose.

In the last decades forest managers and policy makers faced the issue of climate change, with the goal of finding a management that ensures that forest will continue to provide ecosystem services (figure 1).

Maintaining or restoring past conditions is not a solution, as it creates forests ill adapted to current conditions and more prone to undesirable changes. Instead, accepting that the future will be different compared to past and present situations leads to new forms of forests management (Millar, Stephenson, and Stephens 2007; Keenan 2015). It is this new management that will be further designated as management for climate adaptation.

The world "Adaptation" is not used here just as the Darwinian definition, the "process by which a species becomes fitted to its environment [and] the result of natural selection's acting upon heritable variation over several generations" (Gittleman 2019). By definition, all ecosystems that will emerge in the future will be genetically adapted. The challenge is here to achieve a forest that provides ecosystem services and that is also genetically adapted to the future ecological conditions. I designate this adapted forest that provides services an "objective forest" in this report.

I.4. Objective of the study

The question I sought to answer was: Which management for climate adaptation will lead to an objective forest?

I identified different management scenarios for the Klamath forests, and for each one I determined if they lead or not to an objective forest, or a forest that tends toward this ideal.

II) Method

II.1. Modelling

II.1.1. Necessity of landscape modelling

The spatial and temporal scale of landscape and climate processes makes empirical field science hard to use for answering research and management questions (Turner and Gardner 2015). It is possible to use experiments, but they can only capture the ongoing processes and are always spatially and economically limited (e.g. ONF 2019; 2020; 2020).

Simulation modelling then is the most appropriate approach to experiment on large scales, saving time and space and allowing users to forecast the future. *In silico* experimentation can be used at different scales. Stand models for example can account for competition and climatic change (e.g. Hurteau, Robards, *et al.* 2014; Le Moguédec and Dhôte 2012). However, these models do not operate on a scale large enough to consider the population's migrations. Dynamic Global Vegetation Models (DGVM) (Kim *et al.* 2018; Krinner *et al.* 2005) are dedicated to biogeographic approaches, but with an examination of vegetal dynamics typically at continental scale, with a resolution of 10 to 100 km depending on applications. These scales cannot identify microclimates and potential climate refugia, nor to simulate disturbances (e.g., fires) that operate at a landscape scale. Landscape ecology models offer a compromise: the dynamic vegetation processes (dispersion, settling, growth, competition, and mortality) and disturbances are both simulated at the landscape scale. Taking into account these processes is crucial for the understanding of forest ecosystems and their evolution in response to climate change (Thom, Rammer, and Seidl 2017).

The landscape scale for the study of disturbances and forest stands is defined by the landscape ecology science by ranging from 50 m² to 100km² and from 1 to 500 years. Within these boundaries, it is possible to visualise and quantify the effect of the future disturbances on the forests (Serra-Diaz *et al.* 2018b; Liang, Hurteau, and Westerling 2017) while also considering forest management (Liang, Hurteau, and Westerling 2017; Maxwell *et al.* 2020).

II.1.2. LANDIS-II: a powerful spatially explicit and mechanistic model

LANDIS-II (http://www.landis-ii.org/home) is an explicit spatial model focusing on ligneous species (trees and shrubs). Simulations forecast decades or centuries into the future, with study zones that can reach the hundreds of millions of hectares. The core LANDIS-II model is based on the forest dynamic processes and forest succession. Some "extensions" (or submodels) simulate perturbations, management, or land use. For this study, the Net Ecosystem Carbon & Nitrogen (NECN) Succession was used. It takes into account climate, soil species and functional groups information and creates outputs concerning nitrogen and carbon cycles, above and belowground on annual timestep. The Biomass Biological Disturbance Agents (Biomass BDA) extension simulates mortality due to insect outbreaks (epicentres, spreading and intensity). The Social-Climate Related Pyrogenic Processes and their Landscape Effects (SCRPPLE) extension simulates fire ignition, fire spreading, intensity and suppression, making the distinction between fires that are natural (lightning generated) or accidental (human generated, criminal fire is also denominated as "accidental"). The Biomass Harvest Extension simulates thinings, cuttings and plantings. It prioritises the stands to manage depending on the user criteria (economical, age, fire prescription...) and the management area.

II.1.3. Data used

II.1.3.1. Data availability

All data used is available on the project GitHub repository: https://github.com/LANDIS-II-Foundation/Project-Klamath-2021. The repository contains supplementary material that will be designated in the text as "folder/ANNEX" for pdf documents created from ".Rmd" files (using the R software). Other types of documents will be addressed as "folder/name of the document". To ensure transparency and repeatability, all model inputs and installers are available, as well as all the editable R codes used. To open this work to people with colour vision deficiency, all the maps of this report are available in black and white.

II.1.3.2. Model parameterization and calibration

Most of the data used was taken from (Serra-Diaz *et al.* 2018b) and from (Maxwell *et al.* 2020). More precisions about the data used and its origin is available on the GitHub repository. The simulation uses rasters at resolution of 150 m and was performed considering 31 species (28 trees and 3 shrubs, see "Model Parameterization/species_description"). The climatic data comes from the MIROC5 model (Watanabe *et al.* 2010) derived from a high radiative forcing scenario (the RCP 8.5).

However, some changes were needed for rasters that weren't at the study site extent but that included Oregon's part of the Klamath region (Model Parameterization/ANNEX 1). In order to verify a coherent functioning, model simulations with a single cell of all the rasters and without any disturbances were performed (Model Parameterization/ANNEX 2). This led to an upgrade in the user guides of the extensions concerning the format of input rasters and allowed us to identify parameters that needed to be modified (Model Parameterization/ANNEX 3).

II.2. Identification of three forest management scenarios

Forest management can face climate change using two strategies that are not exclusive: Adaptation and Mitigation (Keenan 2015). Mitigation aims to diminish the importance of climate change, in concrete terms by stocking a maximum of carbon. As explained before, we will focus here on the adaptation.

Two different management scenarios for climate adaptation were identified through bibliography, completed by a Business as usual scenario.

II.2.1. Adaptability vs Pro-active management strategies

Two options are possible for the managers and policy makers: (1) trying to facilitate ecosystem adaptation (for instance through change in species composition) or (2) trying to engineer resilience through pro-active management strategies (Joyce *et al.* 2008). These two strategies correspond to managed resilience (Scheller 2020) and are differentiated by the degree to which they emphasize natural resilience, being at the extremes of a continuum of response to climate change. Both scenarios are often motivated by the important uncertainty concerning future climate change (Jandl *et al.* 2019) and have been empowered by the public's opinion willingness to move away from traditional logging and associated economical amenities (Schick and Burns 2020).

The first option will be designated in the document as the "Adaptability scenario". It represents a management that gambles on the passive adaptation of forest, using the natural, inherent resilience and succession processes of forest ecosystems. The assumption is that ecosystem dynamics will naturally self-regulate and adapt the ecosystem to climate change. The objective is then to facilitate these changes. This view is increasingly taken by private owners of small forest properties that are intermittently managed by non-experts (Weiss *et al.* 2019; Mostegl *et al.* 2019) and is a consequence of the idea that human errors (both in management and carbon emissions) are the cause of the issues and therefore can't be a solution (Miller 2002).

The second scenario is the "Pro-active scenario"; it emphasizes active adaptation and the use of silvicultural methods (e.g., tending, thinning, stand conversion, tree species enrichment) to change stand structures and tree species composition in ways that make the resulting forest better adapted to the future climate (Bolte *et al.* 2009; Millar, Stephenson, and Stephens 2007). Silvicultural prescriptions are motivated by the rate of change predicted, which exceeds the abilities of most tree species to move into new habitats (Hebda 1995). This strategy also responds to the recommendation of managing forests that have been neglected or mismanaged (Little Hoover Commission 2018). Finally, the pro-active scenario acknowledges the human responsibility to tackle global warming issues and therefore to use ecological engineering responsibly (Miller 2002).

II.2.2. Scenario 1: Business as usual

Before detailing the two potential management for climate adaptation, the Business as usual scenario - in which everything is done unchanged - needs to be described. The Business as usual (BAU) scenario settings used on the present work are the same as the BAU scenario as used on previous studies (with only slight changes) corresponding to the management done during the year 2016 (*cf.* part II.1.3.2).

II.2.3. Scenario 2: Adaptability

Management for climate adaptation may involve incremental changes to existing management systems (Keenan 2015). Thus, the Adaptability scenario was parameterized for the Biomass Harvest extension by modifying the BAU scenario settings (table 1). Each change was justified by an adaptation strategy inspired from the recommendations found on the bibliography. This part summarises and enumerates these recommendations and the corresponding adaptation strategies, with the code that links them to table 1.

This management approach was designed to enable forests to respond to change, facilitating forest ecosystems to respond adaptively. The treatments implemented would mimic, assist, or enable ongoing natural adaptive processes, for example changing disturbance regimes. The strategic goal was to encourage gradual adaptation and transition to inevitable change, allowing for anticipating surprises and threshold effects (Millar, Stephenson, and Stephens 2007). This led to the adaptation strategies of creating an insect risk prescription (A) and expanding the fire risk prescription (B). The InsectRisk prescription was built following the bark beetle management guidebook (McCallum, n.d.), see Outputs/ANNEX 4.

This management approach also aimed to remove obstacles to migration, including the fragmentation of habitat (Corlett and Westcott 2013), by promoting connected landscapes that aid tree migration. Desired goals include reducing fragmentation and planning at large landscape scales to maximize habitat connectivity (Millar, Stephenson, and Stephens 2007). The implementation of patch cutting was a promising possibility, with optimal patches of 0.1 ha (Steeger *et al.* 1999). This led to the adaptation strategies of implementing patch-cutting (C) and randomly selecting the stands to manage (D).

Increasing diversity was also an objective of this scenario, as managing to promote mixed stands and using silvicultural techniques that fosters complexity could reduce vulnerability (Seidl, Rammer, and Lexer 2011). Indeed, it has been shown that varying the species composition of harvested trees proved the most effective treatment for promoting climatically suited tree species in the stands (Steenberg, Duinker, and Bush 2011). As recurring climatic events have synchronized forest that have then become vulnerable to climate shifts, this diversity also reduces vulnerability by achieving asynchrony (Millar, Stephenson, and Stephens 2007). This led to the adaptation strategies of implementing patch cutting (C) and natural regeneration (E). It also led to the use of the forest type table (F), that allowed to make the rules of the prescriptions less narrowed.

Table 1: Link between parameters set for the Adaptability scenario in the harvest extension and adaptation strategies of the bibliography. Black signifies no change compared to BAU, red signifies a change justified by an adaptation strategy. Unchanged prescriptions are not detailed. For further information about the parameterization, please refer to the user guide (http://landis-ii-foundation.github.io/Extension-Biomass-Harvest/).

Scenario 2 : Adaptability

Parametrisation in Biomass Harvest extention			**Adaptation strategy**
Management area involved	Name of prescription	Definition	
2 (Federal), 7 (Matrix timberlands)	KMC_Fed	Large scale thinning to promote old growth structure	
	StandRanking	Random	(D)
	ForestTypeTable	Same than eco (Doug) but with 70%	
	SiteSelection	PatchCutting 40% 60	
	CohortsRemoved	SpeciesList	
	SOD_Sanit_Fed	Sudden oak death sanitation	
	StandRanking	Economic	
	SiteSelection	PatchCutting 60% 0.1	
	CohortsRemoved	SpeciesList	
	Oak_Restoration_Fed	Promotion of oak woodlands	
	PinuLamb_Release_Fed	Promotion of sugar pine, removal of competition	
	FireRisk-LightThinning	Reduce fire risk by reducing ladder fuels	
	FireRisk-ModerateThinning	Reduce fire risk by reducing ladder fuels +	
4 (Tribal Area)	Tribal	Tribal reserve management	
	StandRanking	Random	(D)
	ForestTypeTable	Same than eco (Doug) but with 70%	(F)
	SiteSelection	PatchCutting 60% 0.1	(C)
	CohortsRemoved	Species list	
	~~Plant~~	~~PseuMenz~~	(E)
~~4, 5, 6, 7~~	~~Salvage_plant~~	~~Post disturbance replanting~~	(E)
5 (PIF)	PIF	Private Industrial Forest	
	StandRanking	Economic	
	SiteSelection	PatchCutting 70% 0.1	(C)
	CohortsRemoved	ClearCut	
	~~Plant~~	~~PseuMenz~~	(E)
6 (PNIF)	PNIF	Private non Industrial Forest	
	StandRanking	Random	(D)
	ForestTypeTable	Same than eco (Doug) but with 70%	(F)
	SiteSelection	PatchCutting 60% 0.1	(C)
	CohortsRemoved	ClearCut	
	~~Plant~~	~~PseuMenz~~	(E)
4, 5, 6, 7 (Matrix timberlands), 8 (Adaptive Managment Areas)	RxFire	Low intensity fire	(B)
	StandRanking	Random	
	MinimumAge	20	
	ForestTypeTable	(2conditions)	
	SiteSelection	PatchCutting 80% 40	
	CohortsRemoved	SpeciesList	
	MxFire	Mixed Lethal Fire	(B)
	StandRanking	Random	
	MinimumAge	80	
	ForestTypeTable	(2conditions)	
	SiteSelection	PatchCutting 80% 40	
	CohortsRemoved	SpeciesList	
2, 4, 5, 6, 7, 8	InsectRisk		(A)
	StandRanking	Random	
	ForestTypeTable	80% PinuPond	
	SiteSelection	PatchCutting 40% 0.1	
	CohortsRemoved	*SpeciesList*	

II.2.4. Scenario 3: Pro-active adaptation

As done for the precedent scenario, this part lists the recommendations found on bibliography and the corresponding adaptation strategies, with the code that links them to table 2.

It was possible, in some extreme cases, to continue to manage close to the traditional management of productive species (e.g. Douglas fir). Indeed, intensive management may enable retention of these species, even if the site was no longer optimal (Dale *et al.* 2001, Spittlehouse andStewart 2003). Whereas this may seem a denial of future change, it was a defensible approach to uncertainty. These options were best exercised in projects that have high amenity, or under ecosystem conditions that are relatively insensitive to climate change effects (Millar, Stephenson, and Stephens 2007). This recommendation led to the implementation of an Economic Resilience scenario (A), built to maximise economic profit, and based on one of the prescriptions of the BAU scenario.

As said before, this kind of prescription had to be done in some environments that were more buffered against climate change and short-term disturbances than others. This was the case of the microrefugia that were recommended to apply Economic Resilience scenarios (Corlett and Westcott 2013). To identify them on the Klamath mountain, the proxy of the soil moisture was used (more detail in the method used in Model Parametrization/ANNEX 1). The Economic Resilience prescription was then used only in a new management area that corresponded to the microrefugia and that was named Economic Resilience Areas (B).

In western North America, treatments might include complete fuel breaks and insect management around highest risk or highest value areas (Agee and Skinner 2005; Millar, Stephenson, and Stephens 2007). As the areas with most investments were the Economic Resilience scenarios implemented before, a Buffer zone was created around them (*cf.* Model Parametrization/ANNEX 1). Fire and insect risk prescriptions were implemented in it (C).

In the areas that were not under an Economic Resilience strategy managed translocation (also called assisted migration or assisted colonization), the opposite strategy, was implemented. The objective was to assist species migrations along expected climatic gradients. In the USA pacific coast, climate change has made the traditional dominant species managed (Douglas fir) move up in elevation. To maintain forest cover, species more suitable for the future climate (notably hardwoods and ponderosa pine) currently in lower elevation should be moved uphill to maintain forest cover (Maxwell and Scheller 2020). On patchy and heterogeneous mountainous terrains, where migration direction was difficult to determine, this can be achieved by experimenting with new species mixes (Corlett and Westcott 2013; Millar, Stephenson, and Stephens 2007). To identify which species were suitable for assisted migration, the situation of the Klamath region on their distribution area was determined. Each species received a note corresponding to the situation (where is the Klamath region situated on the distribution area of the species?) and the shape of the occupation (is the species present only in little patches or in all the region?). The distribution area used, the notes given, and their definition are available on "Model Parametrization/species_description". I made the hypothesis that species that were present in all the Klamath region (not in patches) and for which the Klamath region was on the middle or the north of the distribution area were more likely to thrive in future climates than the others. Thus, these species were planted for the assisted migration prescription (D).

Table 2: Link between parameters setted for the Adaptability scenario in the harvest extension and adaptation strategies of the bibliography. Black signifies no change compared to BAU, red signifies a change justified by an adaptation strategy.

Scenario 3 : Proactive adaptation

Parametrisation in Biomass Harvest extention			**Adaptation strategy**
Management area involved	Name of prescription	Definition	
11 (Economic Resilience Area)	Economic_Resilience	Economic resilience scenario	(A), (B)
	StandRanking	Economic	
	SiteSelection	PatchCutting 40% 60	
	CohortsRemoved	SpeciesList	
2 (Federal)	KMC_Fed	Large scale thinning to promote old growth structure	
	StandRanking	Economic	
	SiteSelection	PatchCutting 40% 60	
	CohortsRemoved	SpeciesList	
	Plant	Potentially adapted species	(D)
	SOD_Sanit_Fed	Sudden oak death sanitation	
	Oak_Restoration_Fed	Promotion of oak woodlands	
	PinuLamb_Release_Fed	Promotion of sugar pine, removal of competition	
	FireRisk-LightThinning	Reduce fire risk by reducing ladder fuels	
	FireRisk-ModerateThinning	Reduce fire risk by reducing ladder fuels +	
4 (Tribal Area)	Tribal	Tribal reserve management	
	StandRanking	Economic	
	SiteSelection	CompleteStandSpread 20	
	CohortsRemoved	Species list	
	Plant	Potentially adapted species	(D)
4, 5, 6, 7	Salvage_plant	Post disturbance replanting	
	StandRanking	MaxCohortAge	
	SiteSelection	Complete	
	MinTimeSinceDamage	1	
	CohortsRemoved	PlantOnly	
	Plant	Potentially adapted species	(D)
5 (PIF)	PIF	Private Industrial Forest	
	StandRanking	Economic	
	SiteSelection	CompleteStandSpread 40	
	CohortsRemoved	ClearCut	
	Plant	Potentially adapted species	
6 (PNIF)	PNIF	Private non Industrial Forest	
	StandRanking	Economic	
	SiteSelection	CompleteStandSpread 20	
	CohortsRemoved	ClearCut	
	Plant	Potentially adapted species	(D)
4, 5, 6, 7 (Matrix timberlands), 8 (Adaptive Managment Areas), 11, 12 (Buffer zone)	RxFire	Low intensity fire	(C)
	MxFire	Mixed Lethal Fire	(C)
2, 4, 5, 6, 7, 8,12	InsectRisk		(C)

II.3. How to measure if a management is producing climate adaptation?

The comparison of the management scenarios was conducted by examining the evolution of the forest over 100 years, and the final condition of the landscape at year 2120. This comparison examined the criteria that allows to define the objective forest. These are enumerated below.

II.3.1. Carbon sequestration

If the management scenarios were improving adaptation, the mitigation of climate change by stocking carbon is an important ecosystem service that is usually used for international environmental policy purposes (Lorenz and Lal 2010). The NEEC (Net Ecosystem Exchange of Carbon) was the value measured. It measures the total flux of carbon (difference between carbon fixed on the ecosystem and carbon released on the atmosphere).

II.3.2. Vulnerability due to disturbances.

The value used in this work was the total mortality (tree biomass killed) generated by disturbances as a proxy for the ecosystem vulnerability. Mortality due to disturbances directly affects the provisioning of ecosystem services (Rocca *et al.* 2014). The biomass removed by harvest was also considered as a way to indirectly measure the effort engaged in management and helped to consider trades off.

II.3.3. Forest sustainability

Having a lasting forest was the obvious necessary condition to have lasting forest ecosystem services. The values used to approach sustainability were forest cover evolution - measured as the difference in final and initial proportion of trees, see equation (1) - and the number of reproduction events - accounting the total number of reproduction events simulated: seeding, resprouting, planting and seroutiny-.

Equation 1: Calculus of the forest cover evolution

$$\Delta FC_i = FC_{100,i} - FC_{0,i}$$
$$\iff \Delta FC_i = 100\left(1 - \frac{BMs_{100,i}}{BM_{100,i}}\right) - 100\left(1 - \frac{BMs_{0,i}}{BM_{0,i}}\right)$$

With:

- ΔFC_i the forest cover evalution for the scenario $i \in [Businessasusual, Adaptability, Proactive]$. It corespond to the evolution of the proportion of trees on the biomass (in percentage).
- $FC_{100,i}$ and $FC_{0,i}$ respectively the final and initial forest cover for the scenario i.
- $BMs_{100,i}$ and $BMs_{0,i}$ respectively the final and initial biomass of shrubs for the scenario i.
- $BM_{100,i}$ and $BM_{0,i}$ respectively the final and initial total biomass (shrubs and trees) for the scenario i.

II.3.4. Forest biodiversity

Not only being a known service of forest ecosystems, the support of biodiversity was a key element to the provision of others services, as instance recreational, health related or production ones (Brockerhoff *et al.* 2017).

II.4. Experimental design and outputs treatment

II.4.1. Experimental design

For each of the three scenarios, two replicates were performed. The outputs were analysed and graphed using the software R. Supplementary results are available on Outputs/ANNEX5, along with all the standard deviation of all maps, the codes and calculus.

II.4.2. Statistical approach

To compare scenarios, the usual method is a mean comparison with statistical tests. To know which test was suited for the set of data, one has to determine if the sets of data are paired or not. As the data considered in this work was the result of a model and not a sampling from a bigger population, the answer is complex. For two sets of data, they are paired if they contain the same amount of measures, taken from the same pool of individuals (usually at different moments in time, (ZACH 2020; Gosall and Gosall 2013; Stat Trek 2021). As the scenarios were implemented on the same study site, and the measures were done cell by cell, it could seem acceptable to consider the cells as individuals from which three paired sets of measures were obtained. However, if the initial vegetation was the same for the three scenarios, the data created by the model became more and more independent from the initial conditions through the stochastic events that were simulated. Because of the complexity of applying classic statistical tests, I decided to not use them. If this decision was unconventional, it however doesn't prevent interpreting the data obtained (Amrhein, Greenland, and McShane 2019). To achieve comparisons of outputs, values will be considered as different if their standard error bars were not overlaying. As this standard deviation was due to model variations and not to the sampling process, the standard deviation used in this study was not a "sample standard deviation". In consequence Bessel's correction was not to be used (Renee 2015), see Outputs/ANNEX5 for more details).

II.4.3. Data presentation

Graphed information was always presented with the standard deviation using the "error bars" format. For maps, legends were built using the following method: first, a visualisation of the BAU scenario (used as a reference) was realised using the equal intervals setting. This option was selected as it allows to identify localised extreme values, unlike a visualisation by quantiles. By testing, I found that 6 intervals was a number that shows interesting information without overloading the map. The breaks obtained were rounded for a better legend visibility. These breaks were then used for the other scenarios, making possible comparison of maps.

III. Results

III.1. Carbon balance

Total Net Ecosystem Exchange of Carbon (NEEC) varied widely for each management scenario (Figure 3). All the values were negative, signifying that the ecosystem, in all scenarios, stock more carbon than it released in the atmosphere. As expected, the carbon stocked increased with the amount of planting implemented. Thus, with these criteria, the suitable management for climate adaptation was the Pro-active one.

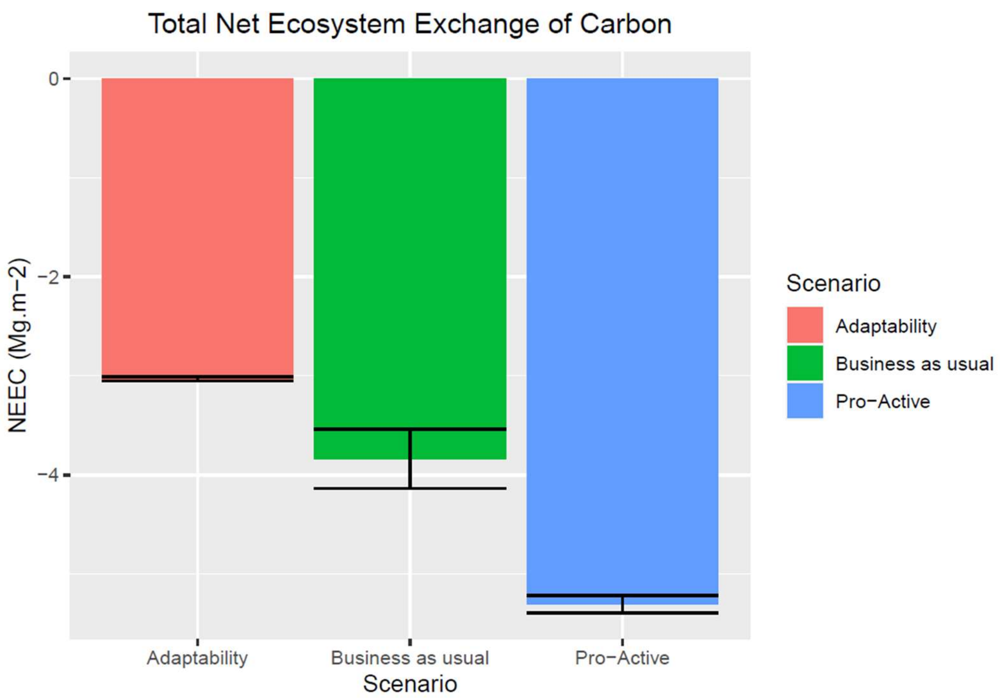


Figure 3: Total Net Ecosystem Carbon (NEEC)(Mg/m²) for three management scenarios, between years 2020 and 2120.

III.2. Mortality due to disturbances

III.2.1. Harvest

In a similar way than the carbon stocked, the total biomass removed by harvest increased with the degree of human intervention in the scenario (*cf.* Outputs/ANNEX5). This was consistent with the way the scenarios were built and validates the willingness of effort that was involved in the scenarios. Biomass harvested was constant against time for the Adaptability scenario, while it increased for the others (Figure 4).

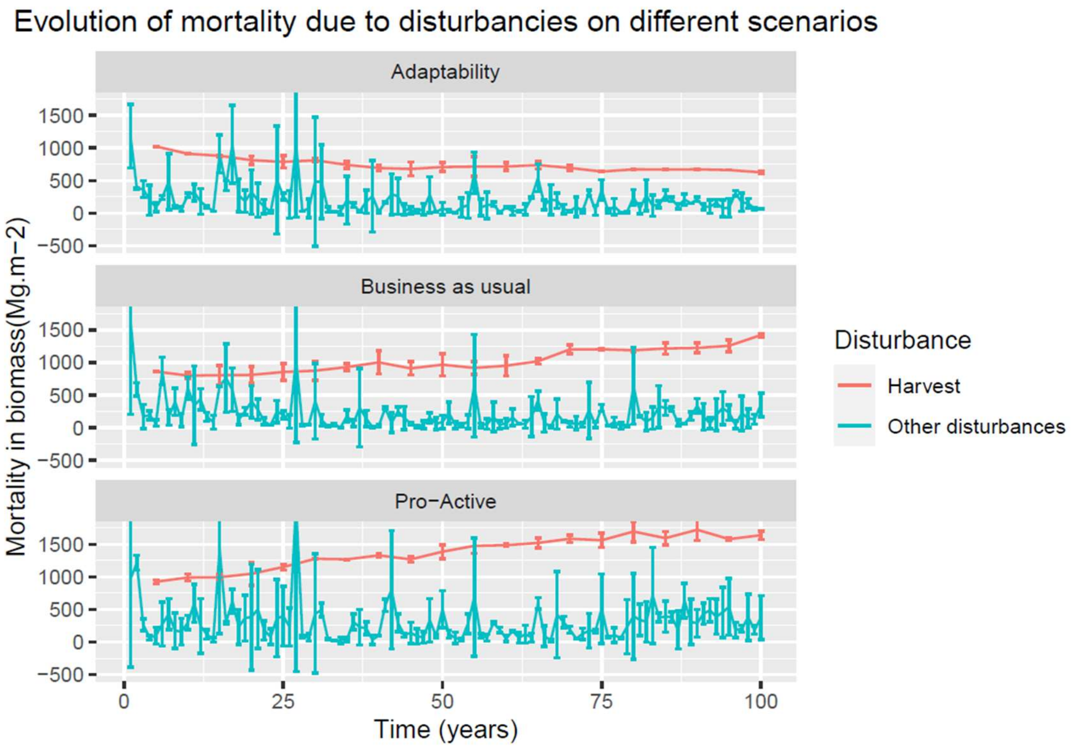


Figure 4: Evolution of harvest and other disturbances mortality (all are in Mg/m²) for three management scenarios.

III.2.2. Insects

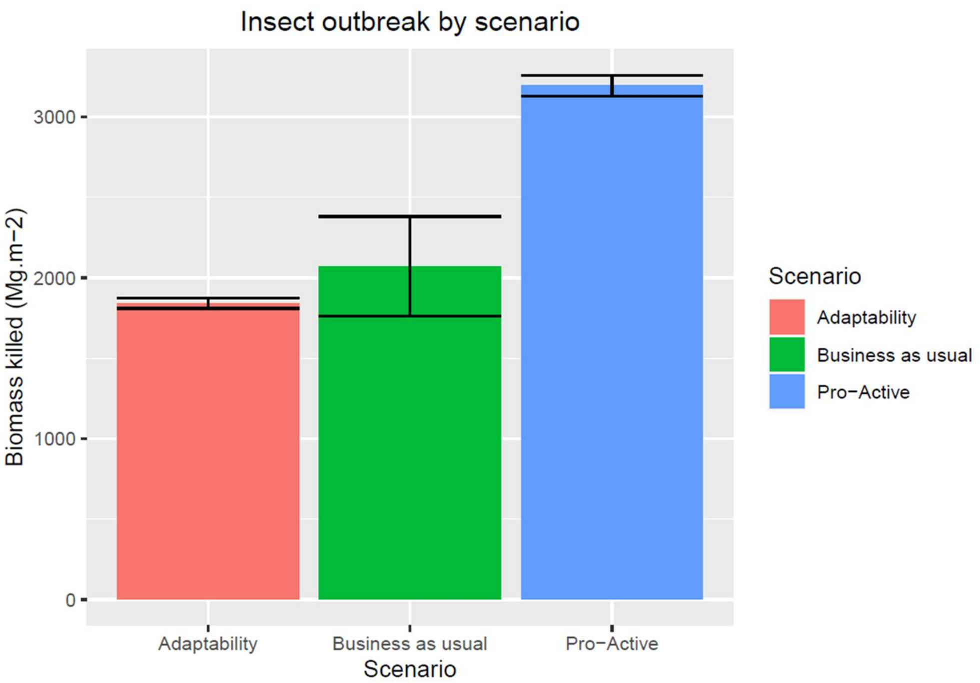


Figure 5: Total biomass killed by insects (Mg/m²) for three management scenarios between years 2020 and 2120.

Concerning insect outbreaks, the Pro-active scenario showed mortality around 3194 Mg/m² compared to the 1840 Mg/m² and 2071 Mg/m² of respectively the Adaptability and BAU scenarios (Figure 5). The standard deviation bars of these two last scenarios were totally overlaid so BAU and Adaptability scenarios seem to have the same effect on insect behaviour.

III.2.3. Fire

Only natural fire ignitions *i.e*. coming from lightning were considered here. Burned biomass was similar between the Adaptability and the BAU scenario (respectively 12050 and 11455 Mg/m²) (Figure 6). The Pro-active scenario in contrast led to an important amount of burned biomass (17701 Mg/m²).

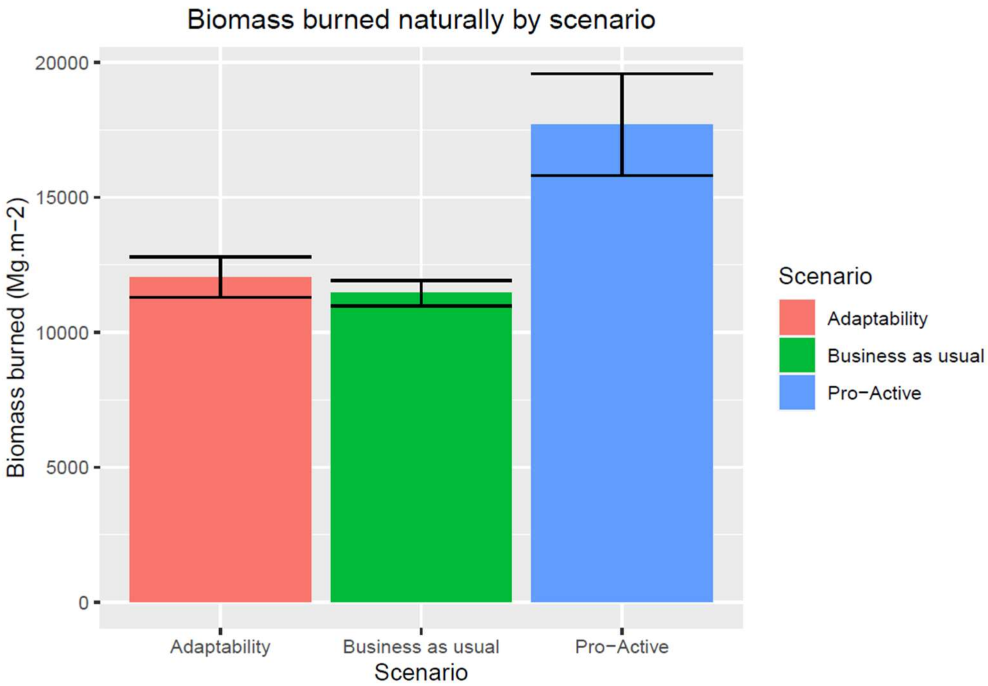


Figure 5: Total biomass killed by fire (Mg/m²) for three management scenarios between years 2020 and 2120.

To see where this increased amount of fires appears, I examined the number of years with at least one fire (Figure 7).

III.3. Forest sustainability

III.3.1. Forest cover

The evolution in the proportion of trees on the biomass (in percentage) showed a decline in forest cover (Figure 8), meaning that none of the scenarios were able to increase shrub biomass relative to tree biomass. This value was low for the Adaptability scenario, with a decrease of 19% of the biomass of trees over the total biomass. The BAU and Pro-active scenarios were both around 8%.

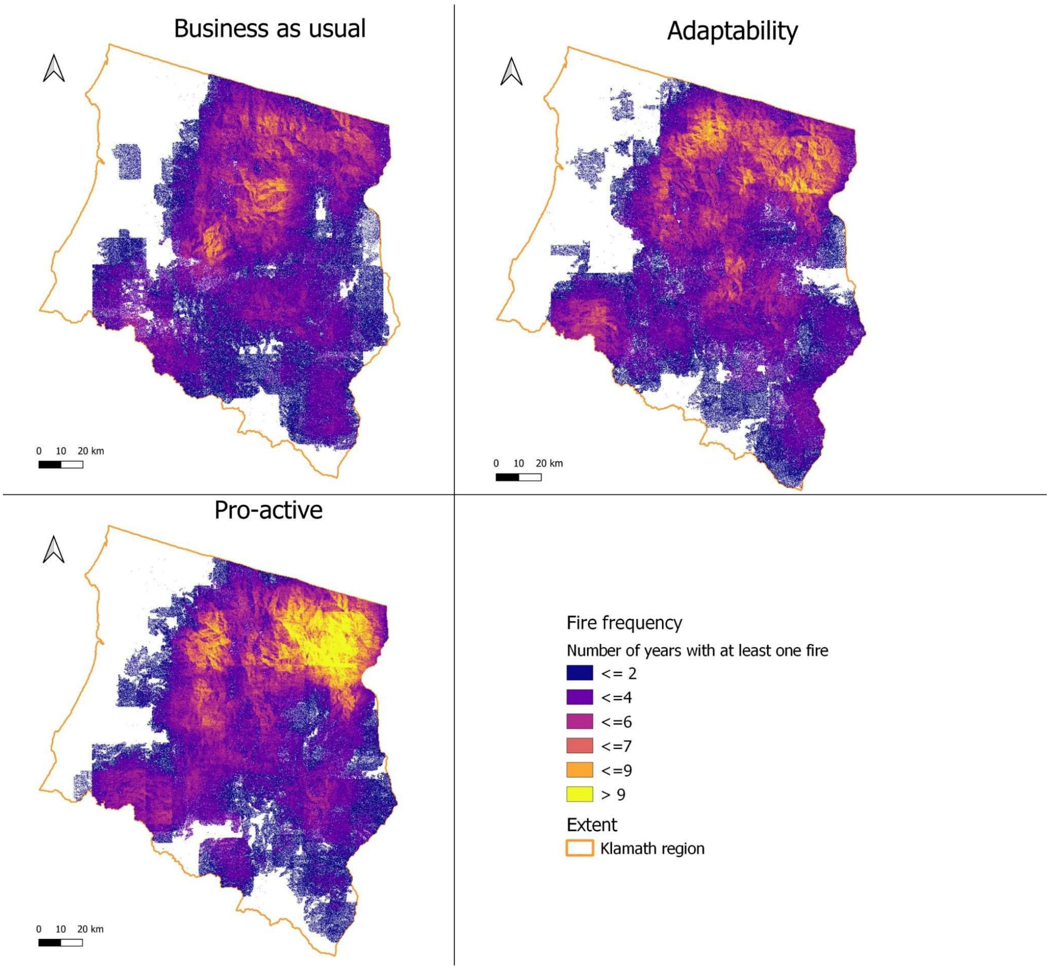


Figure 6: Number of years with at least one fire for three management scenarios between years 2020 and 2120.

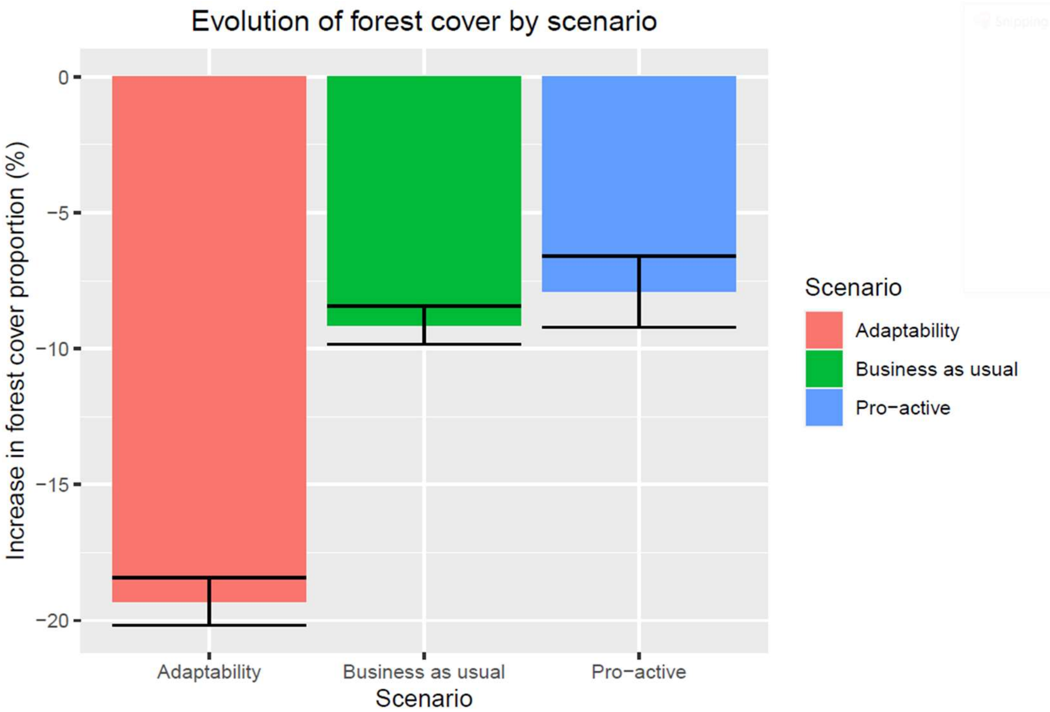


Figure 8: Evolution of the proportion of trees over shrubs (in %) between years 2020 and 2120 for three management scenarios.

III.3.2. Reproduction events

The number of reproductive events (*cf.* Outputs/ANNEX5) followed what would have been expected (data not shown). Indeed, planting was taken into account and the number of events for Pro-active (more than 137.10^6) was superior to BAU (38.10^6) itself superior to Adaptability (30.10^6). Without taking in account planting, the results were similar each other, with a slight superior value for the Adaptability scenario. This light difference demonstrated that by planting (intensively or moderately alike) no consequent competition was done to the other forms of regeneration.

III.4. Biodiversity

Species richness before and after the simulation (Figure 9) showed a loss for the BAU scenario. Zones of maximal and minimal richness were not situated at the same place after 100 years. The Adaptability scenario showed the same pattern that the BAU but with reduced richness. The important number of species planted in the Pro-active scenario (11 species) explained important zones of richness limited to the planted areas. Except for these plantations, the pattern of the final species richness seemed on a stage intermediate between BAU and Adaptability. The average number of species by cell (*cf.* Outputs/ANNEX5) had the same general behaviour in all the scenarios, with a decrease after the 60th year.

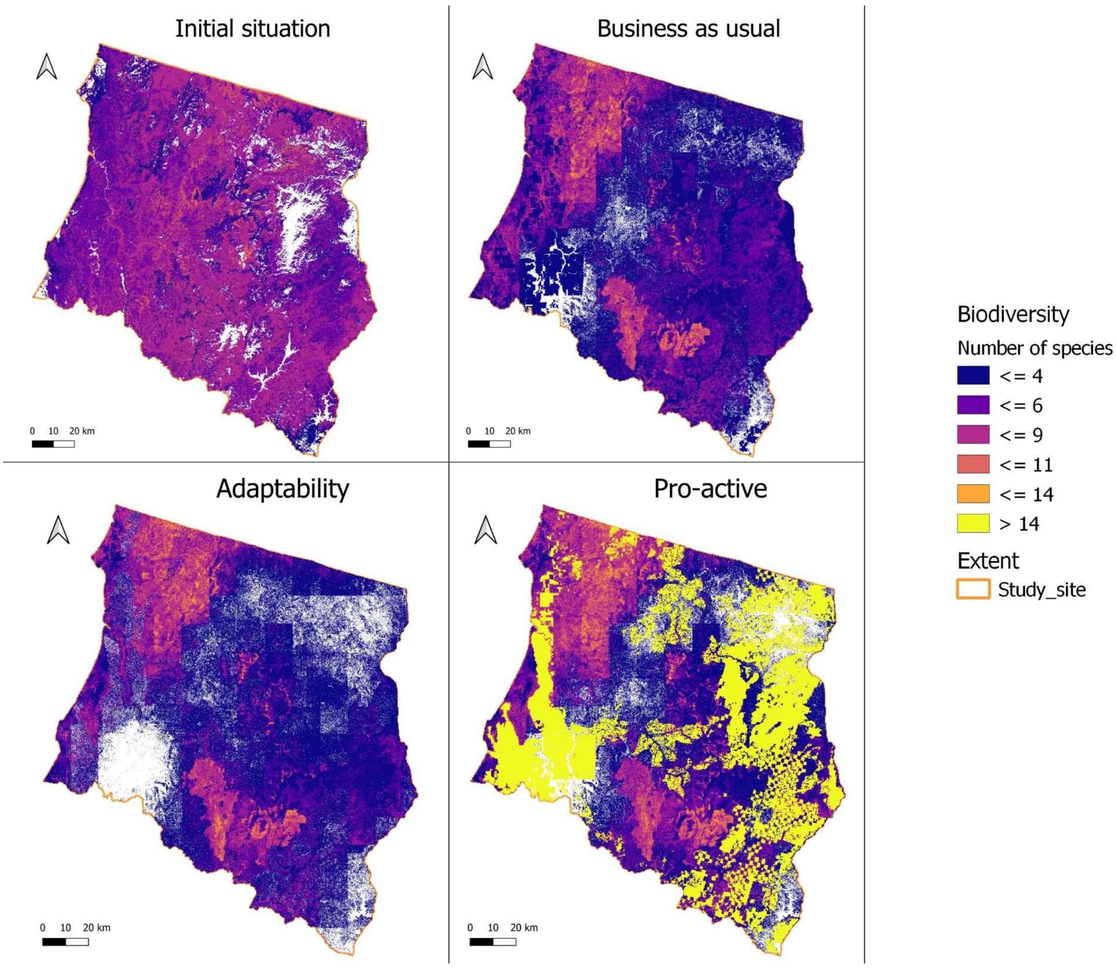


Figure 9: Number of species on year 2020 and for three management scenarios at 2120.

IV. Discussion

IV.1. Strength and weaknesses of the scenarios

The different criteria chosen allowed us to compare the scenarios between them, the figure 10 summarising the strength and weaknesses of the three scenarios.

The fact that the quantity of carbon stored increased with the degree of human intervention in the scenarios shows the success of plantation strategies to stock carbon (Domke *et al.* 2020). Thus, with this criterion, the suitable management for climate adaptation was the Pro-active one. However, if carbon sequestration was a key criterion when choosing a management scenario, prioritising it over the other parameters can lead to deviances potentially negatives for the ecosystem (Lindenmayer *et al.* 2012).

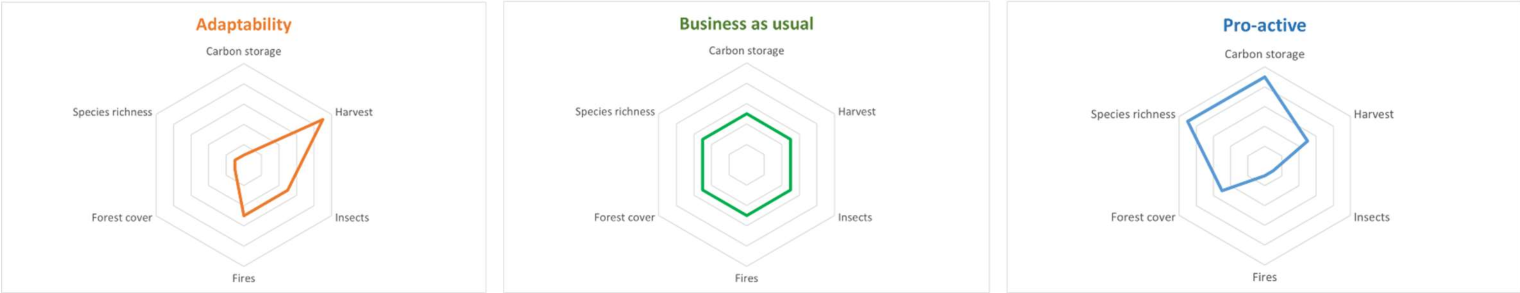
Concerning disturbances, analysis of the results allowed me to rank managements regarding the quantity of biomass killed for the different disturbances. The Pro-active scenario should not be used if facing insect outbreaks or fires is a priority. The Pro-active scenario demonstrates that, despite efforts of management for fire risk, intense plantations can lead to an increase of fires, and that may waste investments. The areas where the fire frequency was maximal correspond to areas with lower precipitation on the Klamath Mountain ecoregion, close to the cascade slopes and foothills ecoregion situated at the eastern edge of the study area, an area that currently experiences greater temperature extremes and less precipitation (National Health and Environmental Effects Research Laboratory and U.S. Environmental Protection Agency 2000).

The Pro-active scenario was the better choice to ensure reproduction of the forest through intensive planting. The similar number of reproduction events other than planting across all scenarios shows that competition of planting did not reduce natural reproduction. Thus, the genetic variability that would have happened with seeding, and the advantages of sprouting and serotiny were kept.

However, this interpretation only considers reproduction, and later competition between species and individuals could modify this conclusion. Moreover, if planting ensure reproduction, the generalised decrease of proportion of tree biomass demonstrates that none of the scenarios were able to tackle the increase of shrub landscapes already observed in California and the Klamath region (Tepley *et al.* 2017; Keyser *et al.* 2020). This was surprising, as it would have been expected that at least the intense tree planting of the Pro-active scenario would increase the proportion of trees. This confirmed that letting natural regeneration (Adaptability) was not a suitable way of regeneration in the Klamath region, given climate change, as it led to the domination of shrubs. The intensive planting (Pro-active) was also not a solution, as the gain compared to moderate planting (BAU) was neglectable. By elimination, the suitable management to tackle increasing shrub landscape dominance was the BAU scenario.

The objective of the study was to find the management for climate adaptation that will lead to an objective forest. As table 3 emphasises, no scenario was absolutely more suitable than the others, but one can be relatively preferable in a given situation. Thus, management for climate adaptation must be chosen regarding the priority issue to tackle on the given place (Krofcheck *et al.* 2018).

Figure 10: Synthesis of the strengths and weaknesses of the compared management scenarios.



IV.2. Perspectives

IV.2.1 Publication

This work will be used as the basis for a publication. However, some modifications to the present study are necessary.

IV.2.1.1. Climatic data

I observed that disturbances other than harvest declined after fifty years, despite climate change (Figure 4). This was surprising as the literature predicts an increase in disturbances in the region, particularly for fires (Hurteau, Bradford, *et al.* 2014; Odion *et al.* 2004). After testing simulations with another climatic model (the Canadian Earth System (CanSM) model (Swart *et al.* 2019), it has been decided to use CanSM (see Outputs/ANNEX6 for the comparison of climatic models). Half of the simulations needed have already been executed thanks to the help of the engineer of research. To quantify the influence of extreme weather events, simulations with modified climatic data that contains more extreme events will also be explored.

IV.2.1.2. insect risk

Because the insect outbreaks have already been analysed, additional information can be obtained by looking precisely on the InsectRisk prescription. The InsectRisk prescription was completely created from bibliographical recommendations instead of observed practices (*cf.* table 1 and part II.2.3, (McCallum, n.d.). Two versions of the Adaptability scenario were initially created: one with a low InsectRisk implementation (Adaptability Low IR), and one with a high InsectRisk implementation (Adaptability High IR) (*cf.* Outputs/ANNEX4 for detail). Simulation shows that the selection of Low IR vs. High IR creates an interesting difference on insect outbreaks, while the biomass harvested was identical. This information was an unexpected observation that could be fully integrated into a future paper.

IV.2.1.3. Species migration

The document Outputs/ANNEX7 presents a code I made to capture migration movements of the simulated species, both toward spatial axes or climate refugia. As substantial bibliography exists on the subject, describing movements of Californian species from which some were simulated in this study (Serra-Diaz *et al.* 2016; Maxwell and Scheller 2020).

IV.2.2 Perspectives for further investigation

IV.2.2.1. Evaluation of the ecosystem resilience

In the present study, effectiveness of management strategies to tackle disturbances was measured through mortality, *i.e.* the biomass killed. A widespread concept used in ecology and landscape management is resilience (Nikinmaa *et al.* 2020). It is a complex concept that has already been adapted to LANDIS-II disturbances simulations (Lucash *et al.* 2019) and that could be used for fires, insects, and harvest.

IV.2.2.2. Economical approach

Even with model simulations, the selection of the management scenario will ultimately depend on their costs and benefits. However, there are few examples of decision-making frameworks that compare costs of the absence of reaction (like the BAU scenario) with the cost of implementing adaptive strategies (like Adaptability or Pro-active scenarios)

(Keenan 2015). Computing an economical criterion, like the Land Expectation Value is possible. Indeed, areas planted as well as age, species and biomass removed are given by the model.

If in the present work the investment was approached by the amount of biomass harvested, this can be criticised as harvest is also the major income. Moreover, this income is highly species-dependent (reason for the creation of Economic Resilience areas). Knowing the Land Expectation Value can bring valuable information when comparing scenarios.

IV.2.2.3. Introduce new species

The decline of tree species on the biomass described in this work could be explained by a shift northward and upward of tree species. This shift could be balanced by new species coming from the north of California (Serra-Diaz *et al.* 2016; Maxwell and Scheller 2020). One advantage of using a forest simulation model is that it is possible to run large scale experiments on the landscape, including testing the introduction of species from outside of the study area (Duveneck and Scheller 2015). Moreover, the plantation of these species can be an adaptation strategie, for instance in the framework of the "Neo-native forests" (Millar, Stephenson, and Stephens 2007).

IV.3. Personal conclusion

This internship has been a rich and intense experience. In continuity with my internship of second year, I found the same topics I was already familiar with (biogeography, modelling, research framework), but driving them to a superior level. I discovered the research process practically in its wholeness, from the discussion of the problematic to the findings of results, and hopefully soon with the adventure of publishing a paper.

Knowing about mechanistic models like LANDIS-II is a valuable item in France where landscape ecology and fire studies typically employ statistical modelling. In parallel with this work, I developed a PhD project in total in continuation of the internship that would have led to an implementation of LANDIS-II in France. This project was supported by the National Office of Forests (ONF), the Ministry of agriculture and the Ministry of ecology, as well as the different actors of the ecological research and forest management I exchanged with. Having a civil servant specialized on this kind of modelling was important to them to not see France "starting to be outdated in the world of management modelling". I am confident that the link between the DE&L laboratory and AgroParisTech created during this internship will soon or later lead to an implementation of LANDIS-II in France, by me or by someone else.

Other than the model itself, the knowledge I learned about forest adaptation, fire regimes, and insect outbreaks mechanisms will ultimately be useful for my future work as coordinator of the forest health observation in the southeast of France.

Finally, the frequent meetings and discussions - both with the DE&L and the discussion group - allowed me to understand and compare some aspects of the USA forestry, ecology, and culture even without having physically moved to the USA. I found this cultural benefit as interesting for my personal development as the scientific knowledge is for my professional career.

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