Ecological restoration of Wairio Wetland, New Zealand: Effect of flooding on woody vegetation, carbon sequestration and recommendations for future plantings

Auteur : Fanal, Aurore
Promoteur(s) : Claessens, Hugues; 3197
Faculté : Gembloux Agro-Bio Tech (GxABT)
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In collaboration with Victoria University of Wellington

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Abstract

This thesis analyses the success of plantings in the Wairio Wetland, a 132-ha area of the Wairarapa Moana wetland complex, located in the lower North Island of New Zealand. In 2011, as part of a restoration project, 2,368 native trees of eight different species were planted in a fenced area using various planting methods. These include: the use of weedmats, topsoil removal, herbicide spraying, the planting of nurse trees, and altered spacing distances. The study aims to (1) analyse the effect of treatments on growth and survival after six years, as well as the effect of elevation (related to water level), (2) develop informed planting strategies for future plantings, and (3) estimate the amount of carbon sequestered by trees.

Six years after planting, results show that all species exhibited poor survival rates. An extreme flooding event in 2016 was responsible for a drop in the survival rates of almost all species. The tolerance to low elevations decreased at the same time. As such, elevation was an important predictor of survival. Topsoil scraping and wide spacing between trees positively influenced the survival of some species. However, most trees grew less in scraped soils. The presence of nurse trees and altered spacing distances did not influence the growth of most species. It is estimated that a total of 1.4 tonne of carbon has been sequestered by planted trees. Survival maps were created and used to inform planting plans in adjacent areas. If utilised, 15.7 tonnes of carbon could be sequestered after six years, or 233 tonnes over the entire Wairio restoration block.

This study highlights the need for an efficient weed control method and emphasises the importance of understanding local hydrology before planting. Also, revising the priority services to restore might be necessary to define the best planting zones. Some objectives might be antagonistic, such as the filtration of water run-off from pastoral lands and the restoration of a *Dacrycarpus dacrydioides* swamp forest providing shelter to native flora and fauna.

Résumé

Ce TFE étudie le succès de plantations au « Wairio Wetland », une zone humide de 132 ha située près du lac Wairarapa, dans le sud de l'Ile du Nord en Nouvelle-Zélande. En 2011, dans le cadre d'un projet de restauration, 2368 arbres furent plantés avec différentes combinaisons de traitements. Cela inclut la mise en place de géotextile, l'étrépage, la pulvérisation d'herbicide, la plantation d'essences d'abri et diverses distances de plantation. Les objectifs de cette étude sont (1) l'analyse des traitements influençant la survie et la croissance des arbres six ans après plantation ainsi que l'effet de l'altitude (liée au niveau d'eau), (2) l'établissement de cartes de survie et de schémas de plantation et (3) l'estimation de la quantité de carbone séquestrée.

Six ans après la plantation, les résultats montrent que toutes les espèces ont un taux de survie faible. En 2016, une inondation d'intensité et de durée exceptionnelles a provoqué une hausse de la mortalité. La tolérance des espèces aux basses altitudes a également diminué. Par conséquent, l'altitude est un bon prédicteur de la probabilité de survie des arbres. L'étrépage et un espacement de 1,5 m influencent positivement la survie de certaines espèces. Cependant, la plupart des arbres ont une croissance plus faible sur les sols étrépés. La présence d'essences d'abri et diverses distances de plantation n'ont qu'une faible influence sur la croissance. Il est estimé qu'un total de 1,4 tonne de carbone a été séquestré par les jeunes arbres. Des cartes de survie ont été construites et utilisées pour proposer un schéma de plantation sur les zones attenantes. Selon cette proposition, 15,7 tonnes de carbone pourraient être séquestrées après six ans, ou 233 tonnes sur la superficie entière du Wairio Wetland.

Cette étude insiste sur le besoin de méthodes de désherbage efficaces et souligne l'importance de comprendre le fonctionnement hydrologique local avant de procéder à des plantations. Revoir les priorités en termes de services écosystémiques à restaurer pourrait se révéler nécessaire pour définir les zones de plantation les mieux adaptées. Aussi, certains objectifs semblent antagonistes, tels que la filtration d'eaux de ruissellement provenant de terres agricoles voisines et la restauration d'une forêt de *Dacrycarpus dacrydioides* fournissant un habitat à une faune et une flore natives variées.

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INTRODUCTION

Wetlands are highly diverse ecosystems found all around the globe, from tropical mangroves to arctic peatlands. These highly productive areas provide numerous ecosystem services, including flood mitigation, water filtration, and climate regulation through the sequestering of carbon. Unfortunately, wetlands have suffered a dramatic decline, with 50% of inland water habitats lost since the 20th century (MEA 2005). In New Zealand, 90% of freshwater wetlands have disappeared since human settlement (Ausseil, Chadderton, et al. 2011). In light of anthropogenic climate change and biodiversity loss, the protection and restoration of wetland ecosystems has never been so legit.

Lake Wairarapa is a 78 km^2 shallow lake, located near the town of Featherston on the Wairarapa Plains. With the Lake Onoke and the adjacent wetlands, they form Wairarapa Moana, the largest wetland complex in the lower North Island of New Zealand. In 2008, the Wairarapa Moana Wetlands Project was launched. It aims to restore the services provided by the wetlands for cultural and recreational purposes, as well as to provide habitat for native biota (Greater Wellington Regional Council 2017).

Wairio Wetland, situated on the western shore of Lake Wairarapa, is part of this complex. This 132-ha area was drained and cleared of its native swamp forest by settlers in the 20th century. Since 2005, Ducks Unlimited New Zealand, an association dedicated to wetlands and waterfowl conservation, has worked with the Department of Conservation to restore the wetland. Four fenced restoration areas (called stages) were set up, in which restoration activities have since taken place. These activities include the construction of dams to retain water, the control of invasive plants and predators, and the planting of native flora. In 2011, 2,368 native trees were planted in Stage 3, a 5.3 ha fenced area. The seedlings were planted in plots receiving different combinations of pre- and post-planting treatments. These treatments include the planting of nurse trees, different spacing distances between saplings, and weed control, such as weedmats, herbicide spraying and topsoil scraping. The survival and growth of the trees have since been monitored by students of Victoria University of Wellington for the last six years to develop effective planting strategies.

During the 2016-2017 summer, the water level was unusually high and a large portion of Stage 3 was flooded, that would have otherwise been mostly dry. This resulted in a higher mortality of tree species that are usually tolerant of intermittent flooding. In light of this, new analyses were needed to determine the best areas to plant trees and methods to maximize survival.

This thesis presents the results of analyses made six years after the first planting in Stage 3. The aims of the study can be divided in three parts:

1. Analyzing the effect of pre- and post-planting treatments on growth and survival. Such analyses to determine the best planting methods have already been done 30 months after planting (Gillon 2014). This study aims to confirm these recommendations and investigate changes since. This analysis also includes the effect of elevation (because of its association with waterlogging) before and after the flood;

2. Creating species-specific survival maps to inform future Stage 3 planting, as well as planting plans for the whole Wairio Wetland;

3. Estimating the amount of carbon sequestered by trees six years after planting, as well as estimations for the whole area if planted according to the plans. This is then compared to that sequestered by native New Zealand forests.

This thesis contains three main chapters. Chapter 1 provides background information about wetlands (types, services, threats, and restoration programs), and covers the history and restoration of Wairarapa Moana and the Wairio Wetland. Chapter 2 is the study itself, including materials and methods, results, discussion and conclusions. The three aims of the study will be addressed in this chapter. Finally, in Chapter 3, I discuss complementary data, and make suggestions of analyses that could be made in the future to improve the restoration of Wairio and other wetlands.

CHAPTER 1: BACKGROUND INFORMATION

Introduction to wetlands

Definition

Several definitions of wetlands can be found in the literature. The Ramsar Convention defines both fresh and marine wetlands as “areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres”. In a nutshell, they are areas where water is the primary factor controlling the environmental conditions and the associated fauna and flora (Ramsar Convention Secretariat 2016). In the Millennium Ecosystem Assessment (MEA, 2003), the distinction is made between inland water bodies and coastal wetlands. If we consider all the inland and coastal water systems (including lakes, rivers and human-made wetlands), the global extent of wetlands is estimated to be around 1,280 million hectares, but it is surely underestimated (MEA 2005).

If we look at the New Zealand Resource Management Act (1991), wetlands are defined as “permanently or intermittently wet areas, shallow water, and land water margins that support a natural ecosystem of plants and animals that are adapted to wet conditions”. This definition includes several freshwater wetland types such as marshes, swamps, fens, bogs and shallow water wetlands, which differ from the position in the landscape, the water source and the degree of fertility (Johnson & Gerbeaux, 2004; van der Valk, 2006; van Roon, 2012).

Types

In “Wetland types in New Zealand” (2004), Johnson and Gerbeaux describe several wetland types found across the country. However, the boundaries are not distinct, as the wetlands vary along gradients of wetness, nutrient richness, and pH. Defining such a classification is useful for the understanding and management of the wetlands.

Johnson and Gerbeaux describe, among others, five main types of freshwater wetlands commonly found throughout New Zealand. These include bogs, fens, swamps, marshes, and the particular cases of ephemeral wetlands and Pakihi/gumlands. The properties of four main wetland types are summarized in Table 1.

Table 1: Key environment characteristics of wetland types (Clarkson & Peters 2010b).

Wetland type	**Bog**		**Fen**		**Swamp**	**Marsh**
Water source	Rainfall	→	Groundwater	→		Surface water
Water fluctuation	Low	→	Medium	→		High
Trophic state	Oligotrophic	→	Mesotrophic	→		Eutrophic
pH	Acidic		→			Neutral
Peat content	High	→	Medium	→		Low/none

Other particular wetlands found in New Zealand are Pakihi (located on the West coast of the South Island) and gumlands, which contain deposits of Kauri gum (located on the North Island). These are local terms for wetlands characterized by a very low fertility and a very acidic pH. The substrate, mainly mineral, is often saturated but drier in summer. These two types of wetands can be induced by fires, especially gumlands that have become more widespread after human settlement (Clarkson & Peters 2010b; Landcare research n.d.).

Ephemeral wetlands, a subset of marshes, are essentially surface land depressions that experience large periodic fluctuations in water levels (Johnson & Rogers, 2003; Zedler, 1987). The substrate is often mineral with an impervious underlying horizon, mesotrophic to eutrophic. The water can come from underground or from an adjacent water body such as a lake or river. The variation in water level is seasonal and can be drastic, going from a ponding in winter to a total drying during summer (Johnson and Gerbeaux, 2004). One typical ephemeral swamp found in New Zealand is the Kahikatea (*Dacrycarpus dacrydioides*) swamp forest. Nearly pure stands of this tall native conifer were once common throughout the country, but have now nearly disappeared (Wardle 1974). The restoration of Kahikatea swamp forests will be one of the main topics discussed in this thesis.

Importance of Wetlands

Ecosystem services

The Millennium Ecosystem Assessment (2003) provides useful definitions of ecosystems and ecosystem services. An ecosystem is a "dynamic complex of plant, animal, and microorganism communities and the non-living environment interacting as a functional unit" that vary in size and scale and of which humans are an integral part of. Ecosystem services can be shortly described as "the benefits people obtain from ecosystems" (MEA 2003). Those services can be provisioning, regulating, supporting or cultural (MEA 2003). The value of those benefits is often unrecorded in the marketplace and thus not recognized by policy-makers, although an increasing amount of techniques are emerging to attribute ecosystems an economic value and encourage their protection or restoration (Finlayson et al., 2003; Levy et al., 2003).

Long considered wastelands, wetlands are extremely valuable ecosystems that provide numerous services, as described in Table 2 (Jones, 2009). The global value of those services has been estimated at 2 to 5 trillion annually, depending on the method and the definition of wetlands used (Finlayson et al., 2003; Ramsar Convention Secretariat, 2016a). Wetlands are among the world's most productive environments and are incredibly biodiverse, housing threatened species of birds, fish, amphibians, reptiles and mammals (Ramsar Convention Secretariat 2016). People living near these ecosystems are particularly dependent on the services they provide, from food and materials, to regulating services such as flood mitigation or water storage (MEA, 2005; Ramsar Convention Secretariat, 2016a). Besides any financial aspect, wetlands are also precious to native people. In New Zealand more specifically, wetlands have a high spiritual and utility value for Māori that obtain food, medicines, materials for weaving and timber from these ecosystems (Cromarty et al. 1996).

Table 2: ecosystem services provided by wetlands (Finlayson et al., 2003; Millennium Ecosystem Assessment, 2005; Ramsar Convention Secretariat, 2016a)

Services	Examples and comments
Provisioning	
Food	Plants (fruits, grains…), fish and game.
Fresh water	Storage of fresh water for domestic or agricultural use.
Materials	Logs, fuel wood, peat.
Genetic materials	Medicine, ornamental species, resistance genes to pathogens.
Biochemical	Extraction of materials from biota.
Biodiversity	High concentration of birds, mammals, reptiles, amphibians, fish, invertebrates and plant species, including a lot of threatened species.
Regulating	
Hydrological regulation	Water storage, drought reduction, groundwater recharge and discharge, regulation of rivers flows.
Water purification	Retention of pollutants, filtration, detoxification of nitrates.
Climate regulation	Carbon storage, stabilization of local climate conditions.
Natural hazard regulation	Flood mitigation, storm protection.
Erosion regulation	Retention of sediments, shoreline stabilization.
Pollination	Habitat for pollinator species.
Cultural	
Recreational	Fishing and hunting, tourism, bird watching, sailing.
Aesthetic	Positive impact on tourism.
Spiritual / religious	Spiritual and religious values of wetlands.
Educational	Opportunities for primary and secondary school education, field research for tertiary education.
Supporting	
Soil formation	Sediment retention, accumulation of organic matter.
Nutrient cycling	Storage, recycling.

In the face of a rapidly changing climate, the carbon sink role of wetlands is often highlighted. Wetlands are estimated to contain between 20 and 30 % of the world's soil carbon pool, and to act as CO_2 sinks, with a net carbon retention of 118 g-C per square meter and per year (Mitsch et al. 2013). In peatlands, carbon is stocked mainly through organic matter accumulation, whereas wetlands on mineral soils sequester carbon *via* sediment deposition and biomass production (Ausseil et al. 2015). Seasonally flooded wetlands also tend to accumulate organic matter in their soil (Betts et al. 2003). On the other hand, wetlands are an important source of methane, by anaerobic respiration of microorganisms in flooded soils (Betts et al. 2003). It is then not sure if wetlands are sinks or sources of greenhouse gas. Some studies reveal that almost all the wetlands monitored are sinks after the balance is made between CH_4 emissions and CO_2 sequestration. A 2010 study of wetlands across Canadian prairies (Badiou et al., 2011) indicated that restored freshwater wetlands could sequester approximately 3.25 Mg CO_2 eq. per ha per year, after accounting for increased CH4 emissions, and that their restoration should be considered for climate change mitigation (Mitsch et al. 2013; Badiou et al. 2011). As some wetland areas act as sinks of carbon and others as sources, a consensus is that the balance is close to zero, especially for the northern peat wetlands.

In the case of ephemeral forested wetlands, we can expect a higher carbon accumulation. This is due to several factors such as the nature of the organic matter produced (high in lignin and cellulose that are difficult to degrade by microorganisms), the protection from the canopy that lowers the litter decomposition rate, and the vegetation biomass itself. Short-term studies reveal high rates of carbon sequestration in newly restored forested wetlands, making these ecosystems more susceptible to mitigate climate change (Li et al. 2004; Bernal & Mitsch 2012; Bridgham et al. 2006).

General trends

Worldwide

Increasing human population and economic development have led to an alarming loss of aquatic habitats (Bohn & Kershner, 2002; Millennium Ecosystem Assessment, 2005). It has been estimated that 50% of inland water habitats have disappeared since the 20th century, exceeding that of forests, grasslands or coastal systems. Species living in these habitats are thus often threatened (Finlayson et al. 2003; MEA 2005). The main drivers of the degradation of wetlands are clearing and drainage for land conversion, nutrient loading by agricultural operations, the introduction of alien species, hydrological modification by drainage or construction of dams, the development of infrastructure, overharvesting (hunting and fishing), sedimentation, and pollution (Finlayson et al. 2003; MEA 2005; Bohn & Kershner 2002). Climate change is likely to exacerbate the degradation of wetlands by adding even more pressure on those ecosystems, but the extent of that impact is not yet known (Betts et al., 2003; MEA, 2005; Finlayson et al.; 2003). It is suggested that the rising temperature could increase CH4 emissions by enhancing microbial activity (Betts et al. 2003).

In New Zealand

The presence of the sea, frequent rainfalls, storms, earthquakes, volcanic activity and glaciation periods are factors that greatly contributed to the formation of wetlands in New Zealand. Unique communities of native plants are associated with wetlands, for example flax swamps (*Phormium* spp.) or Kahikatea (*Dacrycarpus dacrydioides*) swamp forests (Cromarty et al., 1996; Dawson & Lucas, 2012). Unfortunately, the loss of freshwater habitats in New Zealand has been dramatic following human settlement, especially in the North Island which is more populated. It is estimated that 90% of wetlands have been lost, leaving a fragmented landscape of small remnant wetlands, most of them smaller than 10 hectares. Swamp and marshes have suffered the most with little of their historic extent remaining (respectively 6 and 8.2%). This is mainly due to conversion for agriculture since the mid-19th century (Ausseil, Chadderton et al., 2011). Figure 1 shows the historical extent (before Māori settlement) of wetlands in New Zealand as well as the extent in 2003.

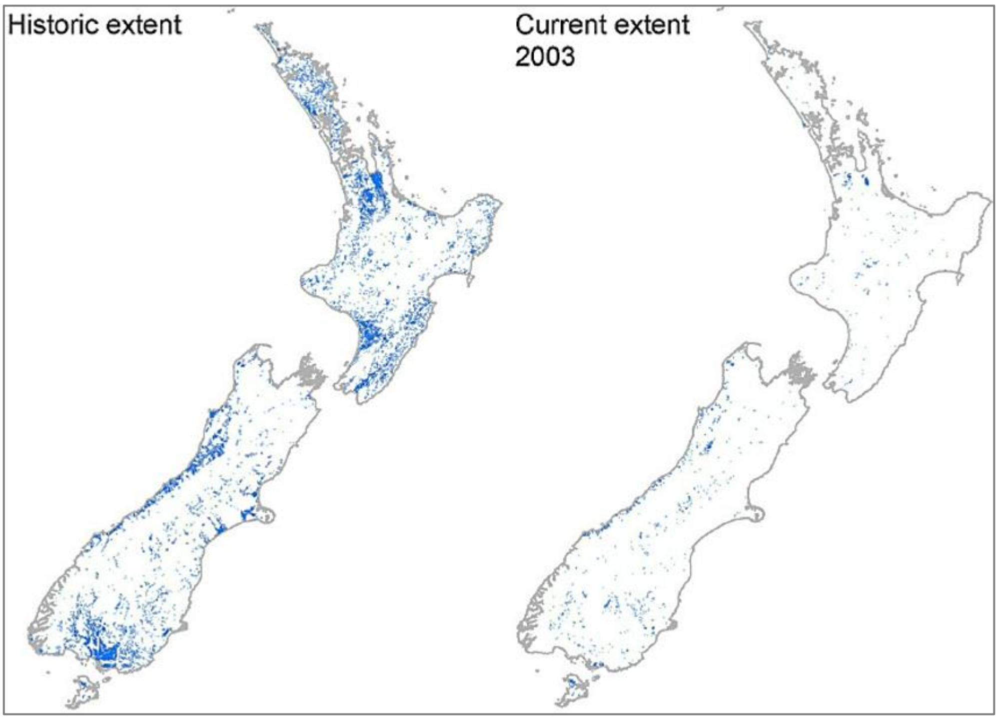


Figure 1: Comparison of historic and 2003 extent of freshwater wetlands (in blue) in New Zealand. The North Island has suffered the greatest loss with 5% of the wetland extant remaining (in Ausseil, Dymond et al., 2011).

New Zealand wetlands are key ecosystems for numerous native species. Twenty-two percent of native birds depend on wetlands, that now only make two percent of the land cover (Greater Wellington

Regional Council 2009). It is also an essential habitat for 27 native fish species, such as the shortfin eel (A*nguilla australis*), the inanga (G*alaxias maculatus*) or the giant kokopu (*Galaxias argenteus*) commonly found in swamps (Ausseil, Dymond et al., 2011).

The degredation of wetlands over the last two centuries has decimated this local flora and fauna : fifteen wetland bird species are now extinct and ten are listed as threatened. Fifty-two wetland plant species have also been classified as threatened and many populations of freshwater fish are in decline (Ausseil, Dymond et al., 2011).

In the Wellington region

The Wellington region has an estimated 10,160 ha of wetlands remaining, of which Lake Wairarapa comprises over 7,000 ha. Aside from this large complex and its associated swamps, only 3,5 % of the wetlands of the region remain, mainly estuaries and swamps on private lands. Some notable ones are the Pauatahanui estuary and the Carter Scenic reserve with its ancient Kahikatea swamp forest (Wetland Trust & Greater Wellington Regional Council 2009).

Wetlands management

The Convention on Wetlands is an international treaty aiming towards the conservation and wise use of wetlands through local and international actions. It is often referred to as the "Ramsar Convention", as it was adopted in the Iranian city of Ramsar in 1971. In January 2016, it counted 169 member States. The "Ramsar List" is a list of wetlands of international importance receiving a special protection status, committing the governments to ensure the ecological character of these wetlands is maintained. More than 2,200 wetlands are already listed as "Ramsar sites" (Ramsar Convention Secretariat 2016). New Zealand was the 13th country to join the convention and has six Ramsar sites on its territory, totaling a surface area of 56,639 ha (Ramsar Convention Secretariat n.d.). These wetlands meet specified criterias outlined in the Convention and have an international significance in terms of ecology (habitat for endemic and/or rare species or communities) or hydrology (New Zealand Department of Conservation n.d.).

In 1986, the Government adopted the New Zealand Wetlands Management Policy, with the entent of preserving and monitoring remaining wetlands, as well as increasing public awareness (Cromarty et al. 1996). Wetlands are also under the *Resource Management Act* of 1991, that identifies the preservation of wetlands as a matter of national importance "which must be taken into account when powers are being exercised and decisions are being made under the Act" (Cromarty et al., 1996). Wetlands are also being monitored with the WERI database (Wetlands of Ecological and Regional Importance) held by the Department of Conservation (DOC). Around 3,000 wetlands have been recorded throughout the country, along with information such as size, ownership, ecological and cultural value, and threats (Cromarty et al. 1996). The DOC is primarly in charge of the management of wetlands on public lands, while local councils must ensure landowners responsibely manage wetlands on private lands.

The National Wetland trust is a non-profit organization established in 1999. It aims to raise public awareness on wetlands conservation, enhance the understanding of wetlands processes and functions, and ensure landowners and government agencies commit to wetlands conservation and restoration (National Wetland Trust n.d.). They provide useful publications related to wetlands restoration, such as the Wetlands Restoration Handbook for New Zealand Feshwater Systems (2010).

Wetlands restoration

Restoration ecology is defined by the Society for Ecological Restoration as “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” (SER 2004). Before restoring an ecosystem, a “reference ecosystem” is often determined as a target for the restoration project. This reference model is often the ecosystem in its pristine condition (before being degraded), but can also be another system, adjusted to the new environmental conditions or chosen for the services it would provide. The reference ecosystem must be characterized in terms of abiotic attributes and species composition (McDonald et al. 2016).

The restoration can be considered a success after the establishment of a biologically viable and sustainable ecosystem similar to the reference ecosystem (Mitsch et al. 1996). The Society for Ecological Restoration (McDonald et al. 2016) and the Ramsar Convention (Alexander & McInnes 2012) provide key attributes of a successfully restored ecosystem: the elimination of threats to the ecosystem (overutilization, invasive species…), the reinstatement of abiotic conditions (substrate, hydrology), the use of native wetlands species to obtain species compositions and functional groups close to the reference ecosystem, and an appropriate functionality (nutrients cycling, species interactions) allowing the wetland to be self-sustaining and integrated within the larger landscape.

Usually, wetland restoration aims to restore lost biodiversity and services. These two goals are not always compatible – for example, species richness is often correlated with low nutrients levels, while a maximized water filtration function requires an important loading of nutrients (Zedler 2000). To achieve success in a wetland restoration project, it is important to understand the wetland functioning and to give the system time to evolve to a self-sustaining ecosystem. Fifteen to twenty years might be necessary before judging the success of the restoration of a wetland (Mitsch et al. 1996).

The first step in a wetland restoration project is the making of a restoration plan. This plan must contain information about the wetland (basic details, vegetation, hydrology, soil type, wetland type), the determined reference wetland, objectives of the project, restoration activities needed and a designed monitoring programme. This plan is helpful to schedule timelines and costs of the activities, clarify the issues and track the results (Peters 2010). Before starting any planting activities, it is necessary to investigate the wetland's water supply (some hydrologic work might be needed), to keep the livestock out of the planting area, and to control weed and animal pests. These two last measures might still be needed after the restoration programme is over (Greater Wellington Regional Council 2009).

Revegetation with native species is one of the main activities undertaken in ecological restoration of degraded wetlands. It often requires the removal of invasive plants before the planting of native seedlings (Clarkson & Peters 2010a). However, high rates of mortality are not uncommon the first years after plantation. This has been attributed to herbivory by deer, rabbits and rodents (Sweeney et al. 2002; Grove et al. 2006; Keeton 2008), competition with weeds (Sweeney et al. 2002; Keeton 2008), soil waterlogging and poor soil conditions (Keeton 2008; Kneitel & Lessin 2010) and extreme environmental conditions (Innes & Kelly 1992). Some management techniques are commonly used to increase the survival rate of seedlings and accelerate their growth, for example the use of tree shelters (Keeton 2008; Sweeney et al. 2002). Techniques to decrease weed competition include topsoil scraping (Patzelt et al., 2001; Klimkowska et al., 2010; Geissen et al., 2013), weedmats (Ogle 1996), diverse tree spacing (Ogle 1996; Padilla & Pugnaire 2006) and the planting of 'nurse trees' (Castro et al. 2002; Padilla & Pugnaire 2006; Filazzola & Lortie 2014; Gomez-Aparicio 2009). The Greater Wellington Regional Council (2009) recommends to apply a weed control method for the three first years after planting in wetlands. The success of these methods varies greatly between sites according to biotic and abiotic conditions, and the species concerned. Using seedlings grown from ecosourced seeds, therefore better adapted to local conditions, might enhance their establishment (Clarkson & Peters 2010a). Some species will also require a shelter from other trees or shrubs to establish successfully. It may be necessary to create a succession scheme (process whereby plant communities gradually change into other ones with time). Pioneer species are therefore planted first to provide protection for the later-successional trees, that are often slower to grow (Clarkson & Peters 2010a; Gomez-Aparicio 2009).

When making a revegetation project in a wetland, it is useful to create a planting zone map. Planting zones evolve along a water gradient, from wet to dry soils, with associated plant communities. The planting zone map compile a list of species to be planted in each zone, with their relative proportions (Clarkson & Peters 2010a).

Finally, continually monitoring the progress of the restoration is essential to improve planting programmes for the following seasons, secure funding and share knowledge with other restoration groups (Clarkson & Peters 2010a)

Wairarapa Moana wetlands complex

Geographical and geological introduction

Lake Wairarapa is a 78 km^2 lake situated in the Wellington region of New Zealand, near the town of Featherston (Figure 2). With its associated wetlands, it forms the largest wetlands complex in the southern North Island (Airey et al. 2000; Wetland Trust & Greater Wellington Regional Council 2009). The western shore of the lake is bordered by the Rimutaka range, while the eastern area is a diffuse zone of sand flats and wetlands, experiencing fluctuating water levels due to rainfall and the effect of wind (Grant 2012; Airey et al. 2000). It then becomes an alluvial plain with agricultural lands, that benefit from the fertile soils (Heine 1975).

As the lake is lying along a geologic fault, seismic activity has shaped the Wairarapa landscape. The last important activity associated with this fault was in 1855 – a magnitude 8.2 earthquake that lifted the ground 30 to 70 cm at the eastern shore of the lake, and after which thousands of hectares become dry (Grant 2012; McFadgen 2003). The lake is only 2.5 meters at its deepest point (Gunn 2012).

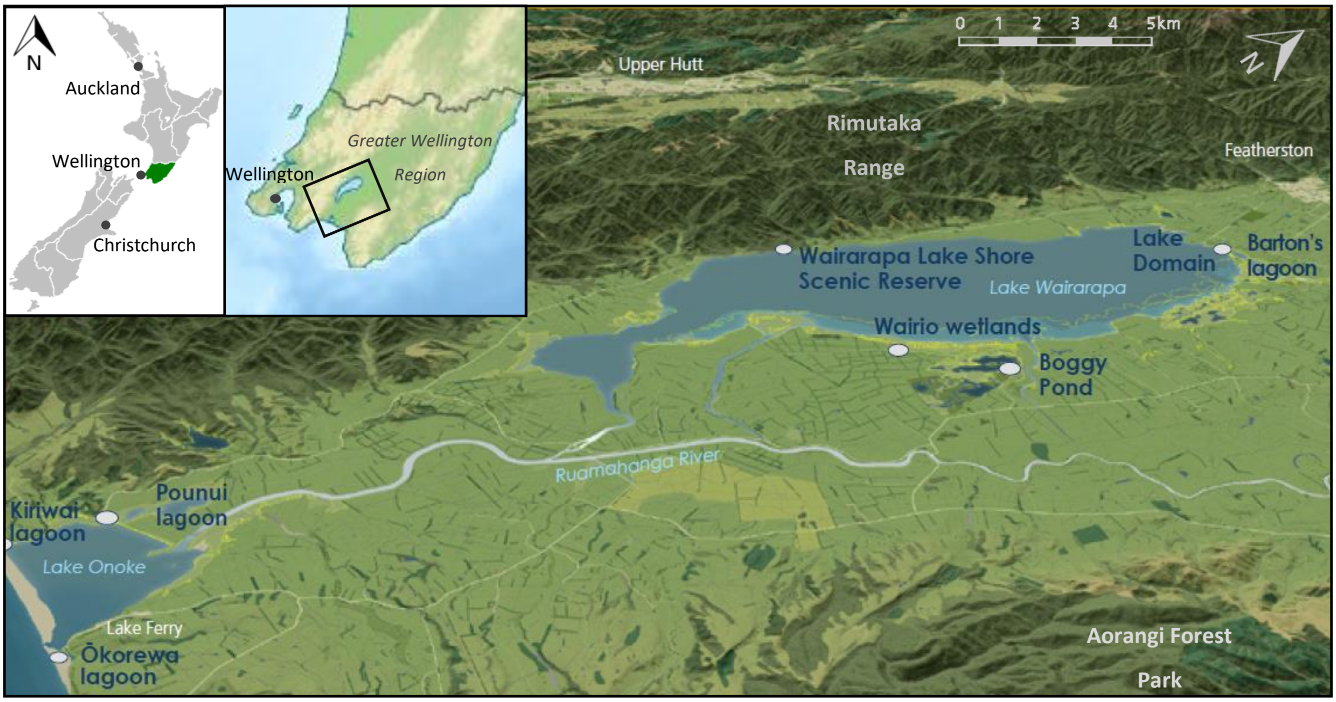


Figure 2: Geographic situation of Lake Wairarapa and Wairio Wetland.
Images source: Greater Wellington Regional Council (2016), Wikipedia.

The climate is characterised by warm, mild summers and cold winters with few frosts. Sudden temperature changes are common with average daily temperatures of 7-17 °C. Rainfall is between 1,326 mm and 1,540 mm annually (Beadel et al. 2000; Gunn 2012). The windy conditions can generate a strong seiche effect in Lake Wairarapa, elevating water levels up to one metre in some areas on the eastern shoreline, including Wairio (Gunn 2012).

History of Lake Wairarapa

Legend has it that the Wairarapa Lake was named by Māori chef Haunui-a-nanaia, the great-grandson of Kupe (explorer who is said to have discovered New Zealand). As he sat at the top of the Rimutaka range after avenging his wife, he contemplated the view on the lake and named it Wairarapa, which means "glistening waters" (Grant 2012).

Māori communities were well-established around the lake, where they hunted, developed agriculture and traded with other communities. A part of the Kahikatea forest was cut down to build villages and for easy access to the lake. Fishery activities were important, as the lake is a habitat for a lot of eels and tuna (Greater Wellington Regional Council 2016). The water (lake and rivers) was considered as *tapu*, sacred, and the lake is still considered as *taonga*, of spiritual and utility value (Airey et al. 2000; Grant 2012). Wetlands have always had an important value for Māori communities in general. They are considered as treasures handed by their ancestors and that need to be cherished. They provide food, medicines, timber, material for weaving, canoe landing sites… This utility value and spiritual linkage explain the strong relationship loca *iwi* ("tribes") and *hapū* (Māori clans or extended families) have with Wairarapa Moana (Cromarty et al. 1996; Airey et al. 2000).

European settlers arrived in the region in the 1840s and quickly installed the first stations near the lake, having noticed the agricultural potential of the area. They purchased land from The Māori and began pastoral farming with cattle and sheep (Airey et al. 2000; Grant 2012). The degradation of the native forests continued and exotic plants were introduced. However, floods were frequent on the new pastoral lands. Settlers put pressure on local *hapū* to be able to control the lake level. Works started after 1896, when the lake was bought by the Crown. As important floods kept occurring despite the first minor works, the Lower Wairarapa Valley Development Scheme (LWVDS) was planned in 1960. Works included the installation of a barrage, the diversion of the Ruamahanga river and the drainage and sale of 1,237 ha of wetlands and lagoons (Grant 2012; Greater Wellington Regional Council 2016). There was no consideration for the environmental value of these lands considered as marginal, or for Māori traditions. From 1943 to 2010, the wetlands area was reduced of 94% (Grant 2012). The lake also became one of the country's dirtiest lakes and is classified as supertrophic (Greater Wellington

Regional Council, 2012a). The poor water quality is mainly due to run-off from dairy factories and the towns' sewage water (Grant 2012).

In 1989, a National Water Conservation Order was placed and recognized the importance of the fluctuating water levels, that creates a unique habitat. A committee was established to act as a mediating system between people having interests in the wetlands (Airey et al., 2000). In 2000, the Lake Wairarapa Wetlands Action Plan was adopted, with guidance by the Department of Conservation. It aims to restore habitats for native species, control invasive species and answer Māori concerns about fishing restrictions. 2008 marked the beginning of the Wairarapa Moana Wetland Project, aiming to "restore our wetland treasure" (Grant 2012). It is led by the Wairarapa Moana Coordinating Committee, that includes members of the LWVDS, landowners, local *hapū*, Fish & Game, Forest & Birds, Ducks Unlimited, the Wellington Conservation Board, the South Wairarapa District Council, the Greater Wellington Regional Council and the Department of Conservation (Grant 2012; Ducks Unlimited New Zealand 2016). In 2012, the project received one million dollars from the Ministry for the Environment to reverse the degradation of wetlands, including Wairio Wetland. The priorities are the restoration of the biodiversity and the improvement of water quality (Grant, 2012).

After decades of degradation, most of Wairarapa Moana is now public conservation land administered by the Department of Conservation. An application has been made for the 10,448 ha of the wetlands complex to receive a Ramsar status (Gunn 2012). A nomination as a Ramsar site would increase the national and international recognition of the area and attract further funding. It is feasible to restore the lake and adjacent wetlands in their pristine conditions, with the native plant and animal communities that used to make the renown of Wairarapa Moana (Airey et al. 2000).

Fauna and flora

Most of the alluvial valley used to be covered by Kahikatea (*Dacrycarpus dacrydioides*) stands. Near the wetlands, the fluctuation of water level creates zones of vegetation with varying tolerances to waterlogging: marshlands with turfs and rushes, sedges (*Cyperaceae spp.*), raupō (*Typha orientalis*) and flax (*Phormium tenax*) in swamps, extensive areas of shrubs such as Mingimingi (*Coprosma propinqua*) and Mānuka (*Leptospermum scoparium*), scattered stands of Cabbage trees (*Cordyline australis*) and Tōtara (*Podocarpus totara*)… More than 40 species of indigenous turf plants have been counted, some of them being nationally threatened (Grant 2012; Airey et al. 2000; Ogle et al. 1990).

Some scattered stands of native trees are still present, but the dominant trees are now species imported from Europe, such as crack willow (*Salix fragilis*), hawthorn (*Crataegus* spp) and alder (*Alnus* spp). In the herbaceous stratum, exotic pasture grasses brought by European settlers invaded the wetlands, such as tall fescue and Mercer grass. They are encouraged by the high levels of nutrients (Airey et al., 2000).

The high habitats diversity of Wairarapa Moana is attracting for wildlife. Ninety-six species of birds have been recorded this wetland complex in the last 15 years, 16 being classified “At Risk” or “Threatened” (Figure 3). It is estimated that at least 20,000 waterbirds use the wetlands every year, mostly mallard, black swan, New Zealand shoveler, paradise shelduck and grey teal, making Wairarapa Moana a hotspot for waterfowls hunting and bird watching (Gunn 2012).

It is also a wetlands complex of national importance for fisheries. Twenty species of freshwater fish have been recorded, the majority being diadromous, which means they need to migrate between freshwater and the sea to complete their lifecycle. Wairarapa Moana is the main pathway for such a migration in the Greater Wellington region. Eleven of the identified fish species are also classified as “At Risk (declining)”, including the Koaro (*Galaxias brevipinnis*), Giant kōkopu (*Galaxias argenteus*) and Longfin eel (*Anguilla dieffenbachia*). A threatened freshwater mussel, Kākahi (*Echyridella menziesi*), is also found in the lake (Gunn 2012).

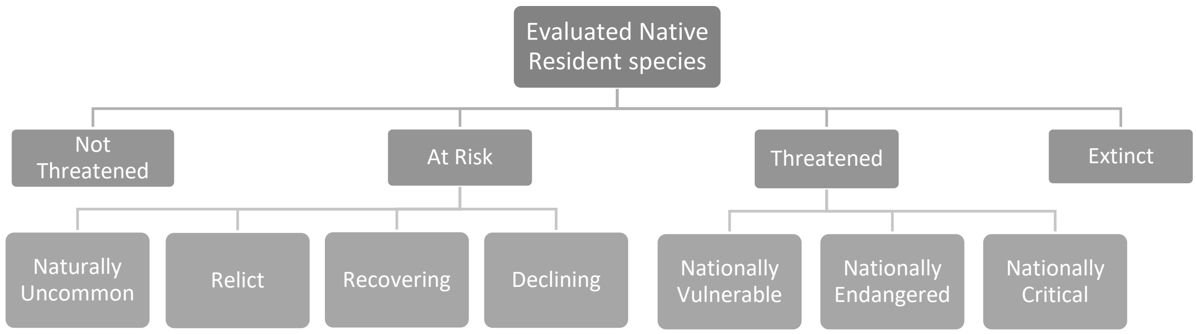


Figure 3: New Zealand Threat Classification System for native resident species (Townsend et al. 2008).

When European settlers installed cattle and sheep in Wairarapa valley, they brought with them several animal pests. Rats, mustelids, hedgehogs, rabbits, hares and feral cats are commonly found and controlled occasionally. Possums are also controlled regularly by the Wellington Regional Council as part of a program to prevent the spread of Tuberculosis. (Airey et al. 2000)

Wairio wetlands

Wairio Wetland is a 132-ha area situated along the eastern shore of Lake Wairarapa. It is separated from the wetland Boggy Pond by Parera Road. Tracks have been made around the wetland and allow visitors to reach a birdhide.

Wairio Wetland used to be covered with a Kahikatea swamp forest and to provide habitats for numerous birds and aquatic fauna. Its degradation first started after Maori settlement, around year

1350, when the forest was cut down or burnt to create villages and to access to the lake (McFadgen 2003). Degradation continued when the Europeans settled in the area in the 1840's and started pastoral farming (Grant 2012). In the years 1960/70s, the Lower Wairarapa Valley Development Scheme greatly affected Wairio by the clearing of remnants forests and sedges, and the drainage of the wetlands. The construction of Parera Road cut off waterflows between Boggy pond and Wairio (Ducks Unlimited New Zealand 2016; Grant 2012). Cattle farming at Wairio and the wider area have also promoted declining water quality levels with excess nitrogen and phosphorus entering waterways (Greater Wellington Regional Council 2012a). Exotic plants also invaded the area, including willow, wild rose, blackberry, gorse, lupin, alders... Willows were later fell and bulldozed across the wetland, that became a highly modified site (Ducks Unlimited New Zealand 2016). Sheep are still grazing in some parts of the Wairio Wetland, and only a few mature Kahikatea, Tōtara and Cabbage trees remain. Wairio Wetland now stands out as one of the priority wetlands to restore in the Wairarapa Moana Wetlands Project (Greater Wellington Regional Council 2012b).

The Wairio Wetland is owned by the Department of Conservation (DOC). DOC signed a Land Management Agreement with Ducks Unlimited New Zealand (DU), renewable after five years. The agreement has already been extended twice, the current period ending in 2020. DU convenes and chairs the Wairio Wetland Restoration Committee, formed in 2005 with the aim of sustainably managing and restoring the degraded wetland. It is composed of representatives from Ducks Unlimited, Greater Wellington Regional Council, Department of Conservation, Fish and Game Council, Forest and Bird, Queen Elizabeth Trust, local *iwi* and resident farmers. The Committee has taken a staged approach for the management of the site. Four stages have already been delimited with fences, and restoration activities have begun in all of them. Those include large-scale native tree planting, earthworks (including ponds and dams creation), weed control, and the construction of fences to exclude lifestock. The aim of this project is that "In 100 years, Wairio will be a fully functional wetland supporting abundant native flora and fauna, with natural hydrological regimes linked to the wider Wairarapa-Moana complex, where people can visit for recreation and to appreciate a natural ecosystem restored to pristine condition" (Ducks Unlimited New Zealand 2016).

For the past six years the Victoria University of Wellington (VUW) has worked with the Wairio Wetland Restoration Trust (WWRT) and conducted research in the restoration stages. VUW's students conduct diverse experiments regarding hydrology and restoration methods, such as trees planting treatments, the effect of nutrients on plants diversity and the effect of mycorrhizae on wetland tree species.

Research aims

In 2011, a Master student from VUW started a revegetation experiment in Stage 3 of Wairio wetland. More than 2,300 trees were planted with combinations pre- and post-planting treatments, including the planting of nurse trees, different spacing distances between the seedlings, and methods to control concurrent weed (weedmats, herbicide spraying and topsoil scraping). The aim was to investigate the cost-effectiveness of these management methods and see how they affected the establishment of the seedlings (Johnson 2012). The survival and growth of the trees have then been monitored by students of the Victoria University of Wellington for the last six years to develop effective planting strategies. Thirty months after planting, analyses to determine the best planting practices have been done by a master student (Gillon 2014), then by two intern students in 2016 (five years after planting).

Because of the re-construction of a dam by DU and a rainy spring and summer, the water level was unusually high during summer 2016-2017. A large portion of Stage 3 was flooded when it would usually have been mostly dry. These flooding events may become more frequent, because of the restoration of the hydrological regime in Wairio but also because climate change might lead to an increased frequency of flood events (Grant 2012). It is therefore important to analyze the effect of the flood on the revegetation project and make recommendations for the upcoming plantings.

There are three main aims in this study:

1. The determination of the best planting practices by analyses of survival and growth before and after the flooding. The analyses also include the effect of elevation (related to waterlogging), to see how the limits of tolerance of the species have shifted.

2. The creation of species-specific survival maps related to elevation, as well as suggestions of planting plans for Stage 3 and the whole Wairio restoration block;

3. The estimation of the carbon content of the trees six years after the beginning of the project, as well as estimations for the whole area if planted according to the planting plans.

CHAPTER 2: STUDY

MATERIAL & METHODS

Study site

This study was carried out in the management stage 3 of the Wairio wetland, a fenced area of 5.3 hectares (Figure 4). Restoration activities have been done by the Wairio Wetland Restoration Committee since 2008. It includes the construction of dams and flood-gates at the northern and southern ends to retain water, the building of the fence and the plantation of native trees (Gillon 2014).

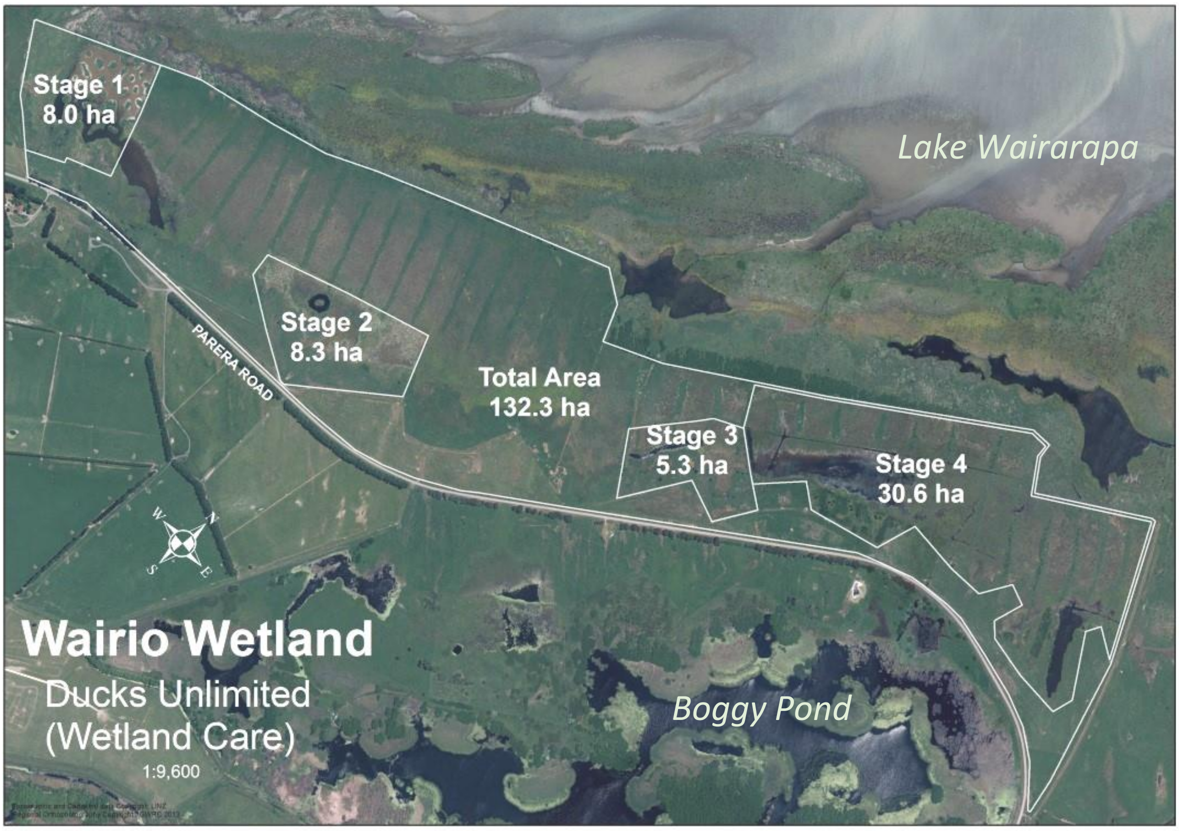


Figure 4: Aerial view of the Wairio wetland and the four management stages (modified by author, original from Ducks Unlimited New Zealand (2016)).

Tree species

Eight different plant species have been planted in the Stage 3 area, including two gymnosperms and six angiosperms. They were selected for their current or historical presence at the site (Ogle et al. 1990) and for their usual association with D. dacrydioides in swamp forests (Wardle 1974). The species are separated into "nurse" species and "focal" species. The focal species are trees that the project mainly aim to re-establish as they are characteristic of mature forests in the area and are believed to have dominated the site before being cleared by settlers. The nurse species are a selection of fast-growing shrubs that may have a facilitation effect on the focal trees, as explained later in the "treatments" chapter. The list of the species with their common name(s) and attributed species code used in the analyses are found in Table 3, and pictures of the species are available in Table 4. Seedlings grown from eco-sourced seeds were purchased from the Norfolk Road Nursery and the Akura Conservation Centre, located in the Wairarapa region (Gillon 2014).

Table 3: Species codes used in data tables, Latin names and common names.

	Species code	Latin name	Common name
FOCAL	OV	*Olearia virgata*	Twiggy Tree Daisy / Bush Daisy
	CA	*Cordyline australis*	Cabbage Tree / Tī Kōuka
	DD	*Dacrycarpus dacrydioides*	Kahikatea / White Pine
	PT	*Podocarpus totara*	Tōtara
NURSE	LS	*Leptospermum scoparium*	Mānuka
	KO	*Pittosporum tenuifolium*	Kōhūhū
	CP	*Coprosma propinqua*	Mingimingi
	CR	*Coprosma robusta*	Karamū

The nurse species are:

- *Coprosma* species: fifty-three *Coprosma* species are found in New Zealand. Natural hybrids are frequently found, in particular between *C. robusta* and *C. propinqua*. *Coprosma robusta* is a shrub with large and thick leaves, growing to six meters high, commonly found in forest margins and shrublands. *Coprosma propinqua* is a small-leaved shrub that occupies a wide range of habitats, including swamps and bogs. It can also reach six meters with a 20 cm wide trunk diameter (Dawson & Lucas 2012).
- *Leptospermum scoparium* is a pioneer shrub found throughout New Zealand, from swampy to dry and infertile soils, where it survives thanks to its numerous mycorrhizal associations. It is up to ten meters tall, the trunk being up to 15 cm of diameter (Dawson & Lucas 2012). Shrublands dominated by *L. scoparium* form the most common secondary-successional community found around forests margins or in abandoned agricultural sites (Scott et al. 2000). The production of aerenchyma (i.e. tissue that allows exchanges of gas between the shoot and the roots) allows *L. scoparium* to survive in waterlogged environments (Stephens et al. 2005). This species is often planted for its ability to stabilize slopes (Watson & O 'loughlin 1985) and for its essential oil that receives considerable commercial attention, particularly *via* Mānuka honey (Stephens et al. 2005).
- *Pittosporum tenuifolium* is a shrub found in coastal to lower-montane forests, of variable morphology. It grows to eight meters tall with a 30 to 40 cm wide trunk. This species is common in cultivation and often establishes itself in gardens. It is easy to recognize by its almost black branches and dark purple to black flowers. The leaves vary in shape in size throughout New Zealand (Dawson & Lucas 2012).

The focal species are:

- *Cordyline australis*, commonly called Cabbage tree or Tī kōuka, is a monocotyledonous species that was used by Māori as a food and fibre source, as well as for medicine (Simpson 1997). It is a pioneer species often found in open habitats and near swamps, as it readily colonizes newly exposed grounds (e.g. following a flood or fire). They then form dense stands lasting for hundreds of years (Dawson & Lucas 2012; Simpson 1997). The below-ground morphology of cabbage trees consists of a large rhizome from which radiate numerous long and narrow roots. This dense root system can completely dominate the surrounding soil. The young roots produce aerenchyma that allow them to survive in wetlands. As they mature, roots produce a hard epidermis that protects them from damages from droughts (Simpson 1997).
- *Olearia virgata* is a shrub often found growing in wetlands. Its common name "Twiggy Tree Daisy" is a reference to its densely interlacing branches. This species exhibits significant morphological variation. In general, it can reach six meters high with a trunk diameter up to 20 cm (Dawson & Lucas 2012).
- *Dacrycarpus dacrydioides* (Kahikatea or White Pine), can live for at least 600 years and is probably the tallest endemic tree in New Zealand with a height up to 65 meters. Trunks often reach 150 cm, but larger trees are not uncommon. They are adapted to wet soils, including swamps. It seems that Kahikatea can survive in waterlogged environments without any special tissue adaptation; however, a significant proportion of the root system lies above-ground, allowing gas exchange (Dawson & Lucas 2012). They also develop large buttresses to support them in wet grounds (Waikato Regional Council n.d.). Seedlings are demanding in light (Dawson & Lucas 2012). Kahikatea swamp forests were quite common in New Zealand, but only a few scattered forests of them remain. It has been estimated that 98% of the pre-European Kahikatea forests has been lost throughout the country (Waikato Regional Council n.d.; Dawson & Lucas 2012).
- *Podocarpus totara* is an endemic conifer prominent on well-drained alluvial plains. It is a pioneer species, up to 30 meters tall and two meters wide. Trees older than 900 years are not uncommon. The young trees have brown leaves which is believed to be a protection against herbivores. *Podocarpus totara* are often associated with *D. dacrydioides* in young forests, however they are not so tolerant of waterlogged soils (Dawson & Lucas 2012).

Table 4: Pictures of the focal and nurse species. Photos with copyrights were found on the website Nature Watch NZ (http://naturewatch.org.nz). The other photos were taken on the field by the author.

Focal species	**Nurse species**
Cordyline australis	*Pittosporum tenuifolium*
 	 
Olearia virgata	*Leptospermum scoparium*
 	 
Dacrycarpus dacrydioides	*Coprosma propinqua*
 	 
Podocarpus totara	*Coprosma robusta*
 	

Treatments

To determine the best practices leading to the highest rates of survival and growth, five methods were investigated (Table 5). Of the 32 possible combinations of treatments, 28 were tested and replicated across the plots.

Topsoil scraping

Half of the trees were planted on a scraped soil. Topsoil scraping is often used in restoration projects as it removes excess soil nutrients (Hausman et al. 2007; Woodward 1996), facilitates natural regeneration (Gardiner & Vaughan 2008) and removes weeds, both established and in the soil seed bank (Buisson et al., 2006; Hölzel & Otte, 2003), allowing new plantings to establish without competitors (Patzelt et al. 2001, Jacquemart et al., 2003). On the other hand, it also reduces the soil quality by removing crucial nutrients and altering soil processes (Geissen et al., 2013; Rasran et al., 2007). In wetland particularly, it can promote waterlogging during flooding episodes by lowering the water table (Hausman et al., 2007; Klimkowska et al., 2010b). It is also an expensive technique, hence the importance of weighing up the costs and benefits (Klimkowska et al., 2010a; Gillon, 2014).

Nurses planting

The facilitation phenomenon is now often studied in restoration projects. Some plants can benefit from their taller neighbours *via* several processes. The micro-habitat can be ameliorated by shading, water retention and protection from wind (Dulohery et al., 2000). Nurses can also compete with weeds (Hardwick et al., 1997; James et al., 2015) and protect seedlings from herbivory (Padilla & Pugnaire, 2006, James et al., 2015). On the other hand, they could also become competitors for both above- and belowground resources (Prévosto & Balandier, 2007). It has been demonstrated that if nurse species often have a positive impact on the survival, they usually have a negative impact on the growth of focal species (Gomez-Aparicio 2009).

Fast-growing species are often used as nurses with the aim to enhance the establishment of slower growing trees (Castro et al. 2002). A review made by Gómez-Aparicio (2009) states that shrubs are excellent nurse species for trees, including in wetlands. By their allocation patterns and architecture (low root/shoot ratio, high rooting depth and general smaller size than trees), shrubs are not as strong competitors than grass or trees (Gomez-Aparicio 2009). A study made by James et al. (2015) in an ephemeral wetland in Australia reported that shrub nurses increased species biodiversity and density in frequently flooded zones. It has been suggested that the microhabitat under shrubs might be slightly more elevated, reducing the abiotic stress associated with waterlogging.

According to Gómez-Aparicio (2009), the cheapest and easiest way to use facilitation for trees would be to first plant shrubs as catalysers of the natural succession, and then to introduce focal species under their canopy. In the Stage 3 of the Wairio wetland, both concurrent and advanced plantings of nurse trees were made, but the effect of advance planting is part of another study and will not be analysed in this thesis.

Weedmats

Weedmats (mats in a degradable material placed around saplings) are another way to prevent competition by acting as a barrier to weeds germination around the seedlings (Harrington & Bedford 2004; Ogle 1996). Felt weedmats of 60x60 cm were installed around half of the saplings one month after planting. The weedmats usually provide weed control from six months to one year (Harrington & Bedford, 2004) before being degraded.

Spacing

Planting the plants close to each other can increase the "nurse effect" explained above. However, it may also increase the competition for space, light and nutrients in the long-term, having then a negative impact on the survival and growth of focal species (Padilla & Pugnaire, 2006). Here, two different planting distances have been tested (1.5 and 0.75 meter).

Table 5: The five investigated treatments with corresponding options.

Treatment	Options
Topsoil	Scraped
	retained
Weed control	Weedmat
	Spot spraying
Planting order	No nurse trees (focal species only)
	Concurrent planting (nurse and focal trees)
	Advance planting (nurse species only)
Trees spacing	0.75 meter
	1.5 meter
Nurse species mix	*C. robusta* and *C. propinqua*
	L. scoparium and *P. tenuifolium*

Site display

In June and July 2011, 2,368 trees were planted in Stage 3 by volunteers. The trees were planted in blocks. Blocks are areas containing four or six plots, each plot containing 16 to 64 trees. In total, 10 blocks made of 56 plots are dispersed on the site (Figure 5). Each plot received a combination of species and cross-over planting treatments.

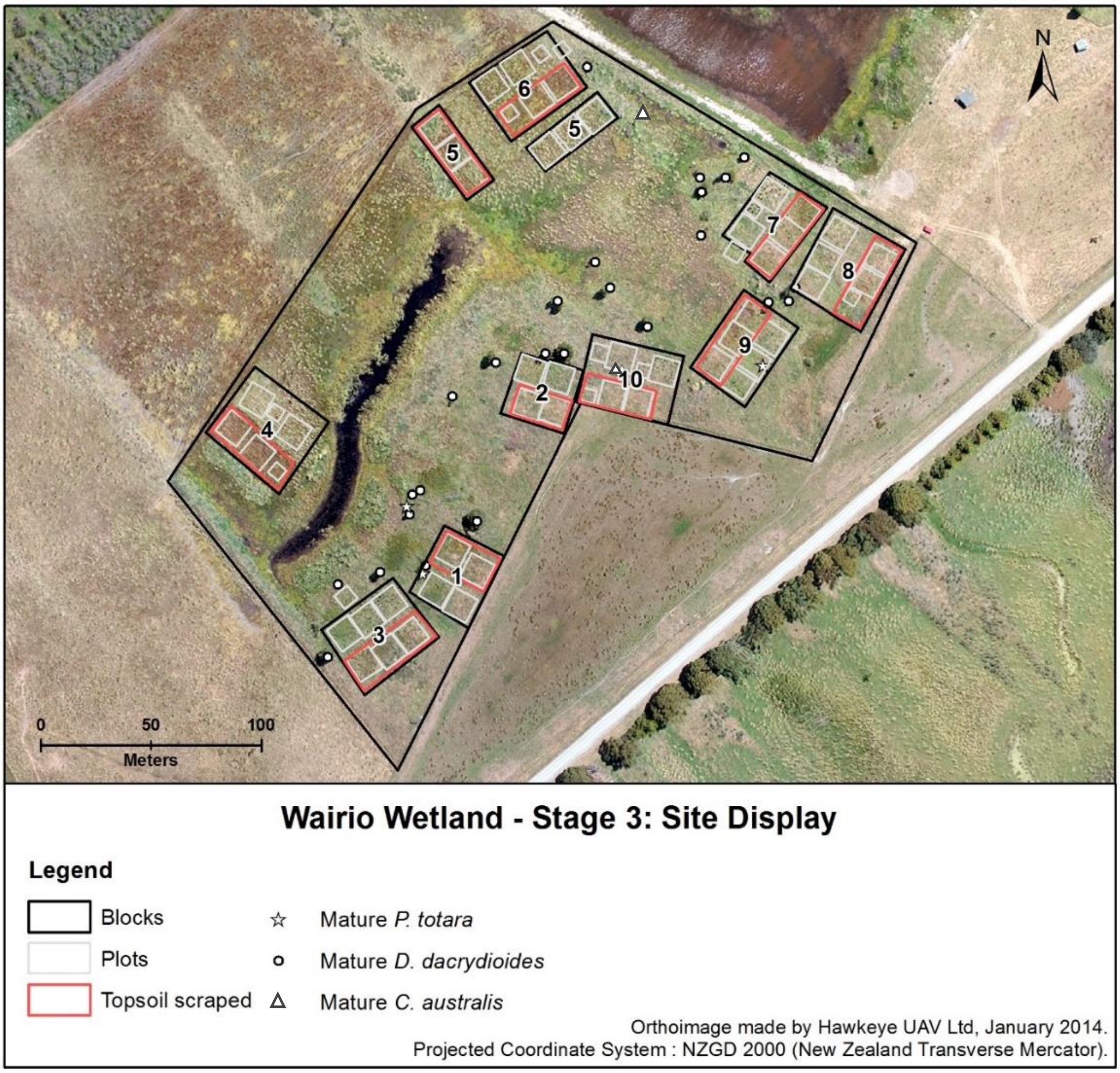


Figure 5: Map of the site display with blocks, plots and scraped topsoil plots. The mature trees remaining on the site are also displayed.

For each block, half of the plots had the topsoil excavated. For the eight blocks containing six plots, three different planting orders were represented: no nurse trees, concurrent planting of nurse and focal trees and advance planting of nurse trees (Figure 6). For the remaining two blocks (blocks 1 and 2), only concurrent planting and planting without nurse trees were made. Each individual plot was then divided in quarters, two quarters having weedmats placed around the trees. The areas without weedmats were sprayed twice a year for two years with a mixture of Buster (glufosinate-ammonium) and Gardoprim (terbuthylazine) (Johnson 2012).

Table 6: Number of trees planted and receiving treatments. Trees identified as hybrids on the field are not considered. For species codes please refer to Table 3.

		OV	CA	DD	PT	LS	KO	CP	CR
Trees planted in 2011		160	159	160	162	435	428	426	428
Topsoil	**Scraped**	80	79	80	81	220	212	212	216
	Not scraped	80	80	80	81	215	216	214	212
Spacing	**1.5 m**	160	159	160	162	318	306	350	362
	0.75 m	0	0	0	0	117	122	76	66
With nurses	**Yes**	80	80	80	82	-	-	-	-
	No	80	79	80	80	-	-	-	-

Nurse shrubs were grouped into two sets. Half of the plots containing nurses were planted with *C. propinqua* and *C. robusta*, the other half being planted with *L. scoparium* and *P. tenuifolium*. Finally, on the whole stage, five plots were planted with a 0.75 meter spacing, containing only nurse trees. The other plots were planted with a 1.5 meter spacing. The total number of trees receiving each planting treatment is given in Table 6.

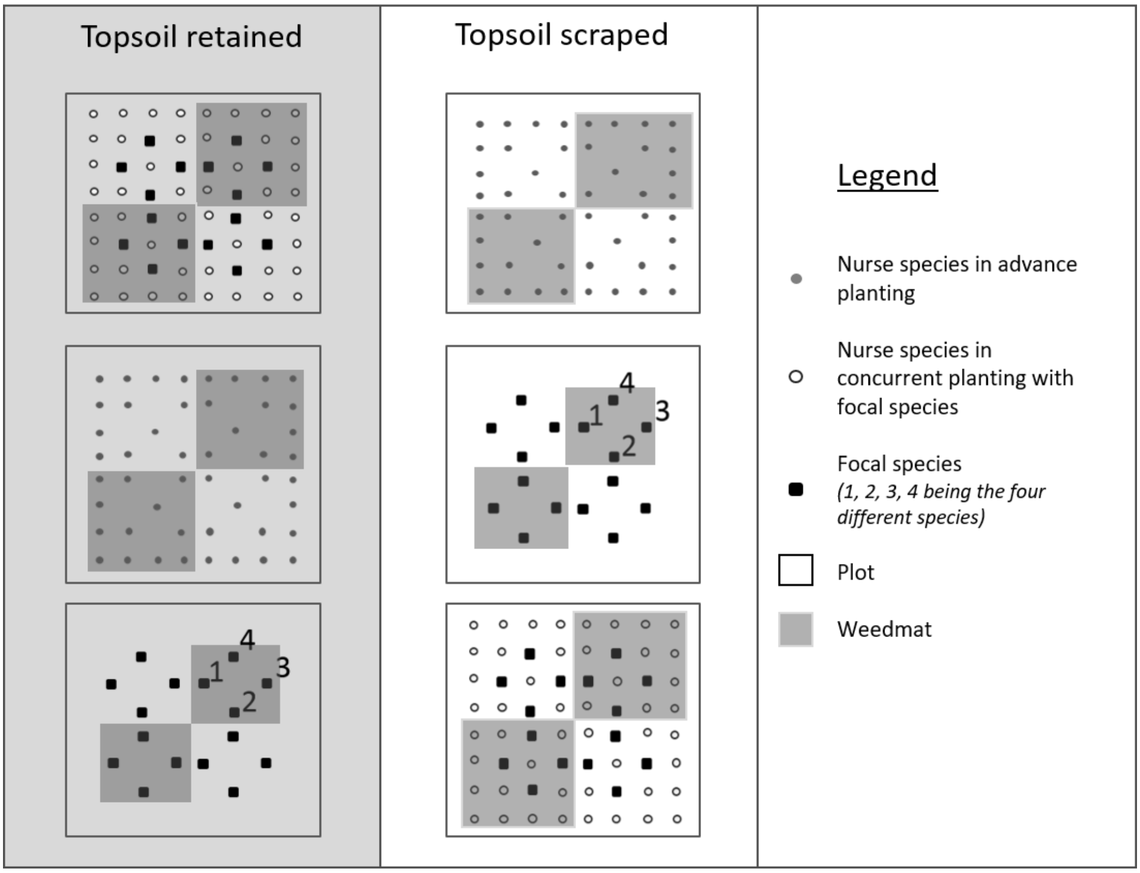


Figure 6: Example of trees and treatment combinations in a block containing six plots. Block is 30 x 40 m. Not to scale. Figure adapted from Gillon (2014).

Monitoring and measurement methods

All the trees are tagged with an individual identification number (1 to 2368) and the species code (as expressed Table 3). Paper tags are replaced when lost or unreadable. The trees' height was measured approximately every six months the two first years, then once a year. Nurse trees were not measured the first year.

Trees height was measured with a 1.5-meter wooden ruler from ground level to the highest leaf, with the result rounded to the closest multiple of five. In autumn 2017, between February and May, basal diameters 10 cm from the ground (explained in the "Biomass allometric equations" chapter) were also measured on a sample of trees across the site (around 30 trees per species). Trunks larger than 2.5 cm were measured with a diameter tape. For smaller trunks, two orthogonal measurements with a calliper were made (Do1 and Do2). The average diameter was then calculated with the formula $D = \sqrt{Do1 * Do2}$. This is consistent with the formula for an ellipse's area and the methodology used in the LUCAS method (Land Use Carbon Analysis System) to estimate carbon sequestration in New Zealand forests (Beets, Kimberley, Oliver & Pearce, 2014). Stems with a diameter smaller than 5 mm were not measured as they were considered to have negligible impact on carbon sequestration and were not worth the extra effort on the field (Riegel et al. 2013; Beets et al. 2014; Mason et al. 2014). A significant proportion of the measured shrubs was multi-stemmed. In that case all the stems were measured and a single equivalent diameter was calculated with the formula $D = \sqrt{D1^2 + D2^2 + D3^2 + \cdots}$, as it is suggested in Beets, Kimberley, Oliver and Pearce (2014) and in Bergin et al. (2011).

Geographic Information System

In February 2014, the company Hawkeye UAC Ltd made a drone survey of the entire Wairio Wetland and adjacent areas. An orthoimage (resolution of 0.1 meter) in true colour and infrared, as well as a Digital Surface Model (DSM), were provided. Another flight was made in January 2017 with the drone owned by the School of Biological Sciences to record the extent of the flood and obtain the exact position of the trees. An orthoimage (resolution of 0.059 meter) and a DSM were obtained with the software DroneDeploy©. All the trees were identified in ArcMap© and an elevation value was extracted from the DSM of 2014 for each of them. The extent of the flooding in January 2017 was photo interpreted on the orthoimage and manually drawn. Maps showing the elevation, the site display and the health of the trees in 2017 were then made.

Analysis for survival and growth

The first aim of the study is to determine the pre- and post-planting treatments that enhance the survival and/or growth of the trees, as well as the suiting range of elevations for planting. Such analyses have already been made 30 months after planting by another student. We want to know if the results obtained after 72 months lead to the same conclusions. Survival and growth of each species were analysed using Generalized Linear Mixed Effects Models to understand the effect of the treatments, the elevation and their interactions on the growth and the height of the trees. A binomial distribution of the residuals was assumed for the survival, and the default gaussian distribution for the height after six years. Randoms effects were "plots" within "blocks". Various models were tested and the ones that explained the best our data were selected regarding the AIC value. The AIC index (for Akaike Information criterion) estimates the quality of each model relative to the others, making a trade-off between the goodness of fit and the complexity of the model. The lowest AIC value correspond to the most relevant model. A variable is considered to have significant effect if the p-value is inferior to 0.05. Once the best model for each species is selected, prediction graphs for growth and height related to elevation are built using bootstrapping (resampling randomly many times in the population).

Analyses of growth and survival were made with the data collected in 2016 and in 2017 to compare the significant treatments and the impact of the elevation before and after summer 2017. Variables considered in 2016 include weedmat presence/absence, topsoil scraping, plantation spacing, nurse trees presence/absence and elevation. The variables considered for the 2017 analyses were the same minus the weedmat presence/absence. Survival analyses were made with binary information (1 = alive, 0 = dead). Growth analyses were made from height values in 2016 and 2017. Trees partially eaten, fallen, half-dead and re-sprouted were not considered in the growth calculations. Transformations of the variable "elevation" (log and squared) were also used, when it was possible, to obtain a quadratic equation giving the optimal elevation value maximizing survival. Finally, survival models without interactions were created adding the variable "Height in 2016" to determine whether the height of the trees influenced the survival between 2016 and 2017. These analyses were made with the "lme4" package (Bates et al. 2015) and "boot" package (Canty & Ripley 2017; Davison & Hinkley 1997) from the software R© version 3.3.1 (R Core Team, 2016).

For each species, the survival model selected is then used to create elevation-related survival maps showing the probability of survival for a specific treatment combination on the whole area of Stage 3. These maps are created by applying species-specific survival equations to all the pixels of the DSM raster. This information is later use for a suggestion of plantation plans for the oncoming planting projects in Wairio.

Biomass allometric equations

Another aim of this study is to estimate the amount of carbon that has been sequestered since the beginning of the project. For this purpose, several allometric equations found in the literature were tried. Allometric equations are used to estimate a difficult measurement, such as tree volume, from another attribute easier to measure, typically the diameter at breast height (DBH) and the height (Picard et al. 2012). However, DBH is sometimes difficult or even impossible to measure for shrubs and small trees. The basal diameter or root collar diameter (RCD), *i.e*. the diameter 10 cm above the ground, can therefore be used for volume and biomass estimations (Beets et al. 2014; Ali et al. 2015; Bergin & Kimberley 2012; Chojnacky & Milton 2008).

All the equations selected (Table 7) use the basal diameter. To determine a basal diameter for all the trees, relationships between height and basal diameter were calculated from a sample of trees of which the diameter was measured on the field. Those species-specific equations (selected from the best AIC) were then used to allocate a diameter to every living tree of the database in 2017.

Calculations include above- and below-ground biomass of trees. The weight of the carbon content is estimated to be half the biomass. The equivalent in CO_2 sequestration is 3.67 times the amount of carbon content (Kimberley et al. 2014; Coomes et al. 2002). Species-specific equations found in the literature are used to evaluate a possible under- or overestimation of the general equation. An allometric equation was also made for *D. dacrydioides,* from weight and height data recorded by a student of the School of Biological Sciences. It is referred in Table 7 as "Fanal & Waring, 2017".

Table 7: Allometric equations used for the calculation of carbon sequestration and common species (used to build the equation and found on the field). RCD = root collar diameter, H = height, vol = volume, BA = basal area (from RCD).

Common species	Equation	Variable	Authors
All nurse species + *O. virgata*	Above ground carbon = 0.0155 (RCD^2 * H) $^{0.976}$ Below ground carbon = 0.2 * AGC	RCD (cm) H (m)	Kimberley et al., 2014 (provided by author Bergin D. in e-mail exchange)
Coprosma propinqua	Dry Weight (kg/plant) = 279 * (BA * H) $^{0.845}$	BA (m^2) H (m)	Beets, Kimberley, Oliver, Pearce, 2014
***Coprosma* species**	Dry Weight (kg/plant) = 238 * (BA * H)$^{0.845}$	" "	" "
Leptospermum scoparium	Dry Weight (kg/plant) = 234 * (BA * H)$^{0.845}$	" "	" "
Dacrycarpus dacrydioides	Dry Weight (kg/plant) = 0.006447*($H^{2.090177}$)	H (cm)	Fanal & Waring, 2017
Pittosporum tenuifolium	Tree carbon content (kg/tree) = −2533.5 vol^3 + 1323.2 vol^2 + 117.59 vol, where vol (m3) = tree height × tree BA	BA (m2) H (m)	Schwendenmann & Mitchell, 2014

Carbon estimations are finally made for the suggested plantation plans and compared to other forests types found in New Zealand. Carbon sequestration in the soil is not considered in this thesis: refer to Marapara (2016) for more information on the subject.

RESULTS

2016 preliminary results

In 2016, two intern students monitored the trees and made analyses of survival and growth. However, some of these analyses had to be redone in 2017. Indeed, some errors in the database were discovered and corrected (especially for the spacing distances or species names allocated to some trees). These corrections were important as the results were used in two publications:

- A paper, currently in writing process, that summarizes the experiment after five years and presents the best planting techniques according to the results obtained in 2016;
- This present thesis, to show the shift in elevation tolerances for each species after the flood of spring and summer 2016-2017.

Results of these analyses will be mentioned in each section before presenting the results of 2017.

Survival analyses

Survival rates

The analyses done with the data obtained in 2016 show that, in average, focal species had better survival rates (43.6 %) than nurse species (38.9 %). *Dacrycarpus dacrydioides* had the best survival rate from the focal species (53 %) followed by *C. australis* (44 %), *O. virgata* (41 %) and *P. totara* (36.5%). For the nurse species, *L. scoparium* had the best survival rate with 53 %. *Pittosporum tenuifolium*'s rate was 51 %, *C. propinqua*'s 34 % and finally *C. robusta* scored the lowest survival rate with only 17.5 %.

Table 8: survival rates since plantation and number of trees per species in 2016 and 2017. OV = O. virgata, CA = C. australis, DD = D. dacrydioides, PT = P. totara, LS = L. scoparium, KO = P. tenuifolium, CP = C. propinqua and CR = C. robusta.

	OV	CA	DD	PT	LS	KO	CP	CR
Number of trees planted in 2011	160	159	160	162	435	428	426	428
Survival after 5 years	41 %	44 %	53 %	36.5 %	53 %	51 %	34 %	17,5 %
Number of trees remaining in 2016	66	70	85	59	231	218	144	74
Survival after 6 years	30 %	43 %	34.5 %	34 %	45 %	38 %	25 %	9.5 %
Number of trees remaining in 2017	48	68	55	55	195	163	107	40

As visible on Figure 7, 2017 is marked by a drop of survival rates for most of the species. For the first time since the beginning of the experiment, *D. dacrydioides* is not the species with the best survival anymore as it has decreased of nearly 20 % in one year (Table 8). Most of the other species also experienced an unusual mortality rate, the percentage of living trees dropping of 8 to 13 % between 2016 and 2017. Only *C. australis* and *P. totara* maintained their survival rate constant. All species have now a survival rate below 50 %. Focal species still have the greatest mean survival with 35.4 % compared to 29.4 % for the nurse species. *Coprosma robusta* shows the lowest survival with only 9.5 % of the planted trees still alive, followed by *C. propinqua* with 25 %. *Leptospermum scoparium* and *C. australis* have the best survival rates with respectively 45 and 43 %.

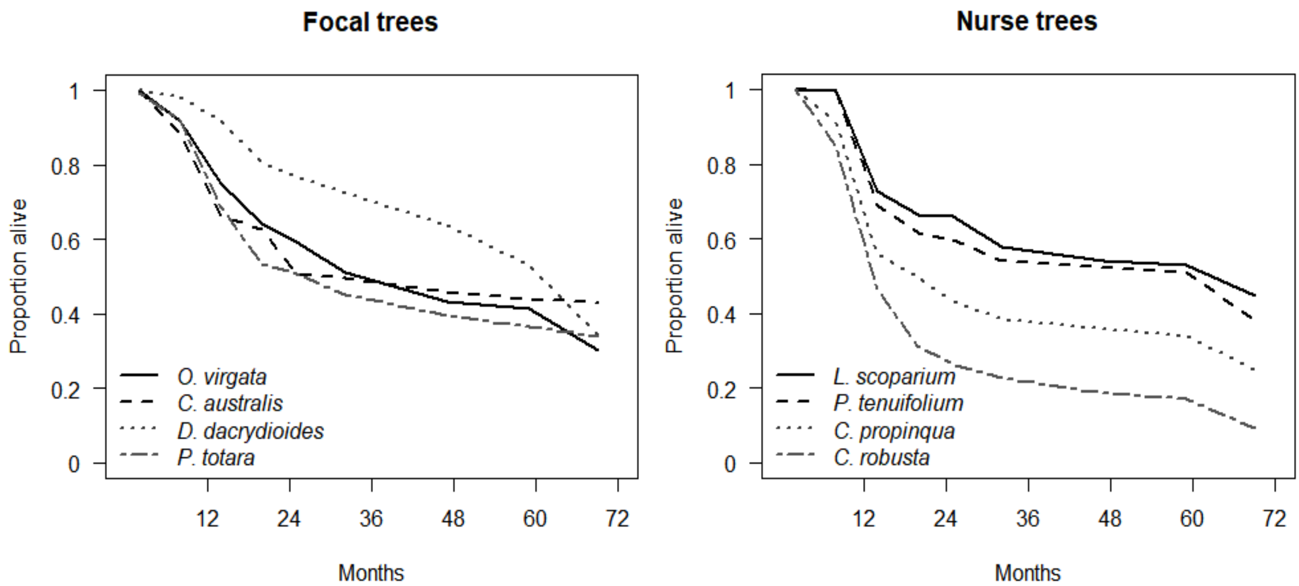
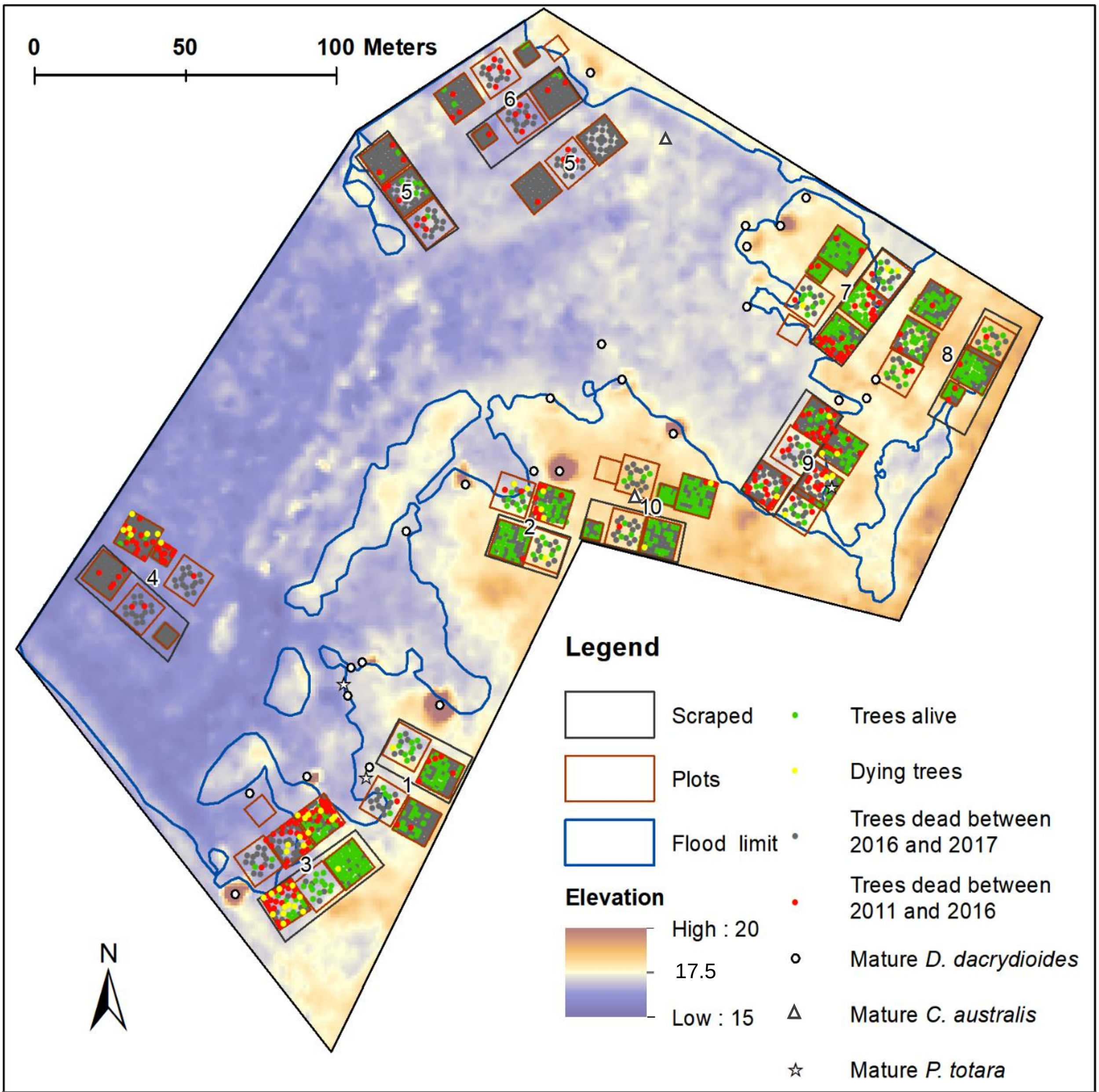


Figure 7: Survival graphs for focal and nurse species since plantation.

Map of trees' health

The map in Figure 8 shows the position of all the trees planted as well as their health condition (dead since less than one year, dead for more than one year, dying or alive). Dying trees are trees showing an important defoliation or leaf discoloration, or having only a few living branches left. The position of remnant mature trees and the flooding limit in January 2017 (determined by photointerpretation) are also shown on the map. Interpretation of the map is given in the "Discussion" part.



Trees health and elevation, Wairio wetland Stage 3, Autumn 2017.

Figure 8: Map showing the position of the trees and their health in Autumn 2017, as well as the flood limit in January 2017 and the site layout (Stage 3).

Treatments' effects

The models made for survival in 2016 showed that, for *L. scoparium*, weedmat presence and 1.5 meter spacing increased the probability of survival (p value = 0.0206 and $3.37*10^{-5}$ respectively). Concerning *P. tenuifolium*, the topsoil scraping had a strongly positive impact (p = $7.37*10^{-6}$). The survival of *C. propinqua*'s was positively impacted by elevation (p = 0.0192) and the combination of topsoil scraping and 1.5 m spacing (p = 0.0485). Elevation also had a positive significant impact on *C. robusta* (p =0.007), as well as 1.5 m spacing and topsoil scraped (p = 0.014 and 0.035). Concerning the focal species, none of the variables seemed to have any significant impact on the survival of *C. australis* and *D.*

dacrydioides. The elevation had a highly significant impact on the survival of *P. totara (p = 0.0001)* and *O. virgata* ($p = 2*10^{-16}$). The survival of *O. virgata* was also positively influenced by the presence of nurse trees (p = 0.02).

Table 9 shows the coefficients, odd ratios and p values of all the variables used in every species-specific linear mixed-effects model selected for the survival six years after plantation. Odds ratio are intuitive values useful to understand the single constant effect of a variable. However, their interpretation becomes difficult when a variable is also involved in a secondary term (a logarithm for example) or an interaction term. In these situations, odds values are not displayed. Variables are considered to have a significant impact when the p-value is inferior to 0.05.

The effect of the topsoil scraping differs according to the species. *C. robusta* is negatively influenced (p < 2E-16) but *P. totara* and *P. tenuifolium* have better survival rates with a scraped topsoil (p = 0.021 and 5.9E-05 respectively). The effect of the topsoil on *P. tenuifolium* is also linked to the elevation as shown by the interaction term (p = 5.9E-05). *Dacrycarpus dacrydioides* is just under the threshold for a significant positive interaction with a p-value of 0.053. The wider spacing distance (1.5 m) has a significant positive impact on *L. scoparium* (p = 0.0007) and *C. robusta* (p < 2E-16). If the effect of the presence of nurse species seems globally positive, it is never significant – even if nearly significant for *C. australis* (p = 0.05).

Response to elevation

In 2017, the elevation has a significant effect on every species, except for *C. australis*. *Podocarpus totara, L. scoparium* and *C. propinqua* clearly show higher survival rates when the elevation increases. For the other species, the models include the term Log(elevation). As a result, the response to elevation takes the shape of a bell curve with an optimum elevation. It is possible to visualise this optimum on the graphs in Figures 9 and 10.

Figures 9 and 10 represent the response of trees survival to elevation, based on the species-specific models. Species-specific models were created for the three periods (2011-2016, 2016-2017 and 2011-2017), the variable to explain being either the survival in 2016 or the survival in 2017. The models for 2011-2017 are shown in Table 9.

The model for the survival between 2016 and 2017 was made considering only the trees still alive in 2016. The number of trees per species being reduced compared to the other models, the predictions are less precise. This is also due to the lack of data in lower and/or higher elevations, as shown by the raw data displayed on top of the graphs. The models are also les accurate for *C. australis* and *P. totara* as their mortality rate was particularly low between 2016 and 2017.

Table 9: Results of the species-specific linear mixed effects models analysing the survival of the trees six years after planting (2011-2017) related to elevation and treatment methods. Odd ratios (OR) are calculated with the formula OR = $e^{\beta\ coef}$. Asterix indicate significant p-values (< 0.05, ** < 0.01, *** < 0.001). Spacing is not a variable for focal species as all the focal trees have been planted with a 1.5 meter spacing.*

	C. australis			***O. virgata***			***D. dacrydioides***			***P. totara***		
	β coef.	OR	p value	β coef.	OR	p value	β coef.	OR	p value	β coef.	OR	p value
Topsoil Scraped	-0.77	0.46	0.15	-0.78	0.46	0.14	1.41	4.13	0.053	**1.24**	3.46	**0.021 ***
Nurses present	1.05	2.86	0.05	0.54	1.72	0.33	0.14	1.15	0.86	0,51	1.67	0.34
Elevation	-43.79	-	0.10	**-117.10**	**-**	**0.011 ***	**-94.71**	-	**0.034 ***	**2,97**	19.58	**0.0001 *****
Log(elev)	774.46	-	0.09	**2081.96**	**-**	**0.010 ***	**1670.98**	-	**0.033***			
Intercept	-1450.46			-3910.03			-3126.24			-53.82		

	L. scoparium			***P. tenuifolium***			***C. propinqua***			***C. robusta***		
	β coef.	OR	p value	β coef.	OR	p value	β coef.	OR	p value	β coef.	OR	p value
Topsoil Scraped	0.32	1.37	0.17	**60.27**	**-**	**<0.0001 *****	-8.65	-	0.41	**-0.20**	**0.82**	**<2E-16 *****
Spacing 1.5	**1.07**	2.92	**0.0007 *****	0.14	1.15	0.68	0.33	1.39	0.66	**66.10**	**-**	**<2E-16 *****
Elevation	**1.77**	5.86	**<0.0001 *****	**-90.64**	**-**	**0.0016 ****	**1.12**	**3,07**	**0.017 ***	**-135.60**	**-**	**<2E-16 *****
Log(elevation)				**1683.67**	**-**	**0.001 ****				**2508**	-	<2E-16 ***
Topsoil S * elev				**-3.39**	**-**	**<0.0001 *****	0.52	-	0.39			
Spacing 1.5 * elev										**-3.69**	-	<2E-16 ***
Intercept	-32.40			-3234.23			-21.14			-4810		

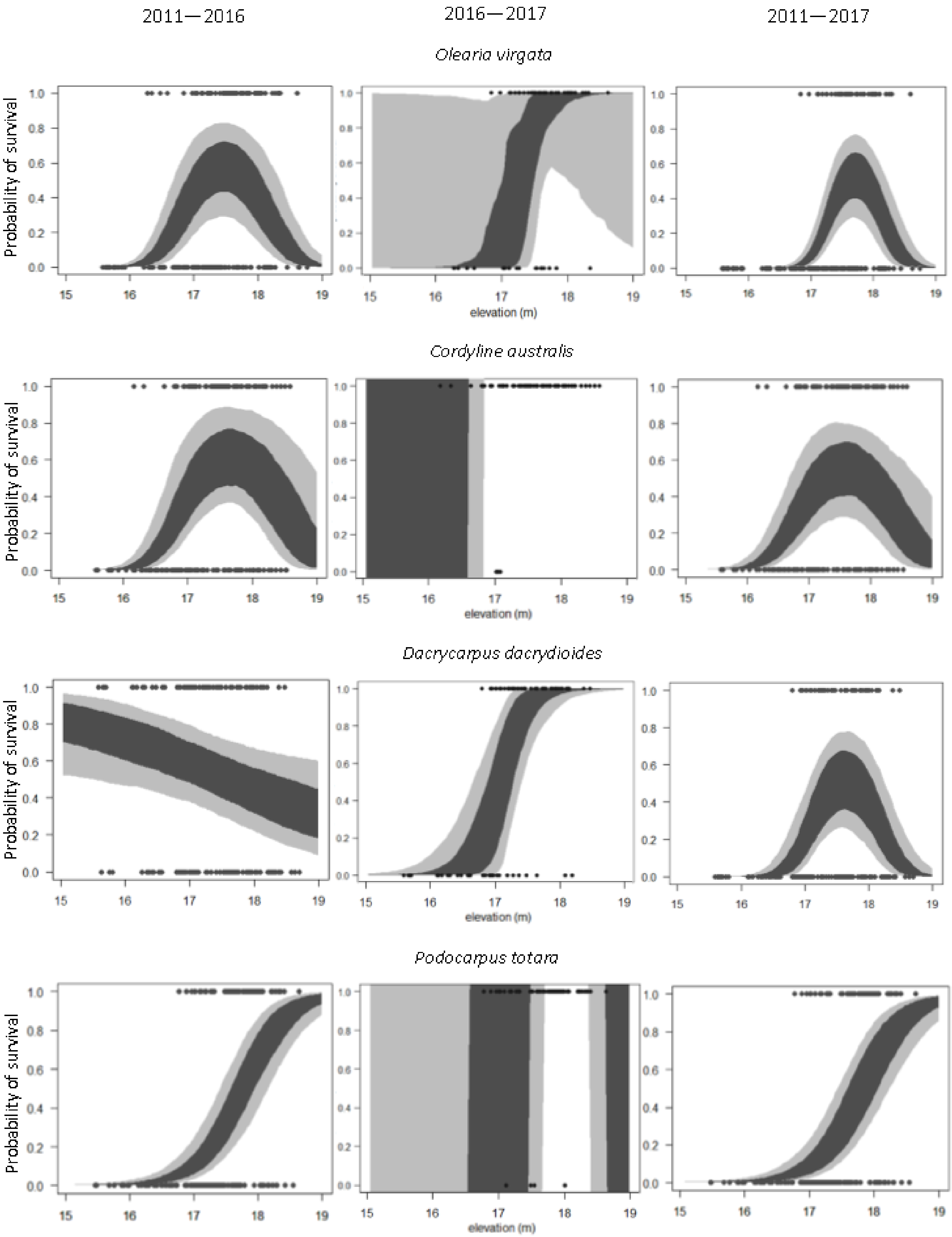


Figure 9: Effect of elevation on the 6-years survival probability of focal trees and changes in elevation tolerance after the 2016-2017 flooding. Obtained by bootstrapping (n = 100) from the species-specific models (combination of all the treatments). Raw data points are also displayed. Different models were created for the three time periods. Dark grey = 50 % confidence interval, light grey = 80%.

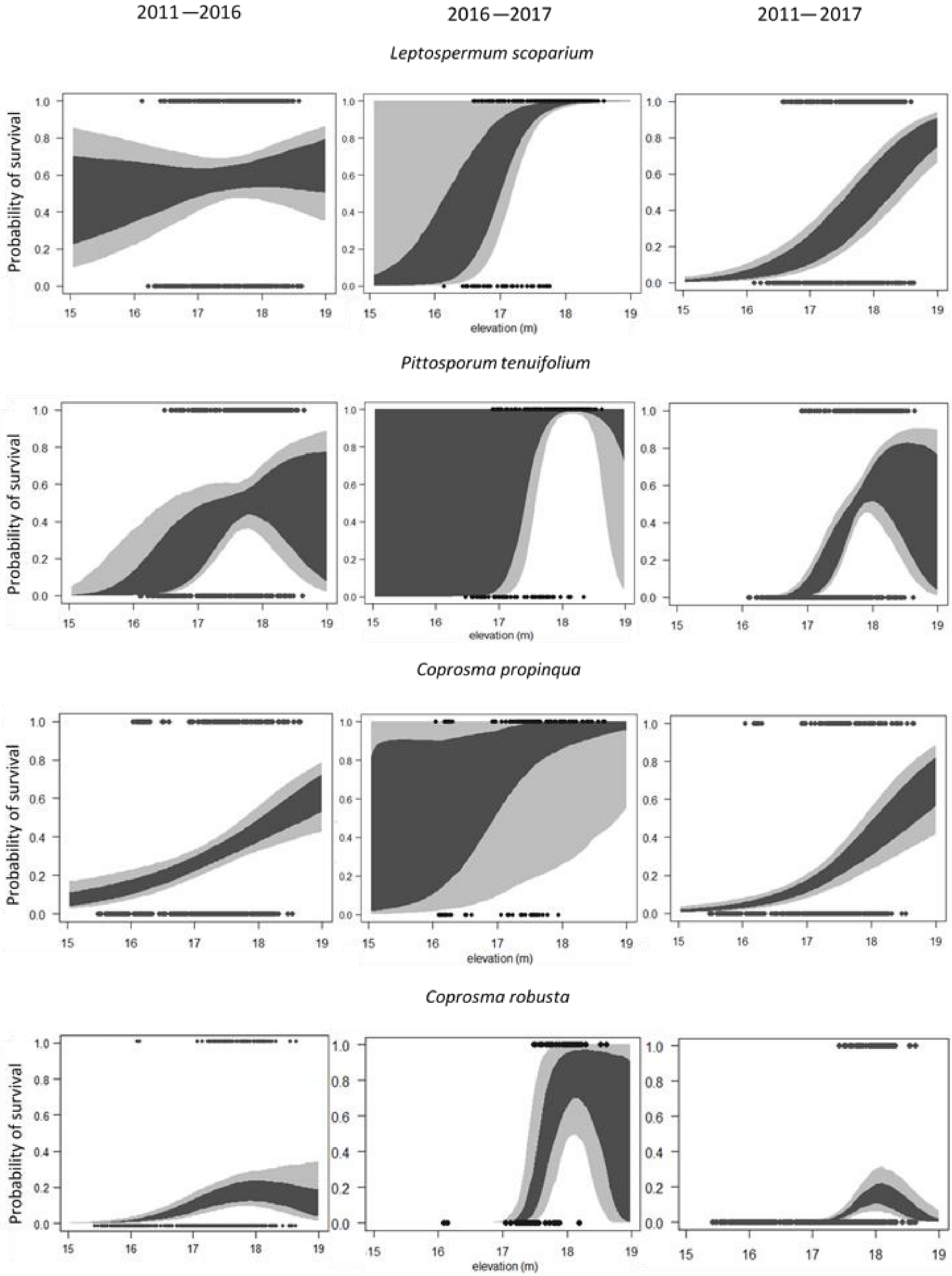


Figure 10: Effect of elevation on the 6-years survival probability of nurse trees and changes in elevation tolerance after the 2016-2017 flooding. Obtained by bootstrapping (n = 100) from the species-specific models (combination of all the treatments). Raw data points are also displayed. Different models were generated for the three time periods. Dark grey = 50 % confidence interval, light grey = 80%.

Two types of response are observable on the graphs:

- A sigmoid response to elevation (positive or negative).
- A bell-shaped curve with an optimum of survival for an elevation value. This is the case when the best model selected for the species (according to the AIC value) contains the variables “elevation” and “log(elevation)”, making it a quadratic equation.

The comparison between the models made for 2011-2016 and 2011-2017 highlights a general narrowing of the ranges of tolerance to elevation. This is particularly evident for the nurse species. If the optimum values tend to stay the same, the tolerance to lower elevations decreases. In 2016, *L. scoparium* had a mean survival around 50 % between 16 and 17 meters. This survival rate drops to 10 % in 2017. The optimum elevation for this species is the highest (19m), as well as for *C. propinqua*. For *P. tenuifolium*, this optimum is around 18.5 meters. *Coprosma robusta* reaches a maximal mean survival rate of 15 % at 18 m, the survival being null under 17 m.

Concerning the focal species, *O. virgata* presents a distinct bell curve, the optimum being between 17.5 and 18 m. The tolerance in low elevation decreased, with a null survival under 16.5 m in 2017, when it used to be 20 % in 2016. Predictions for *C. australis* don’t change with a bell curve reaching a mean survival of 60 % at 17.5 m. Predictions for *P. totara* are also constant from 2016 to 2017, with a defined sigmoid curve reaching 50 % of survival around 18 m, and 90 % at 19 m.

In 2017, a radical change in the response to elevation is observed for *D. dacrydioides*. The model for 2011-2016 shows it was the only species to have better survival rates in lower elevations, with 80 % of survival under 16 m. However, the flooding of the next year led to a high mortality of the saplings in low elevations, as shown by the sigmoid curve in 2016-2017. The 2011-2017 prediction model is now a bell curve with an optimal survival at 17.5 m, and not a living tree under 16 m.

Effect of the height on survival

Survival models (2016-2017) were created adding the variable “Height in 2016” to the planting treatments to determine if taller trees had higher probabilities to survive the flooding. The height of the trees had no significant effect on the survival for any of the eight species. Taller trees had therefore no better probabilities of survival than small trees when enduring waterlogging.

Growth analyses

Mean heights

Concerning the growth in 2016, the nurse species were overall higher (170 cm) than focal species (148 cm). *Leptospermum scoparium* was in average the tallest of the nurse species (222 cm), followed by *P.*

tenuifolium (195 cm) and the two *Coprosmas* (132 cm). *Cordyline australis* was in average the tallest focal species (212 cm), followed by *O. virgata* (145 cm), *P. totara* (128 cm) and finally *D. dacrydioides* (108 cm).

Table 10: Mean, minimum and maximum of trees' height six years after plantation, by species. OV = O. virgata, CA = C. australis, DD = D. dacrydioides, PT = P. totara, LS = L. scoparium, KO = P. tenuifolium, CP = C. propinqua and CR = C. robusta.

		OV	CA	DD	PT	LS	KO	CP	CR
Number of trees remaining in 2017		48	68	55	55	195	163	107	40
Height after 6 years	**Mean**	184.8	262.0	134.0	140.8	247.0	232.9	135.6	157
	Min	60	105	80	60	85	85	60	40
	Max	285	400	225	210	360	345	240	250

Table 10 presents the growth results for 2017. In average, *C. australis* is the tallest species with a mean height of 2.62 m and a maximum height of 4 meters. *Dacrycarpus dacrydioides* and *P. totara*, both slow-growing conifers, are the smallest of the focal trees with 1.34 and 1.4 m respectively. *Olearia virgata* is slightly taller with a mean height of 1.85 m.

For the nurse species, the association *L. scoparium – P. tenuifolium* is the tallest with a mean height of 2.47 and 2.33 m respectively. On the other hand, the mean height of *C. robusta* is 1.57 m, and only 1.36 m for *C. propinqua*. This association is therefore nearly two times smaller than the first one. Hybrids of the two *Coprosma* were found on the field and were in general slightly taller, as shown in Figure 11. However, data on these trees will not be used in further analyses.

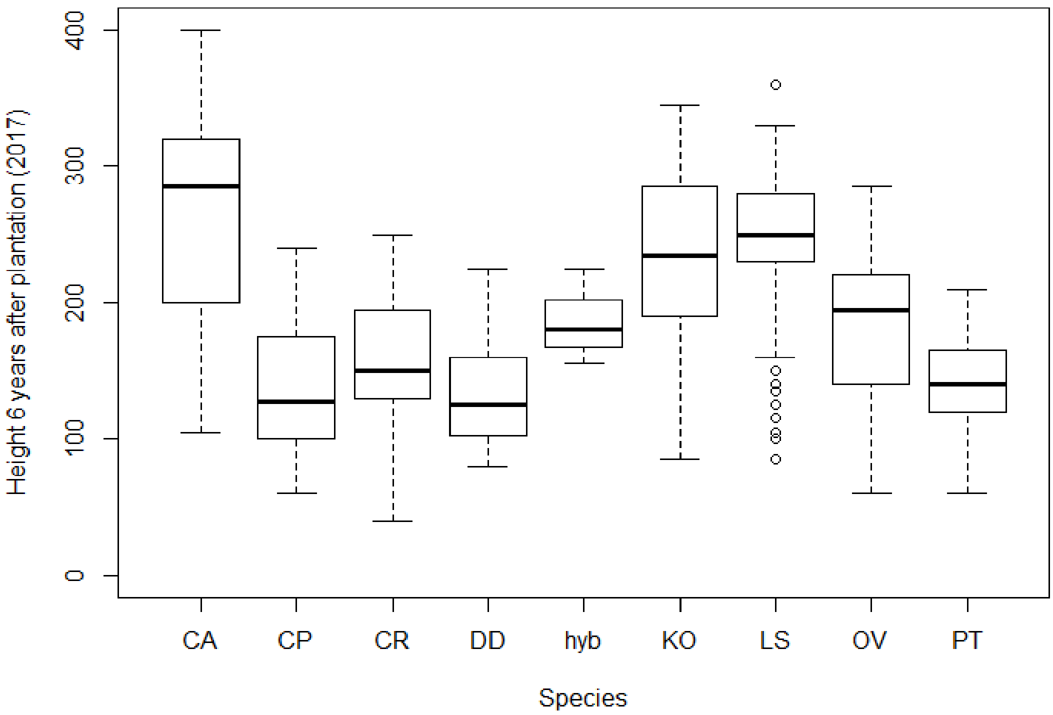


Figure 11: Boxplots of height distribution for each species six years after planting.

Treatments effects

In 2016, only a few treatments were found to have a significant effect on some species' growth. The growth of *C. australis* was negatively influenced by the topsoil's scrapping and positively influenced by the presence of nurse trees. A spacing of 1,5 m had a positive influence on the growth of *P. tenuifolium*, but the presence of weedmats had a negative influence. Finally, the interaction of a scrapped topsoil and a 1.5 meter spacing has a positive influence on the growth of *L. scoparium*. Overall the trees were smaller when the soil was scraped.

Table 11 summarizes the linear mixed-effects models obtained for each species regarding the height in 2017, six years after plantation. When using a glmer model with default family (here, Gaussian), the call is replaced by a call to lmer with the same arguments. Due to difficulties in defining the degrees of freedom form a mixed effects model, the author of the lmer code chose not to provide p-values but t-values instead (Bates 2006). The t value furnished by the lmer function is calculated with the formula: t value = β coefficient / Standard error. We took a conservative approach by identifying significant terms with a t-value greater than 2 in absolute value, as this is the threshold for $p < 0.05$ when the degrees of freedom are superior to 30. In our data, the sample sizes vary from 40-195, therefore we believe this is a conservative threshold for identifying significant terms in the model.

There are a few treatments that have a significative effect on the species' growth. The presence of nurse trees has a significant positive impact on the growth of *P. totara*. Topsoil scraping has a significant negative effect on the growth of five species*: D. dacrydioides, C. propinqua, P. tenuifolium, C. australis* and *C. robusta*. In general, trees planted on a scraped topsoil have a lower mean height, as shown in Figure 12.

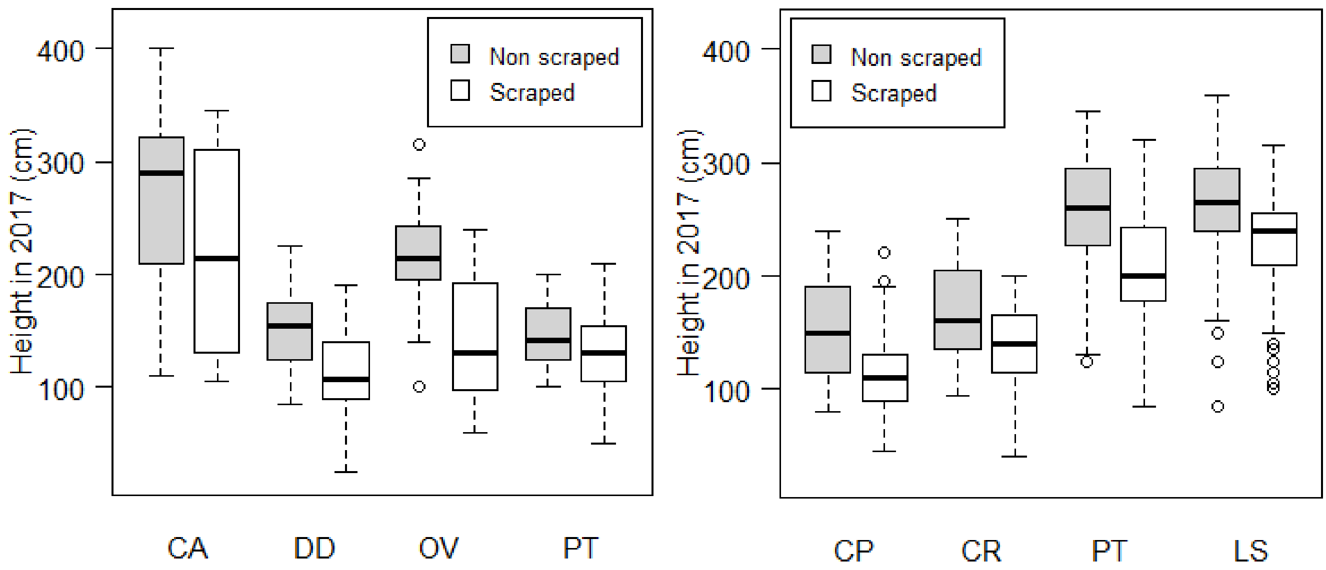


Figure 12: Effect of topsoil scraping on growth.

Table 11: Results of the species-specific linear mixed effects models analysing the growth (height in 2017) of the trees six years after planting (2011-2017) related to elevation and treatment methods. Odd ratios (OR) are calculated with the formula OR = $e^{\beta\ coef}$. t values = β coef / Std Error. These t values can be compared to values in a Student t table to define the degree of significance (if p value < 0.05, ** if p < 0.01, *** if p < 0.001). Spacing is not a variable for focal species as all the focal trees have been planted with a 1.5 m spacing.*

	C. australis ***n = 68***			***O. virgata*** ***n = 48***			***D. dacrydioides*** ***n = 55***			***P. totara*** ***n = 55***		
	β coef.	OR	t value	β coef.	OR	t value	β coef.	OR	t value	β coef.	OR	t value
Topsoil scraped	**-64,67**	**8,21E-29**	**-3,04*** **	1021,29	-	1,09	**-41,19**	**1,30E-18**	**-4,65*****	-5,27	0,005	-0,595
Nurses present	31,46	4,60E+13	1,45	32,67	1,54E+14	1,77	-821,67	0	-1,95	**22,45**	**5.62E+09**	**2,352***
Elevation	1229,32	-	1,03	-1027,60	-	-0,59	-902,16	-	-0,91	1018,27	-	1,314
Elevation²	-33,67	-	-0,99	29,08	-	0,60	24,55	-	0,87	-28,40	-	-1,297
Topsoil S * elevation				-61,82	-	-1,17						
Nurse * elevation							46,98	-	1,96			
Intercept	-10933,99			9264,73			8424,42			-8991,71		

	L. scoparium *n = 195*			***P. tenuifolium*** *n = 165*			***C. propinqua*** *n = 107*			***C. robusta*** *n = 40*		
	β coef.	OR	t value	β coef.	OR	t value	β coef.	OR	t value	β coef.	OR	t value
topsoil Scraped	224,61	-	0,62	**-62,1**	**1,07E-27**	**-3,31*** **	**-39,6**	**6,34E-18**	**-4,60*****	**-38,85**	**1,34E-17**	**-2,17***
Spacing 1.5 m	17,34	-	1,25	21,55	2,29E+09	0,93	10,01	2,22E+04	0,81	-5,51	0,004	-0,22
Elevation	-809,57	-	-1,25	1268,41	-	1,41	657,92	-	1,53	928,86	-	0,31
Elevation²	23,89	-	1,32	-34,91	-	-1,38	-18,14	-	-1,48	-26,69	-	-0,32
Topsoil S * spacing 1.5	36,79	-	1,51									
Topsoil S * elevation	-16,58	-	-0,82									
Intercept	7068,23			-11268,64			-5811,45			-7906,96		

Survival maps and plantation plans

Another aim of this thesis was to produce species-specific survival maps, in order to suggest plantation plans for the whole Stage 3 area. Survival equations were obtained by the linear mixed-effects models generated for the 2011-2017 period. To obtain these equations, it was necessary to fix all the terms of the treatments variables. From the results obtained in previous studies and the present analyses, it is difficult to find a combination of treatments that is appropriate for all species. I chose a cost-effective option that also favours diversity: topsoil non-scraped, nurse species present and 1.5 m spacing distance. This combination was chosen for all the equations, the elevation being therefore the only undefined variable.

In Figure 14 are all the survival maps obtained from these equations with the fixed treatments options. The scale goes from 0 (0 % of survival) to 1 (100 % chances of survival). *Cordyline australis* has good chances of survival on a large proportion of Stage 3. *Dacrycarpus dacrydioides* and *P. totara* have, in general, low survival rates and are to be planted on higher grounds. *Olearia virgata*, *L. scoparium* and *C. propinqua* can tolerate the wet soils of a reasonable proportion of Stage 3, while *P. tenuifolium* is to be planted only on higher elevations along the east side of the Stage. Finally, *C. robusta* shows low survival probabilities on the whole area. Remnant trees are visible on the map as red spots (if bell-shaped survival curve) or green spots (if sigmoid survival curve). This is because a high elevation value is attributed by the DSM. These points must not be considered. DSM and teledetection methods are commented in Chapter 3.

Dacrycarpus dacrydioides and *P. totara* being the two main focal species the project aims to restore, I compared the survival probabilities on Stage 3 with and without removing the topsoil. Indeed, the survival of the two species is positively influenced by a scraped topsoil. In order to illustrate the importance of weed competition management or nutrients control for these slower-growing trees, more survival maps were made with a topsoil considered scraped in the equations (Figure 15). The resulting maps show better survival probabilities for both species on scraped soils, especially *D. dacrydioides* which displays good survival probabilities on a large proportion of the stage.

From these survival maps, propositions of planting plans were made. A precise plan was first created for Stage 3. By analysing the models presented in Figures 9 + 10 and the Figure 13, a choice of species associations to plant in three elevation ranges was made:

- Under 17 m: no planting (plantation zone 0);
- 17 – 17.5 m: *L. scoparium* + *C. propinqua* + *D. dacrydioides* + *C. australis* + *O. virgata (zone 1)*;
- Above 17.5 m: *L. scoparium* + *P. tenuifolium* + *D. dacrydioides* + *C. australis* + *P. totara (zone 2)*.

The proportion chosen is three nurse trees for one focal tree, the same as for the plots already planted. The graphs in Figure 13 represent the survival probabilities for every species with treatment options fixed (topsoil not scraped, nurses present, 1.5 m spacing). Except for *C. australis*, survival rates barely reach 20% for all species under 17 m. I do not consider any planting under this elevation (zone 0). Between 17 and 17.5 meters (zone 1), *L. scoparium* and *C. propinqua* are the nurse species having the best survival rates. After 17.5 m, the survival rate of *P. tenuifolium* exceeds the one of *C. propinqua*, and is therefore recommended for zone 2 (17.5 m and higher). For the focal species, *D. dacrydioides* is recommended in the two planting zones (zones 1 and 2) to answer the main goal of the restoration project which is the re-creation of a Kahikatea swamp forest. *Cordyline australis* and *O. virgata* are also recommended for zone 1, whereas *P. totara* is recommended in zone 2 as it presents better survival rates on higher elevations.

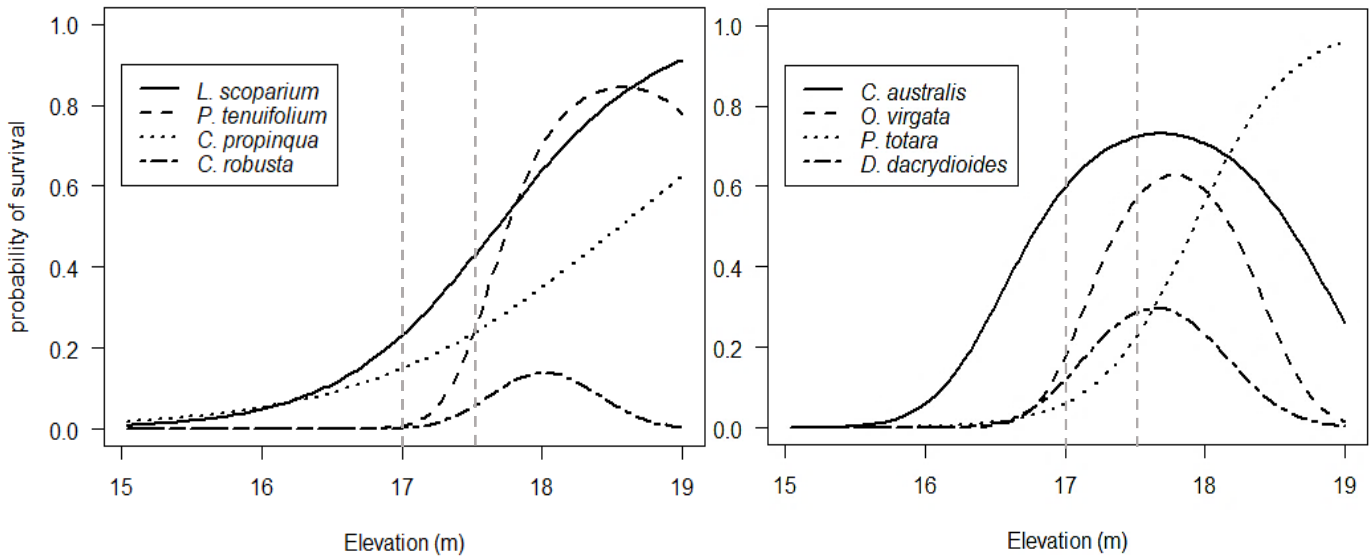


Figure 13: survival probabilities for nurse and focal species related to elevation. From survival models made on the 2011-2017 period with selected treatments options being topsoil not scraped + 1.5 m spacing + nurses present. Grey dotted vertical lines are the chosen elevation limits for planting zones.

Plantation zone 0, 1 or 2 was attributed to pixels of the DSM (2014) according to the elevation value. After a manual simplification followed by dissolving and smoothing the polygons, the map in Figure 14 was obtained. In total, 2.85 ha should not be planted as the survival probabilities are too low. The plantation zone 1 represents 1.12 ha, and the zone 2 covers 1.23 ha. Another plantation map (Figure 15) was obtained following the same procedure for the whole Wairio block.

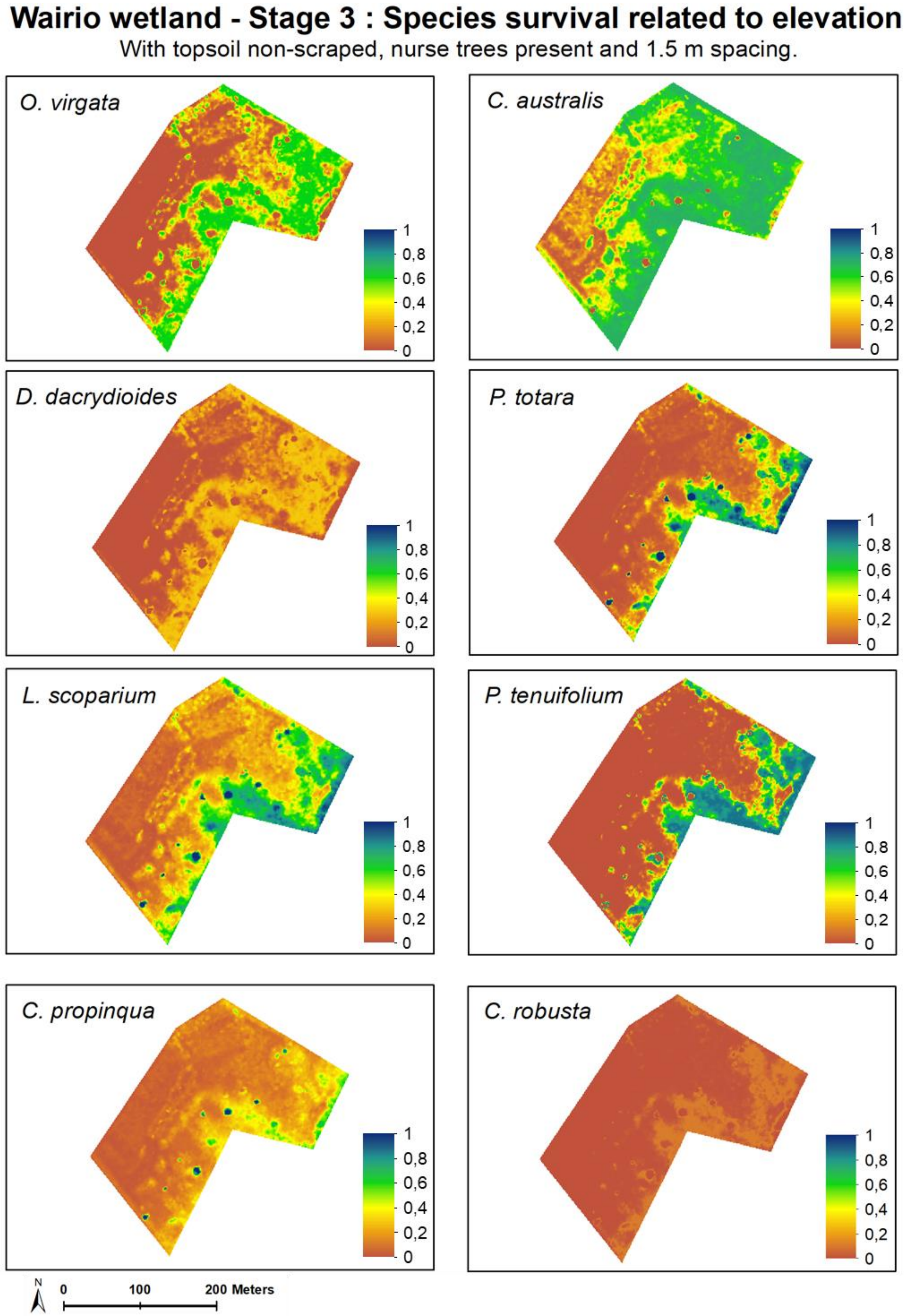


Figure 14: Maps of survival probabilities for each species on the Stage 3 area, related to the elevation.

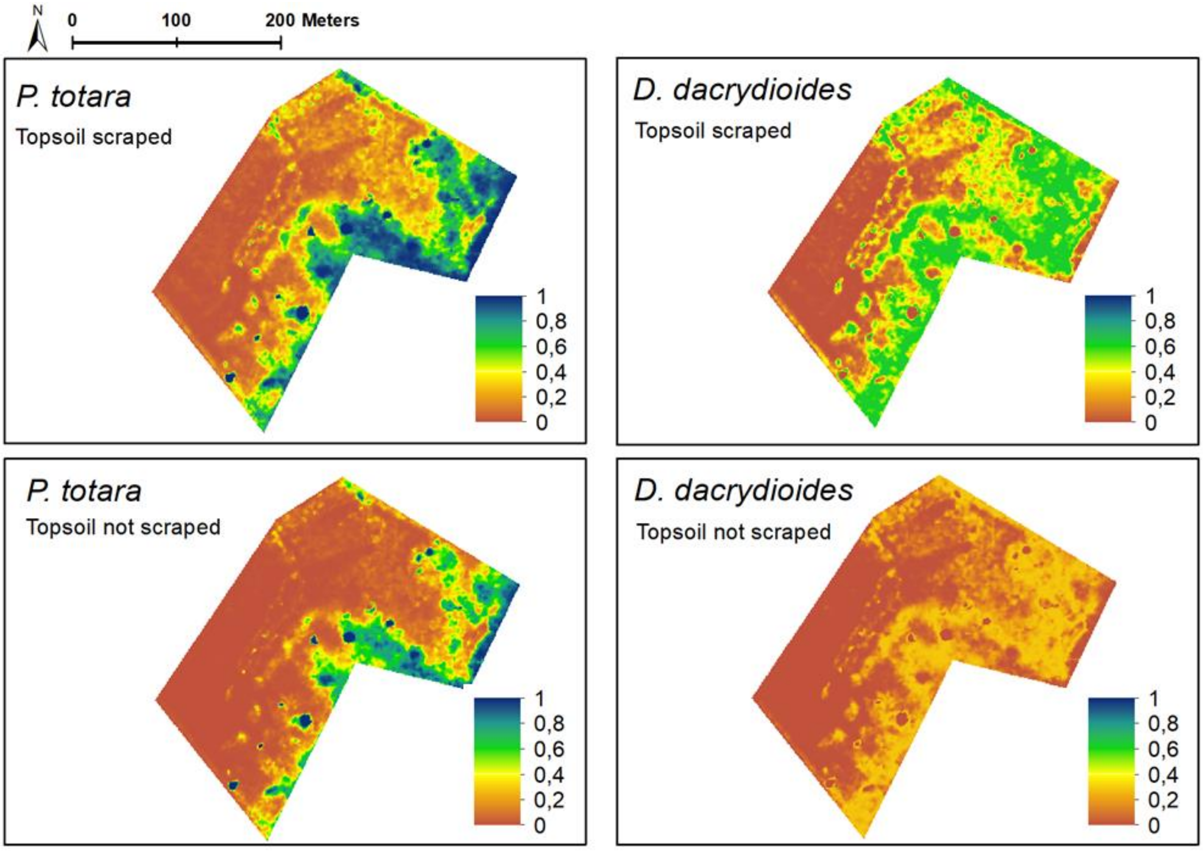


Figure 15: Comparison of survival maps with topsoil scraped and not scraped for D. dacrydioides and P. totara.

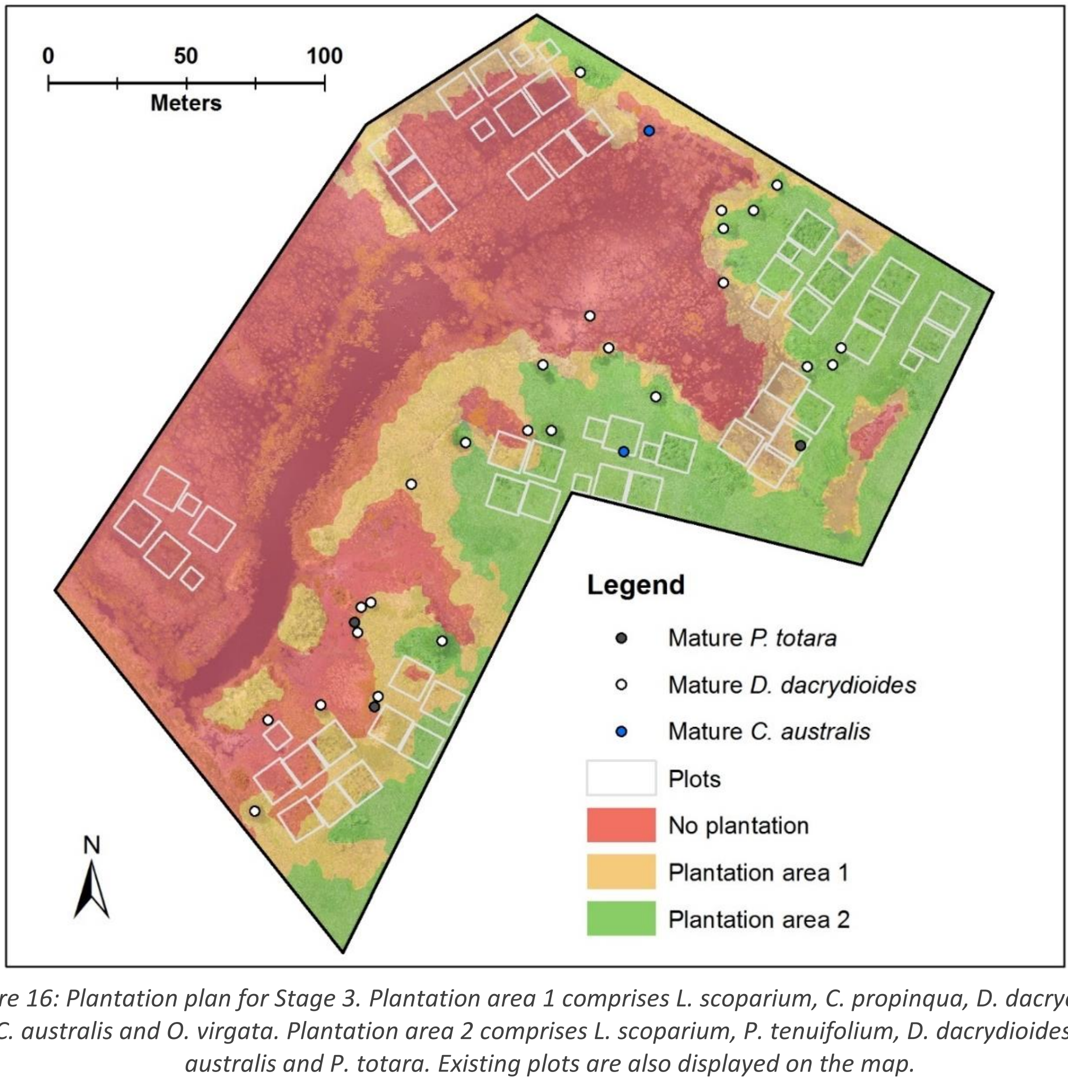


Figure 16: Plantation plan for Stage 3. Plantation area 1 comprises L. scoparium, C. propinqua, D. dacrydioides, C. australis and O. virgata. Plantation area 2 comprises L. scoparium, P. tenuifolium, D. dacrydioides, C. australis and P. totara. Existing plots are also displayed on the map.

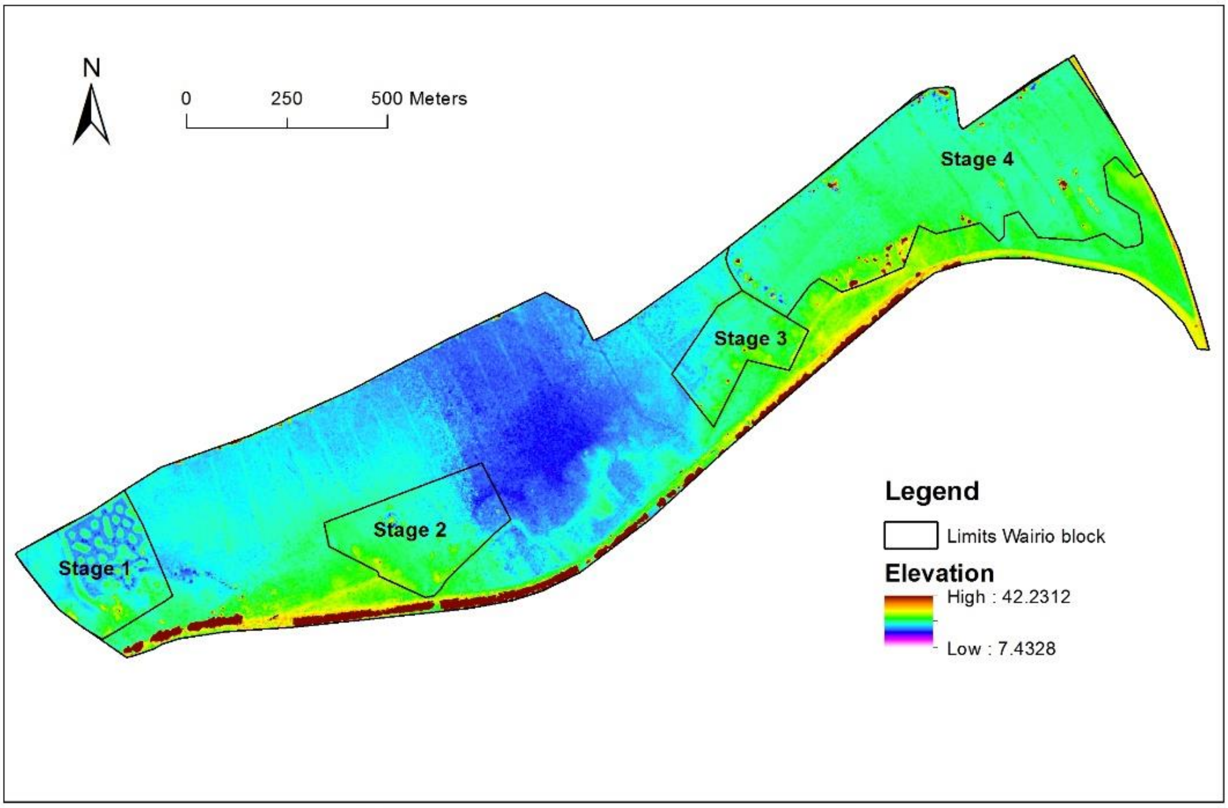


Figure 17: Elevation map of the Wairio Wetland (2014).

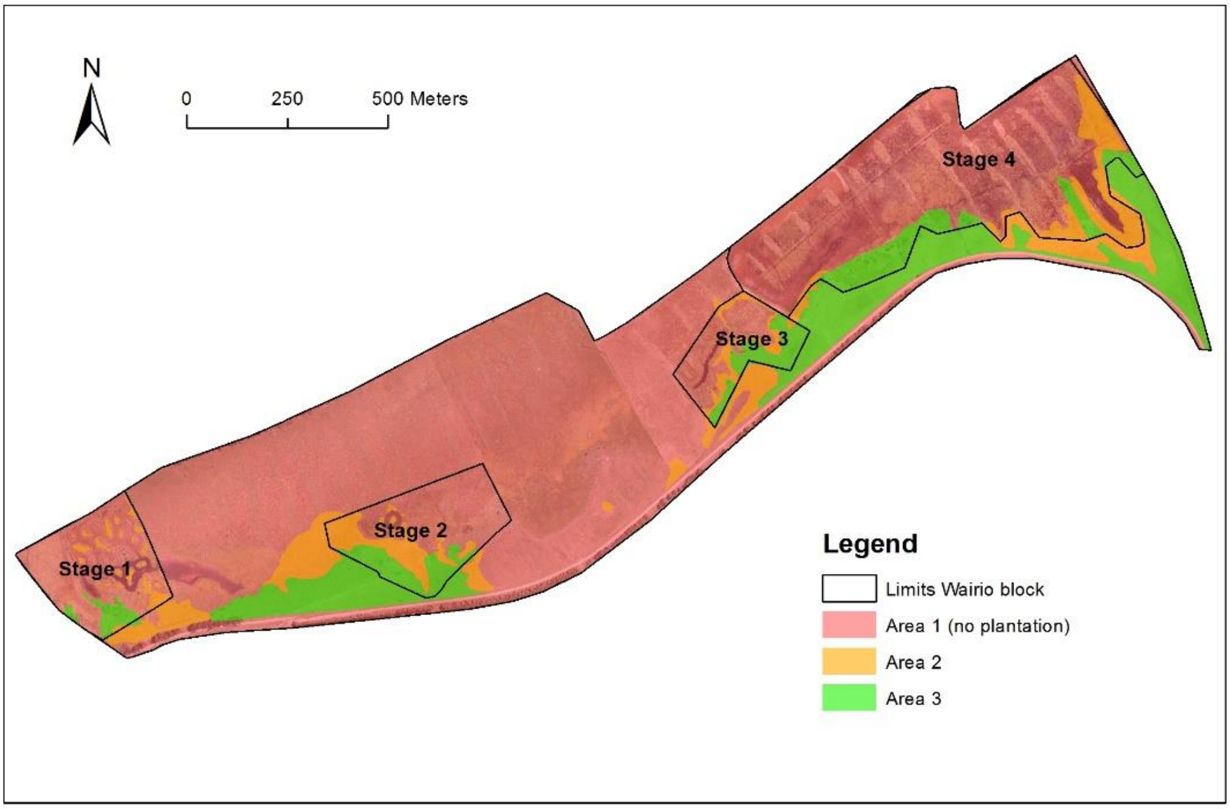


Figure 18: Example of a simplified plantation plan for the Wairio block. Area 1 (no planting) is 107.02 ha, Area 2 (planting zone 1) is 13.19 ha and Area 3 (plantation zone 2) is 20.23 ha.

Carbon sequestration

Table 12: Comparison of carbon estimations (kg carbon) on Stage 3 with different allometric equations (general and species-specific). The equation "Fanal & Waring, 2017" was made by the author for this thesis.

Equation	All species		*Coprosma* species	*Coprosma propinqua*	*Leptospermum scoparium*	*Dacrycarpus dacrydioides*
	Total on stage 3	Per ha				
(Kimberley et al. 2014)	1355.8	255.8	85.3	51.7	282.1	2.7
Beets, Kimberley, Oliver, Pearce, 2014	-	-	106.3	77.0	328.8	-
Fanal & Waring, 2017	-	-	-	-	-	5.1
Schwendenmann et al., 2014	1048.4	197.8	-	-	-	-

Table 12 summarizes the results obtained with the several species-specific equations and the general allometric equation. Height to diameter species-specific equations are available in the appendix (Table 20). A first estimation of the amount of carbon sequestered in trees still living six years after plantation was made with the general equation by Kimberley et al. (2014). This equation was built with height and diameter data from several shrub species, including all the nurse species planted in Stage 3 and *O. virgata*. The data comes from natural stands, aged from 12 to 24 years, in three locations (Canterbury, Nelson and Waikato). With this equation, it is estimated that the living trees in Wairio contain 197.8 kg of carbon per hectare, which is equivalent to 938.8 kg of CO_2 sequestered (below-ground carbon included). On the whole Stage 3, it represents 1.4 tonne of carbon, or around five tonnes of CO_2.

When specific equations or data were available, the amount of carbon was also calculated for some species. Equations provided by Beets, Kimberley, Oliver and Pearce (2014) show that the general equation might tend to under-estimate the carbon sequestration for *Coprosma* species and *L. scoparium*. However, it is important to consider that these equations were made for a subalpine vegetation from a sample of 90 shrubs, only three of them being *C. propinqua* and 21 being *L. scoparium*.

The result from the equation for *D. dacrydioides* (5.1 kg) is almost twice the result obtained with the general equation (2.7 kg). However, this specific equation was created from weight data of small trees (harvested only one year after plantation, height from 76 to 130.5 cm). For young saplings, the below-ground biomass is heavier than the above-ground biomass (sometimes five times more important). It is likely that the general equation neglects the root biomass of the small trees.

Finally, we obtain a slightly smaller amount of carbon with the general equation provided by Schwendenmann et al. (2014). This equation was created with samples made in an urban park in Auckland, the only species also found in Wairio being *P. tenuifolium*.

Previsions of carbon sequestration were made for the Stage 3 if the whole area was planted according to the suggested plan. Using the general equation by Kimberley et al. (2014), it is estimated that 15.7 tonnes of carbon could be sequestered after six years (3.3 tonnes in plantation zone 1, 12.4 tonnes in plantation zone 2). This is equivalent to 57.6 tonnes of CO_2. For this calculation were considered a 1.5 m spacing distance (4,444 trees per ha), and survival and growth rates as obtained with the linear mixed-effects models 2011-2017. The elevation used was the mean elevation per planting zone.

The same calculation was then made for the whole Wairio Wetland, according to the plantation plan in Figure 18. In total, 233 tonnes of carbon might be sequestered after six years, equivaling 855 tonnes of CO_2. The planting zone 2 has the best contribution with 194 tonnes of carbon (9.6 tonnes per ha), mainly due to the better survival and growth rates on higher elevations.

DISCUSSION

Mortality

Most mortality occurred in the first year after planting. Mean mortality rates were 20 % and 35 % for focal species and nurse species, respectively. This is not surprising, as the first year is often the most crucial, when saplings experience transplantation stress, damage from incorrect planting, herbivory by hares or rabbits, and competition (Keeton 2008; Sweeney et al. 2002; Grove et al. 2006; Kneitel & Lessin 2010; Innes & Kelly 1992). After two years, mortality rates decreased and stabilized. Thirty months after planting, Gillon (2014) found that waterlogging was the primary cause of mortality, except for *D. dacrydioides* that suffered from competition with weeds. Indeed, exotic grasses are common on Stage 3 (Johnson 2012). *Cordyline australis* was particularly affected by herbivory from hares and rabbits, and accidental herbicide spraying (monocotyledons are more susceptible to the herbicides used to control grasses). Multiple factors may have caused mortality. As such, the exact cause of death was sometimes difficult to establish. Mortality due to a combination of environmental stresses can also be a long process taking several years.

In 2017, a drop of survival was observed for all species except *P. totara* and *C. australis*. This was primarily due to an unusually large and persistent flooding event that lasted from July 2016 to winter 2017. Competition with vines and blackberries was also responsible for some mortality. As such, survival of after six years was relatively low (<50 % for all species). This is lower than the "acceptable minimum" threshold considered by Sweeney et al. (2002) for a riparian forest restoration project. *Dacrycarpus dacrydioides* previously exhibited the highest survival rate. However, this dropped significantly after flooding. *Coprosma robusta* exhibited the lowest survival, with only 9.5 % of planted trees left after six years.

Future plantation treatments

Johnson (2012) analysed the survival of saplings after six months. She stated that the most successful management technique for focal species was a scraped topsoil with *L. scoparium* and *P. tenuifolium* as nurse trees, irrespective of whether or not weedmats were used. Thirty months after planting, Gillon (2014) re-examined the survival and growth of the trees and found that the best combination of treatments for focal species was "topsoil excavated, planting of nurse trees and 1.5 m spacing" with 63 % of survival, whereas nurse trees reached 50 % of survival with the combination "topsoil excavated, 1.5 m spacing and weedmats present". However, when cost-benefit analysis was made, it was found that limited interventions (intact topsoil, no nurses, no weedmats and 1.5 m spacing) was the most cost-effective option. Response to treatments varied among species.

Five years after planting, new analyses of survival and growth were made. Treatments significantly impacted the survival of some species, and results differed greatly between species. The presence of nurse trees and wider spacing (at 1.5m) was either neutral or significantly beneficial. Topsoil scraping and weedmat presence can be beneficial for nurse species but detrimental to the growth of other species. Therefore, this study recommends a combination of nurse species, 1.5 m spacing, no weedmats, and intact topsoil to increase survival and growth, while reducing costs. However, given the highly heterogeneous response of the species to treatments, a general recommendation is difficult to make. Species-specific treatments should be considered (as informed in Table 13 below).

The analyses made in 2017, six years after planting, show slightly different results (Table 13). Scraping topsoil showed a negative impact on the survival of *C. robusta*, in contrast to the positive effect seen in 2015. Scraped topsoil also negatively affects the growth of five species (*P. tenuifolium*, D. *dacrydioides*, *C. australis C. propinqua*, and *C. robusta)*. This might be explained by the reduction of nutrients in the soil when the topsoil is removed, or more stressful abiotic conditions because of the potential soil compaction by the bulldozer. Also, lowering of the ground-level promotes waterlogging as the scraped plots collect water from the adjacent non-scraped areas. This can potentially be beneficial by reducing drought stress during dry summers, but detrimental in wet winters. Seedlings may allocate less energy to grow when immersed (Pezeshki 2001; Blom & Voesenek 1996).

Table 13: treatments significantly improving survival and/or growth according to 2011-2017 GLME models. "⨱" = not recommended, "⊻" = recommended, "-" = neutral.

Species	**Topsoil scraped**	**Nurse trees**	**1.5 m spacing**
Cordyline australis	⨱	-	-
Olearia virgata	-	-	-
Dacrycarpus dacrydioides	⊻ for survival ⨱ for growth	-	-
Podocarpus totara	⊻	⊻	
Leptospermum scoparium	-	-	⊻
Pittosporum tenuifolium	⊻ for survival ⨱ for growth	-	-
Coprosma propinqua	⨱	-	-
Coprosma robusta	⨱	-	⊻

Weed control methods, such as weedmats and topsoil scraping, might have an important effect during the first few years after planting. However, this effect likely reduces over time. It might therefore be difficult to assess their effect after a few years, especially considering flooding was the main cause of mortality after 2016. This is why the effect of weedmats is not considered in the 2017 analyses. Topsoil removal is still considered, as the removal of nutrients and lowering of elevation may have longer-term effects.

Scraping the topsoil has a significant positive effect on the survival of *P. totara*. Survival maps also reveal that removing topsoil would considerably extend the suitable planting zone for *D. dacrydioides*. However, this should be considered with caution, as the effect of topsoil scraping for *D. dacrydioides* was just under the significance threshold. Johnson (2012) suggested that topsoil scraping could favour slow-growing native species over competing exotic grasses given their tolerance of nutrient-poor soils. *Podocarpus totara* and *D. dacrydioides* are both slow-growing conifers. *Dacrycarpus dacrydioides* is also more resistant to fluctuating water levels, having an advantage over other species on scraped soils. As the goal of the restoration project is to restore historic vegetation on the site, considering these two species is crucial to re-creating *D. dacrydioides* swamp forests. It is therefore necessary to apply an efficient weed control method to ensure a better survival of these trees. Several methods can be considered:

- The spraying of herbicides for a longer period – at least three years according to the Greater Wellington Regional Council (2009), or four years like the Rapaura wetland revegetation project in the Marlborough district (Clarkson & Peters 2010a). Care should be taken while spraying around the saplings to avoid mortality.

- The use of weedmats that decompose slower. However, weedmats may enhance the risk of herbivory and waterlogging (Marcar et al. 2000).
- As suggested by Marapara (2016), the use of tree shelters. Even if tree shelters increase the planting costs, they offer a lasting protection against herbivory, but also reduce competition with weeds and provide protection against strong winds and flood debris.
- The advance planting of nurse trees, followed by the planting of focal trees a few years later. The shading provided by the nurses should then have reduced the number and height of competing weeds (Padilla & Pugnaire 2006). On the other hand, nurse trees might compete with the focal trees for above- and below-ground resources after a few years (Castro et al. 2002; Padilla & Pugnaire 2006; Cavieres et al. 2006). P. totara, particularly, is light-demanding and usually can't grow well in a shady environment (Bergin 2000).
- Scraping the topsoil, even if it is detrimental to other nurse species.

The "advance planting" method is currently being tested on Stage 3. The focal species (*P. totara*, *D. dacrydioides, O. virgata* and *C. australis*) were planted in 2015. A first report made by Waring (2017), who analysed survival and growth after one year for *D. dacrydioides* and *P. totara*. Surprisingly, it reports that *P. totara* benefits from the presence of nurse trees for its survival, while *D. dacrydioides* does not. This contrasts with the literature; *Podocarpus totara* do not typically tolerate shade (Bergin 2000), whereas *D. dacrydioides* often benefits from nurse trees (*Coprosmas* and *P. totara)* in natural forests (Wardle 1974). Analyses on a longer time frame are necessary to assess the effectiveness of the "advance planting" method. Unfortunately, more than half of the saplings were already dead one year after planting because of the flooding in Spring 2016.

As mentioned previously, it is difficult to recommend one combination of pre- and post-planting methods that is appropriate for all species. A solution is to assemble species with the same responses to treatments in zones, and apply different treatments per zone. For the two planting zones recommended in the plantation plans, a possibility would be to use nurses and 1.5 m spacing for the two zones, but to scrape the topsoil only in zone 2. Indeed, a scraped topsoil is detrimental for *C. australis* and *C. propinqua*, planted in lower elevations. Lowering the water table in zone 1, more subject to waterlogging, should be avoided. However, a scraped topsoil positively impacts the survival of *P. totara* and *P. tenuifolium*, planted on higher elevations in zone 2. Plots with only *P. totara* and *D. dacrydioides* on a scraped topsoil could also be set up, or even plots containing only *D. dacrydioides*, as swamp forests can be purely composed of Kahikatea in wetter zones.

Consideration must be given to the choice of nurse trees. In the "Material and Method" section, nurse trees were defined as fast-growing species providing shelter to focal species, shrubs being the most efficient. That being said, *C. australis* and O*. virgata* should maybe be considered as nurse species because of its fast growth for *C. australis* (the highest on average on the site) and shrub characteristics for *O. virgata*. However, *C. australis* may prove to be too competitive to be a nurse species, as its root system often dominate the soil on several squared meters (Czernin & Phillips 2005).

Coprosma species exhibit a small mean height. They probably don't provide an important shading for weed reduction, however they have other benefits, such as abundant fructifications attracting birds and encouraging natural regeneration of other bird-dispersed species. *Leptospermum scoparium* and *P. tenuifolium* are growing faster and providing a good protection to focal species, but they might also compete faster with focal trees.

Effect of elevation

The wetland areas at the eastern shore of Lake Wairarapa used to experience frequent flooding events due to the fluctuating level of the lake, caused by precipitations and wind. The Lower Wairarapa Valley Development Scheme, that started in the 1960s, completely changed the hydrological function of the wetlands complex (Grant 2012; Greater Wellington Regional Council & New Zealand Department of Conservation 2010). Since the beginning of the Wairarapa Moana Wetlands Project in 2010, works have been done to restore this hydrologic function, such as the blocking of drains and the construction of bund walls to re-flood the wetlands. One of these walls was completed in early 2015 next to Wairio Wetland. Summer 2015-2016 was very dry, and no clear effect of these hydrological modifications was seen. 2016 was actually the warmest year ever recorded in New Zealand's history with mean temperatures 0.5 to 1.2 °C above the 1981-2010 annual average. The rainfall was also below average for the Wairarapa region during summer and autumn, which reflected in lower soil moisture levels (NIWA National Climate Center 2017). But a reversal of the situation was observed the next year. Summer 2016-2017 was described in the media as "the worst summer New Zealand has known". Abundant rainfalls in spring 2016 contributed to soil moisture levels that were above normal in Wellington (NIWA National Climate Center 2017). January 2017 was also particularly wet and cold in the Wellington region (1.1°C under average). Hence, in Stage 3 of Wairio Wetland, the water did not evaporate as much as usual and could not evacuate by the blocked drains. This led to the most important flooding seen for years on the Wairio Wetland. By photo-interpretation on drone imagery, it is estimated that 62 % of Stage 3 was flooded in January 2017. At that time of the year, the permanent pond is usually the only under-water part of the area.

Since the planting of trees in 2011, analyses were made to predict the effect of flooding on tree species. The “average water depth” was measured around the saplings during early monitoring fieldwork. In 2014, the results of these analyses showed that increasing water levels were detrimental for the survival of *P. totara*, *O. virgata*, *P. tenuifolium*, *L. scoparium* and *C. propinqua*, and for the growth of *D. dacrydioides*, *P. totara* and *C. propinqua, L. scoparium* and *C. australis*. In 2014, a DSM was obtained for the Wairio Wetland. Since then, it was used to predict the effect of elevation on the survival and growth of the sapling. Indeed, it is expected that lower elevations sites experience wetter soils and higher likelihood of flooding than higher elevation sites. With the growth and survival data from 2016 and 2017, elevation-related graphs were obtained. They allow us to identify the preferential planting zones for every species, maximizing the survival if a flooding of the same amplitude occurs again. These analyses are only usable for the topographic context of the Wairio Wetland – especially for Stage 3, as we still don’t know if it is accurate for the other restoration stages.

On the map of trees health, the flood limit of January 2017 seems to follow elevation curves. Using the elevation values provided by the DSM is therefore a valid approach to assess waterlogging effects. It is also clear that most of the trees that died between 2016 and 2017 were within or close to the flood limit. It accords with our field observations, which revealed that waterlogging was the main cause of mortality during that year.

According to the growth models obtained in 2016, the elevation has no significant effect on the growth of any species over four years. The results are the same in 2017, even if the resulted graphs suggest some species, especially *C. australis* and *P. tenuifolium,* are taller on higher elevations (Figure 26 in appendix). On the contrary, the elevation has a strong impact on the survival of the trees. In 2016, it is significant for *O. virgata*, *P. totara* and the two *Coprosma* species. In 2017, the impact of elevation is significant for all species except *C. australis*.

An optimum of elevation is observed for some species in the graphs. Trees planted on high grounds might experience a deficit of water during dry summers and be more exposed to strong winds, competition and herbivory. On lower elevation, flooding is the main cause of low survival rates. However, the number of trees planted above 18.5 meters is small, so we must be cautious when interpreting data on high elevations.

The analysis of the graph for *D. dacrydioides* is interesting. This species is tolerant to waterlogging (Dawson & Lucas 2012; Wardle 1974), which explains the good survival rates during the five first years. However, the trees could not cope with the unusually long time of flooding experienced in 2016-2017. This led to the death of most of the trees in low elevations.

Information provided in the graphs and survival maps was used to create a proposition of planting zones. The zones correspond to elevation ranges, where a combination of species is suggested according to their tolerance to waterlogging. *Podocarpus totara*, *O. virgata* and *P. tenuifolium* must be planted in higher areas where they are safe from flooding, especially during spring and summer months. *P. totara* showed high mortality rates in flooded areas since the first year after plantation. Trees under 16.7 m were already dead in 2016, therefore no major change was observed after the flooding in 2017. If *P. totara* is often associated with *D. dacrydioides* on dry soils, it is not as well adapted to swampy areas (Dawson & Lucas 2012).

Leptospermum scoparium and *C. propinqua* are doing slightly better than the other nurse species on wet soils. *Leptospermum scoparium* can survive in waterlogged environments through the production of aerenchyma, and *C. propinqua* is commonly found in swamps (Stephens et al. 2005; Dawson & Lucas 2012). *Coprosma robusta*, on the contrary, is not well adapted to the conditions in Stage 3 and its planting will not be recommended in the planting plans.

The focal species *D. dacrydioides* and *C. australis* are adapted to waterlogged environments and therefore commonly found on swampy soils (Dawson & Lucas 2012; Simpson 1997; Wardle 1974). On Stage 3, *C. australis* has the best survival rate in low elevation, even after the 2016-2017 flooding. *Dacrycarpus dacrydioides* shows good survival rates when it is not flooded during the entire year.

The elevation-related prediction models are valid for a fluctuation of water level like the one experienced between 2016 and 2017. As it is the first time for at least twenty years that a flood of this amplitude is seen in Wairio Wetland, it is difficult to predict the recurrence of similar events. Stronger floods might occur after construction works aiming to restore hydrologic flows are completed.

The building of features to regulate water flows has completely changed the water regime in Stage 3 and led to a high mortality of the young trees. In the future, it is important to finish restoring the water regime before starting any planting, to avoid similar situations. The restoration of abiotic conditions such as the hydrological function must be the first step of a restoration project. Once the annual fluctuation of the water level is understood, a plantation plan can be created and the revegetation can start (Stromberg 2001; Clarkson & Peters 2010a).

Suggestion of plantation plan

In ephemeral wetlands such as Wairio Wetland, plant associations are organized in zones along a gradient of hydrological stress (Figure 19). The sequence goes from turfs, sedges ad grasses in wet zones, then waterlogging-tolerant grasses, trees and shrubs, and finally less water-tolerant tree and herbaceous species (Clarkson & Peters 2010a; Enright et al. 2008).

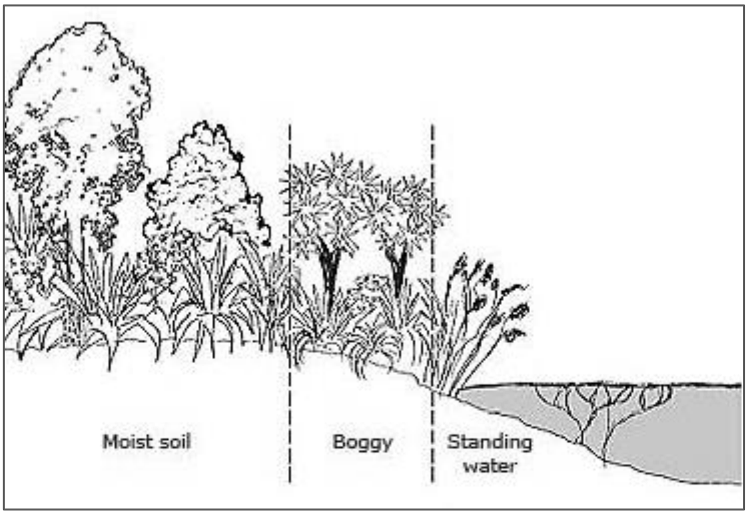


Figure 19: planting zones according to the Waikato Regional Council (n.d.). The boggy zone is a temporary flooded zone. The Council recommend to plant C. robusta in the "moist soil" zone, and C. propinqua, C. australis, D. dacrydioides and L. scoparium in the "boggy" zone. It is consistent with the suggested plantation plan.

From the observation of the elevation-related prediction models, the planting zones suggested in the "Results" section were:

- Under 17 m: no planting (plantation zone 0), because of the high mortality rates for all species after the flooding event;
- 17 – 17.5 m: *L. scoparium* + *C. propinqua* + *D. dacrydioides* + *C. australis* + *O. virgata (zone 1)*;
- Above 17.5 m: *L. scoparium* + *P. tenuifolium* + *D. dacrydioides* + *C. australis* + *P. totara (zone 2)*.

Three focal species and two nurse species are included in each planting zone. As the main objective of the restoration project is to re-create the pristine conditions of the wetland, hence a Kahikatea swamp forest, *D. dacrydioides* was recommended for the two zones. The proportion of one focal tree for three nurse trees, as in the current plantings, has been maintained. However, a smaller proportion of nurses may reduce competition with focal species – more information should be obtained in the coming years, as competition effects may start occurring in plots with good survival and growth rates.

Leptospermum scoparium is the nurse species exhibiting the best survival, and is hence recommended in the planting zones 1 and 2. *Coprosma propinqua* is the second nurse species recommended in lower elevation (zone 1), whereas *P. tenuifolium* is more adapted to higher grounds (zone 2). The planting of *C. robusta* is not recommended because of its mean survival rate lower than 10 %.

The elevation range of the planting zone 1 (from 17 to 17.5 m) may seem tight, but it represents 1.12 ha (21 % of the area of Stage 3). It is a critical area in terms of water tolerance. On the map of trees' health in the "Results" section, we see that remaining mature trees (*D. dacrydioides*, *C. australis* and *P. totara*) roughly follow the limit between zone 0 and zone 1. These remnants of the forest that used to cover Wairio Wetland may mark the limit between commonly flooded zones before settlement and drier zones that were used by sheep. Therefore, the position of old remnant trees can provide useful information about hydrological flows and favourable planting areas. This would also mean that flooding events of the same amplitude than the one experienced in summer 2016-2017 did probably occur before the water level was controlled for pastoral farming.

The suggested planting map has been manually simplified, but not enough to create a real, easy to implement plantation plan. This is to avoid losing to much information and to let the operator exercise some freedom in the delimitation of planting blocks for the oncoming projects. Also, the creation of planting zones for the whole Wairio block is probably not as accurate, as the topographic situation may differ. Nevertheless, it informs on the areas to avoid and the ones to favour for planting, and it should lower the mortality rates in future revegetation projects until further specific analyses are done for each stage. We can expect that non-planted zones will be colonized by natural regeneration when the trees are well established and produce seeds.

In his 2016's thesis about Wairio hydrologic function, Marapara raised a question about the planting areas to favour. Typically, revegetation projects target areas with the highest survival rates. However, these areas might not be the ones where the trees will have the most significant ecological impacts. Poorly drained soils are not optimal for the survival and growth of most trees, but the development of their root systems may improve significantly the permeability of these soils, hence contributing to flood mitigation. *Cordyline australis* exhibits the best survival rates in low elevations and might therefore be planted under 17 m for this purpose. Depending on the priority services the Restoration Committee aims to restore, different planting zones and species combinations must be considered.

Carbon sequestration

If shrubs usually only make around 2 % of the carbon content of a mature forest, they often dominate the early successional stages on open areas. They also constitute a major source for the soil carbon pool (Chojnacky & Milton 2008). Five species used in the restoration project in Stage 3 are shrubs. Most of the allometric equations to calculate trees biomass use the DBH (diameter at breast height), but this measurement was impossible to obtain for Stage 3. Indeed, most of the trees were still too small to have a measurable DBH, and shrubs were often multi-stemmed. To remedy this issue, the

Basal Diameter (BA) 10 cm above the ground is often used for estimations of shrubs' biomass (Ali et al. 2015; Chojnacky & Milton 2008; Coomes et al. 2002; Kimberley et al. 2014; Mason et al. 2014).

The general equation for shrubs furnished by Kimberley et al. (2014) estimates the biomass of the trees planted on Stage 3 around 2,712 kg. As the carbon content is usually considered to be half the biomass (Paul et al. 2013; Chojnacky & Milton 2008; Beets et al. 2014; Kimberley et al. 2014), it is equivalent to 1,356 kg of carbon (256 kg/ha). The opportunity in terms of carbon sequestration is important on the entire Wairio block. If it was planted according to the plantation plan, and with survival and growth rates similar to the ones in Stage 3, 5.1 tonnes of carbon could be sequestered after six years. If the treatments are adjusted to improve the survival rates, especially for weed control, the amount of carbon sequestered would be more important.

The general equation seems to slightly underestimate the biomass when compared to species-specific equations. There are several factors implying an uncertainty of the estimations:

- If the root/shoot ratio is often considered to be between 0.2 and 0.25 (Schwendenmann & Mitchell 2014; Kimberley et al. 2014; Beets et al. 2012), the young age of the trees might imply a more important proportion of roots and an under-estimation of the model, as for *D. dacrydioides* (in the "Result" section). For *C. australis* particularly, the rhizomes can make up 38 % of the total biomass. For young trees (1 to 4 years old), 21 to 58 % of the total dry weight consists in fine roots (Czernin & Phillips 2005).
- Three of the species are not shrubs but conifers or monocotyledon, for which the general shrub equation is probably not adapted as the wood density and the morphology differ (Simpson 1997; Ketterings et al. 2001);
- None of the equations was built with trees and shrubs harvested in similar abiotic conditions, except for *D. dacrydioides* (equation built for purpose of this study). However, the range of height values of the weighed trees (76 – 130 cm) does not encompass the range of height values of *D. dacrydioides* on the field (80 – 225 cm).
- Basal diameters are also estimated values, as they have been allocated from species-specific height-diameter equations built from a subset of measured trees. Measuring the diameter of all the trees would be too time-consuming, especially as a lot of shrubs are multi-stemmed and the ground is often difficult to reach because of weeds or flooding.

The difference of wood densities of the trees is a source of uncertainty. *Coprosma* species, *L. scoparium* and *P. tenuifolium* have a density between 500 and 600 kg/m³. On the other hand, *D. dacrydioides* and *P. totara* are lighter with a density around 330 kg/m³. They should then store less carbon, at least the first years, but the important root biomass seems to counter-balance, at least for young Kahikateas.

Cordyline australis is the only monocot species, and therefore does not produce "real" wood but a tangle of conducting bundles scattered in the parenchyma (Simpson 1997). No density data was found for *this species*; however palm trees density can range from 150-300 kg/m³ in the central zone of the tree, and from 300 to 700 kg/m³ in the periphery area of the trunk (Wong n.d.).

Estimating the carbon sequestered by young trees of different morphologies is a complex task. Making accurate estimations will be easier once *D. dacrydioides* and *P. totara* are tall enough to measure the DBH. In the future, I would advise to use:

- The general equation for shrubs (Kimberley et al. 2014) for *O. virgata*, *L. scoparium*, *P. tenuifolium* and the C*oprosma* species;
- Species-specific equations using DBH for *P. totara* and *D. dacrydioides*, available in the literature (Beets et al. 2012; Williams & Norton 2012);
- A species-specific equation for *C. australis*.

There is no available allometric equation for *C. australis*. There is a need in building a species-specific equation for Cabbage trees, especially as they are frequently used in restoration programs (Carswell et al. 2009; Czernin & Phillips 2005; Simpson 1997).

The shrub species planted in Stage 3 do not grow past six to ten meters. It means the biomass will reach a cap after a few years, when the shrubs become mature. The monocotyledon *C. australis* does not have secondary growth and the trunk often become hollow after a few decades, reducing the biomass. On the contrary, the podocarps *D. dacrydioides* and *P. totara* can reach 65 and 35 meters high respectively, even if they are often smaller on swampy soils as specified by Wardle (1974). The carbon sequestration is therefore increasing every year on a longer period.

Figure 20 shows the CO_2 sequestration for native New Zealand species, a mix of native shrubs, and radiata pines (exotic coniferous often planted in production forests). The curve representing shrub species was built with data from natural stands aged from 12 to 24 years in three locations (Kimberley et al. 2014). It shows that high levels of carbon sequestration are possible in the 20 years after planting (usually because of the high stockings used), with a mean annual increment of 30 tonnes/ha/year (Kimberley et al. 2014). After 25 years, Totara's sequestration rate exceeds the one of mixed native shrubs and can reach 900 tonnes/ha/year after 80 years. Planting shrubs on open sites is therefore a way to provide faster sequestration rates over the two first decades, the time that native tree species accelerate in growth rate (Kimberley et al. 2014; Scott et al. 2000).

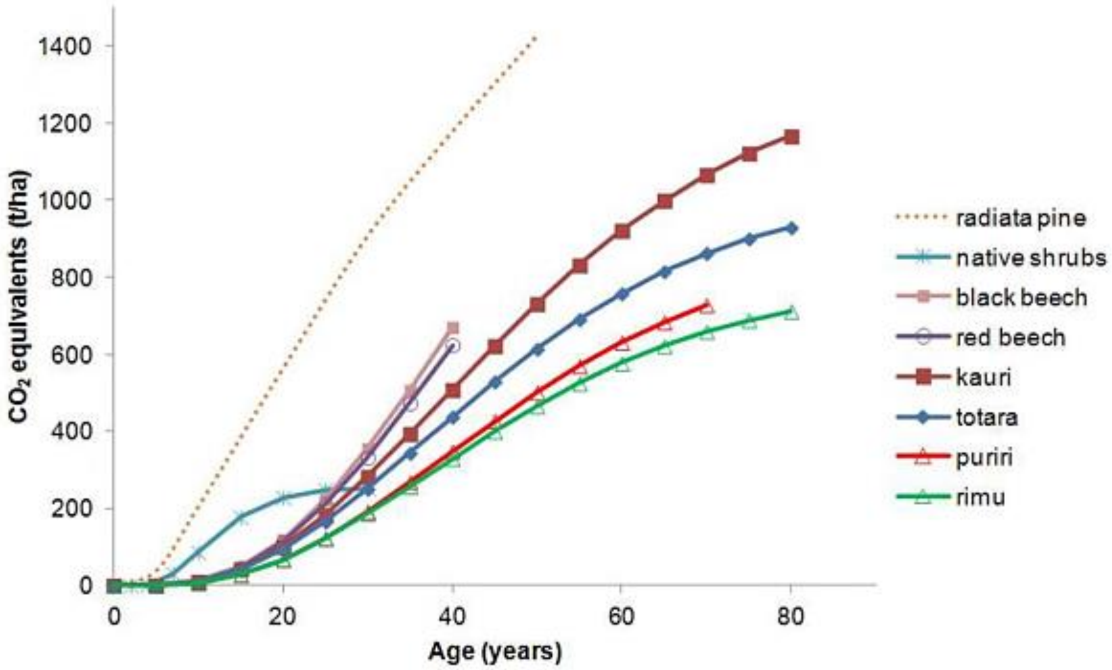


Figure 20: Predicted carbon sequestration rates for several native tree secies, a mixed species shrub planting and a radiata pine stand. Figure from Kimberley et al., 2014.

Six years after planting of the entire wetland according to the plantation plan, we could expect a sequestration of 9.6 t/ha of carbon (35.2 t/ha of CO_2) for the planting zone 2 and 3.1 t/ha of carbon (11.1 t/ha of CO_2) for the planting zone 1. For comparison, a mixed-species shrubland in Waikato with the same stocking (4,444 stems/ha) has been estimated to contain 457 tonnes of CO_2 per ha after twelve years, which is twelve times higher (Kimberley et al. 2014). This difference can be explained by the fact that the studied shrubland is two times older, but also because it is more dense, whereas predictions for Wairio include the mortality rates from the 2011-2017 survival models.

Other values provided by Kimberley et al. (2014) are 93 t/ha of CO_2 for a 20-years old Totara stand, that quickly increases to 437 tonnes for a 40-years stand and 577 tonnes for a 60-years stand. A 30-years old Kahikatea stand with a stocking of 2831 stems/ha in Waikato contained approximatively 289 tonnes of CO_2 per ha, with a sequestration rate of 9.6 tonnes per year. In Carswell et al. (2009), a mean mass of 34 t/ha of carbon is given for different types on New Zealand shrublands. Finally, Coomes et al. (2002) indicate a carbon content of 169.1 ± 18.4 t/ha for indigenous mature forests, 48.6 ± 13.5 t/ha for native shrublands and 123.6 ± 14.6 t/ha for the combination of forest and shrubland. These values give an indication of the carbon storage we can expect for Wairio Wetland if the revegetation leads to a mature forest or shrubland ecosystem.

All the carbon calculations done in this thesis do not include carbon stocked in the soil and in the grasses and turfs. In 2016, analyses were made by Marapara to assess the effect of the saplings on soil organic carbon, but it was no different from that of sedges, turfs and grasses already present. This could be due to the young age of the trees and analyses should therefore be re-done when the trees are more mature. It is also important to outline that the herbaceous vegetation also sequester carbon, and that the weed control and shading by trees diminishes this carbon pool. The carbon storage gain is therefore not a raw gain at the scale of the ecosystem.

Success of the restoration

The vision of the restoration project is “in 100 years, Wairio will be a fully functional wetland supporting abundant native flora and fauna, with natural hydrological regimes linked to the wider Wairarapa-Moana complex, where people can visit for recreation and to appreciate a natural ecosystem restored to pristine condition” (Ducks Unlimited New Zealand 2016). The objectives are the restoration of a pristine vegetation, the increase of the filtration of water run-off before it enters the lake, the education of primary and secondary school students and the availability of a recreation area for the various stakeholders and visitors (Ducks Unlimited New Zealand 2016).

The educational objective is already well on the way, with the involvement of primary and secondary school students in trees planting. It raises awareness about restoration ecology and the importance of wetlands. Information signs are also displayed for visitors. A new board explaining the revegetation project, that I have made within the framework of this thesis, should be soon displayed near the walking track that goes along Stage 3.

The planting of native trees answers several objectives as it aims to recreate a native swamp forest, which will provide habitat and shelter for endemic animal and plant species, and offer to local people and visitors a distinctive natural feature of New Zealand’s landscape (Wardle 1974). However, survival rates of tree species planted in Stage 3 are low (less than 50 %). Given the high cost of planting projects (for the seedlings but also the treatment methods applied and the monitoring), finding cost-effective management methods is critical. Attention must be given to the two main causes of mortality, which are the competition with weeds and waterlogging.

Key attributes defining successfully restored ecosystems include: the elimination of threats, the reinstatement of abiotic conditions and a species composition close to the reference’s one (McDonald et al. 2016; Alexander & McInnes 2012). The current threats to Wairio Wetland are invasive plant and animal species, grazing by cattle and contamination by water run-off from pastoral farming. Programmes to control weeds (blackberry, alder, willow, lupin…) and mammals (especially possums, stoats and ferrets) are ongoing, operated by DU, DOC and the Greater Wellington Regional Council. Sheep and cows are slowly being excluded from Wairio, and fences are installed around restoration stages to prevent them from entering. On the other hand, the project plans to divert nutrient-rich water from Boggy Pond through Wairio Wetland to improve its quality before it enters the lake. It would achieve one of the restoration goals, *i.e.* the filtration of water run-offs, but it may also compromise the establishment of native species, as the high levels of water inflows would provide a near continuous water cover that is not suitable for trees growth. Also, species richness is often correlated with low nutrients levels while a few exotic species thrive in eutrophic ecosystems (Zedler 2000; Kneitel & Lessin 2010). Dumont (2015) addresses this issue and raises the question about a potential choice between giving the priority to water filtration and let Wairio Wetland become a "novel ecosystem", or to focus on the restoration of a pristine swamp forest. An acceptable compromise might be found; however, the ability of the native trees to establish and create a self-sustaining forest in a nutrient-rich area and with substantial competition with exotic weeds should be investigated, as well as their ability to filtrate water run-offs compared to the current novel ecosystem.

An ecosystem is said "novel" when it arrived spontaneously in response to anthropogenic changes (invasion by exotic species, land-use changes, eutrophication…), is self-sustaining and differs from any historic ecosystem known (Murcia et al. 2014; Marris et al. 2013). Some ecosystems might be so profoundly transformed that trying to return them to their historic state would be futile – as if a "threshold" of no-return was crossed. However, this "threshold of irreversibility" is not well defined and may be crossed back with appropriate restoration efforts (Murcia et al. 2014; Marris et al. 2013). A review assessing the degree of recovery of 621 restored wetlands shows that one century after restoration efforts, the biological structure and the biological functioning remain, respectively, 26 and 23 % lower than in reference sites. Either the recovery was slow, or the wetland evolved towards an alternative state (Moreno-Mateos et al. 2012). However, the notion of novel ecosystem should not be used to lower standards in ecological restoration endeavors. Increased efforts are necessary to avoid further loss of biodiversity and spread of biological invasions. In New Zealand, Kahikatea forests are now found in small scarce fragments (Wardle 1974; Waikato Regional Council n.d.). Their protection and restoration is therefore crucial to preserve this distinctive feature of New Zealand (Wardle 1974).

Nevertheless, restoring a highly modified ecosystem, such as Wairio Wetland, takes a long time and involves an important funding. The "threshold" to restoration is therefore more socio-economic and cultural than ecological. Expectations should be realistic for the money and time available. While defining restoration goals, it is important to recognize the limits of what can be achieved (Murcia et al. 2014) as well as the priority ecosystem services that the operators and fund-raisers want to restore.

CONCLUSION

Wairio Wetland is a highly modified wetland that has undergone drainage, clearing of its native forest, nutrients loading and invasion by exotic plants and mammals. Restoring the wetland is a long investment that requires prioritisation of the objectives in order to apply the best restoration methods. The planting plan and treatment methods suggested in this thesis aim to maximize the survival of trees to re-establish a native swamp forest on the Wairio block. Effects of treatments differ between species and it is therefore difficult to recommend one combination of methods that would be satisfying for the eight species. Defining several planting zones with different species and possibly different planning methods might be a solution.

To define the planting zones in Wairio, it is important to understand the hydrological functioning of the wetland. Further investigation is needed regarding water flows and temporal sequences and amplitudes of floods. To ensure the success of the restoration, making a detailed plan with the time line of the operations is useful. Plantings must not be precipitated; it is better to complete works concerning the hydrological function and analyse the new water regime before starting the revegetation phase (Peters 2010; Bedford, 1996).

Restoring wetlands takes time, especially when considering components of woody vegetation (Mitsch et al. 1996). For Wairio Wetland, it is too early to evaluate the success of the restoration, but a continued monitoring allows us to adapt planting methods and accelerate the restoration process at lower costs.

This thesis, as well as the former ones made on this revegetation project (Marapara 2016; Gillon 2014; Johnson 2012; Waring 2017), provide useful information and recommendations for the continuation of the Wairio Wetland revegetation project; in particular, to reduce the mortality rates for the oncoming planting projects in Stages 1, 2 and 4 scheduled by DU before 2020 (Ducks Unlimited New Zealand 2016).

CHAPTER 3: EXTRA ANALYSES AND PERSPECTIVES

Imagery and DTM

As explained in the "Material and Method" section, two DSM (Digital Surface Model) were obtained, the first one in February 2014 for the whole Wairio block and the second one in January 2017. Information about the two DSM are displayed in Table 14:

Table 14: Attributes of the two DSM used for analyses in this thesis.

	Operator	Resolution	Extent	Use
2014	Hawkeye UAC Ltd	0.1 m	Entire Wairio block	Models with relation between survival/growth and elevation; Survival maps.
2017	Pr Stephen Hartley (VUW)	0.059 m	Stage 3	Location of every single tree in ArcGIS©; Photointerpretation of flood limit.

Although the 2017 DSM has a finer resolution, the 2014 DSM was used in the statistical models analyzing the effect of elevation on survival and growth. This is explained by the fact that 2017 being particularly wet (62 % of the stage being still flooded), the DSM low values mainly correspond to the level of water. On the contrary, summer 2014 was drier, the permanent pond being the only area of open water. Therefore, the elevation values correspond better to the ground elevation. The difference between the orthoimages and DSM for the two years is shown on Figure 22. We can clearly see that elevation values in 2017 are influenced by the high water level.

However, we must keep in mind that we are using a DSM and not a DTM, which would be more accurate. Indeed, DSM values correspond to the height of features in the ecosystem, for example the vegetation (Figure 21). Producing an accurate DTM (with ground values) in wetlands and flood plains with dense vegetation and periodic inundation is particularly challenging, as the values are often overestimated (Miroslaw-Swiatek et al. 2016). Yet an accurate representation of a wetland's topography is crucial for its appropriate management, as microtopography and dense vegetation may play an important role in floods distribution and amplitude. In their paper, Miroslaw-Swiatek et al. (2016) recommend a methodology to improve DTMs for wetlands, but it is a long and laborious task.

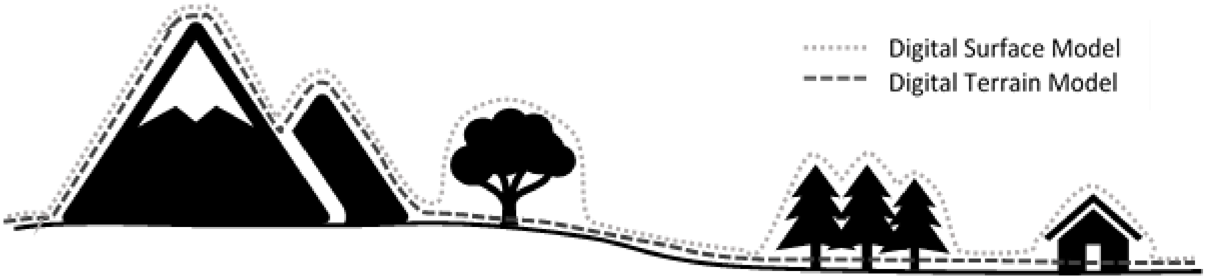


Figure 21: difference between a DSM (Digital Surface Model) and a DTM (Digital Terrain Model).

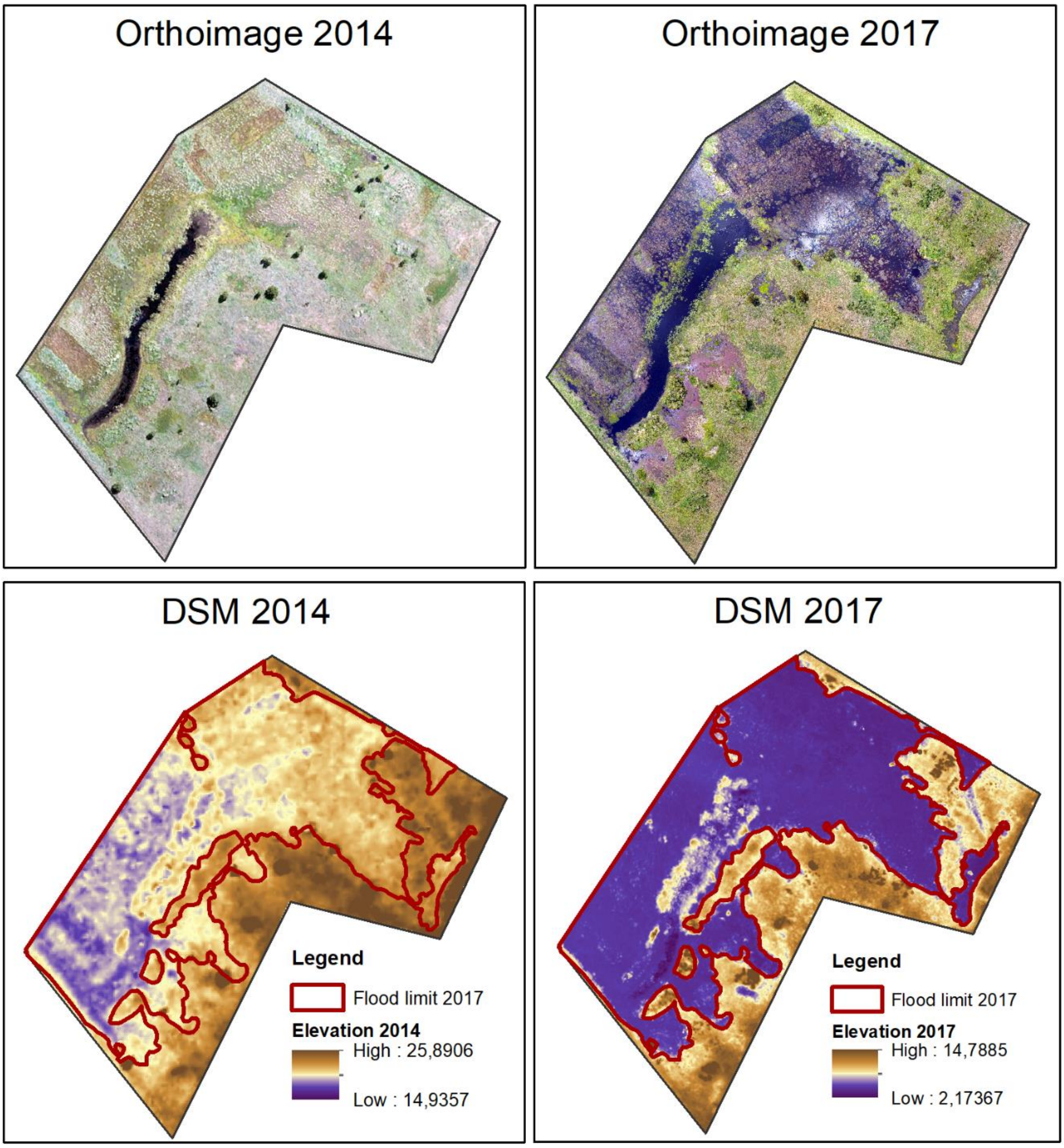


Figure 22: Comparison of orthoimage and DSM between February 2014 and January 2017. The effect of the 2017 flooding is clearly visible. We can also see that the elevation scales are different for the two DSM.

As the trees' height increase on Stage 3, measuring the tallest leaf with a wooden ruler becomes difficult and leads to more uncertainty in the height data. In the future, we could try using DSM to calculate trees' height. By using the drone owned by the School of Biological Science every year at the same period over Stage 3, the data collection would be easier. As each tree is individually identified in a shapefile, species-specific growth analyses can then be done in a GIS software.

Unfortunately, it was not possible to try this measurement method with the two DSM we already have. Indeed, a problem of compatibility occurred as the DSM were not in the same coordinate system. The DSM made in 2014 was recorded in WGS-84 whereas the DSM made in 2017 was recorded in New

Zealand Transverse Mercator. When the transformation was made to display the two raster files in the same coordinate system, information for the z values was lost and the scales of elevation are therefore not comparable. Unfortunately, I couldn’t access the raw files and the software license of DroneDeploy©, the software used to process drone imagery, had expired.

For future monitoring, I would recommend subscribing to a license for DroneDeploy© or another similar software and proceed to drone imagery collection every year, while making sure the selected coordinate system is always the same (if possible New Zealand Transverse Mercator).

Predictions of carbon sequestration

As part of this thesis, growth models were made in R Studio© for each species to predict the future carbon sequestration (Figure 23). Mean heights at every monitoring were used. The resulted equations have the form log H= a + b *(number of months). Parameters a and b as well as R-squared values are displayed in Table 15.

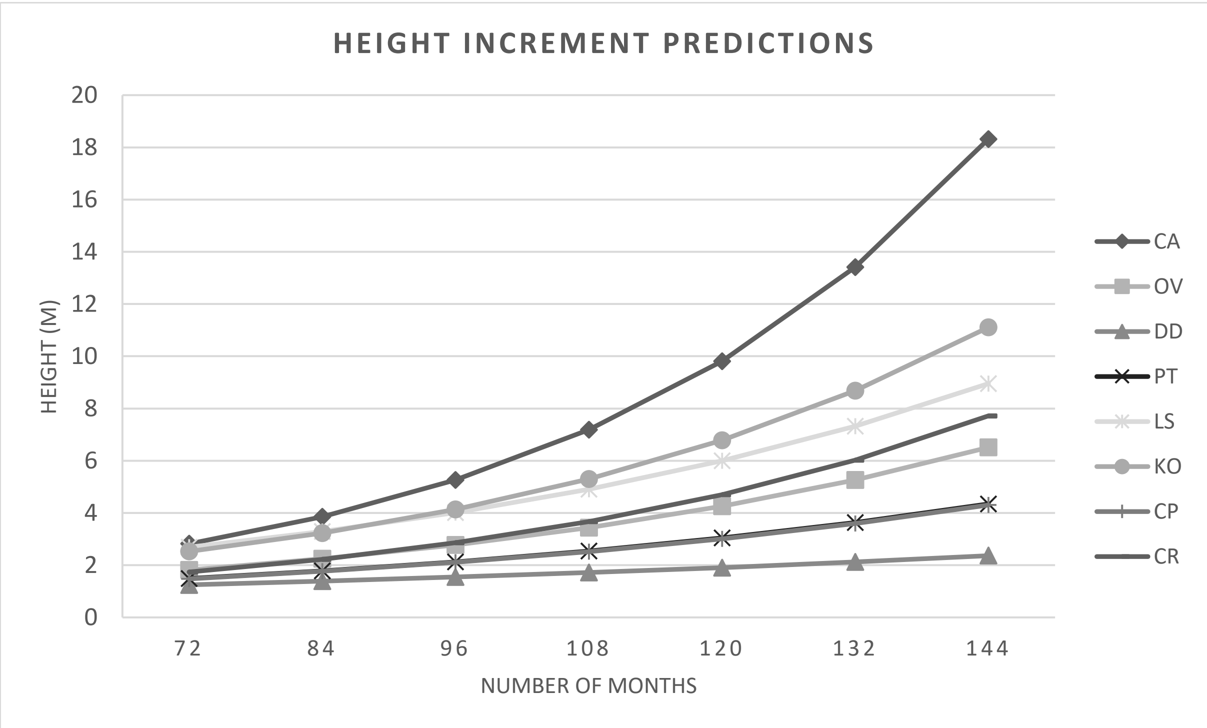


Figure 23: growth models for each species made with mean heights.

These equations and the diameter-height relationships were used to predict the biomass of the trees for the next six years, *i.e.* until twelve years after planting. However, the results were completely unrealistic, especially for *C. australis* for which predictions indicated a basal diameter of 1 meter after twelve years. This is explained by the fact that the growth models describe an exponential growth. The diameter-height relationships were made with the range of height values obtained on the field, and are therefore not accurate for taller trees. Building specific equations with data from older trees in similar abiotic conditions or use some referred in the literature will be necessary for these analyses.

Table 15: parameters and R-squared values of the growth models. Equations have the form log H= a + b(months).*

Species	a	b	R-squared
C. australis	3.769	0.0260	0.99
O. virgata	3.923	0.0178	0.98
D. dacrydioides	4.186	0.00889	0.96
P. totara	3.936	0.0149	0.99
L. scoparium	4.392	0.0167	0.99
P. tenuifolium	4.051	0.0206	0.99
C. propinqua	3.923	0.0149	0.98
C. robusta	3.667	0.0207	0.99

Soil analyses

According to analyses made by Marapara (2016) in Stage 3, "Poorly drained, sandy and mottled sandy soils are the characteristic soil types of the wetland". Soil material (silt/clay/sand ratio) might differ within the stage. We saw during fieldwork that the block 3 looked notably sandy and that the trees were particularly tall (mean height for all species of 226.6 m, the average being 199.6). This could maybe be explained by a better drainage.

Making soil samples across the Stage 3 and analyzing variations of the silt/sand/clay ratio and the eventual effect on the survival and growth could be interesting for the future studies.

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APPENDIX

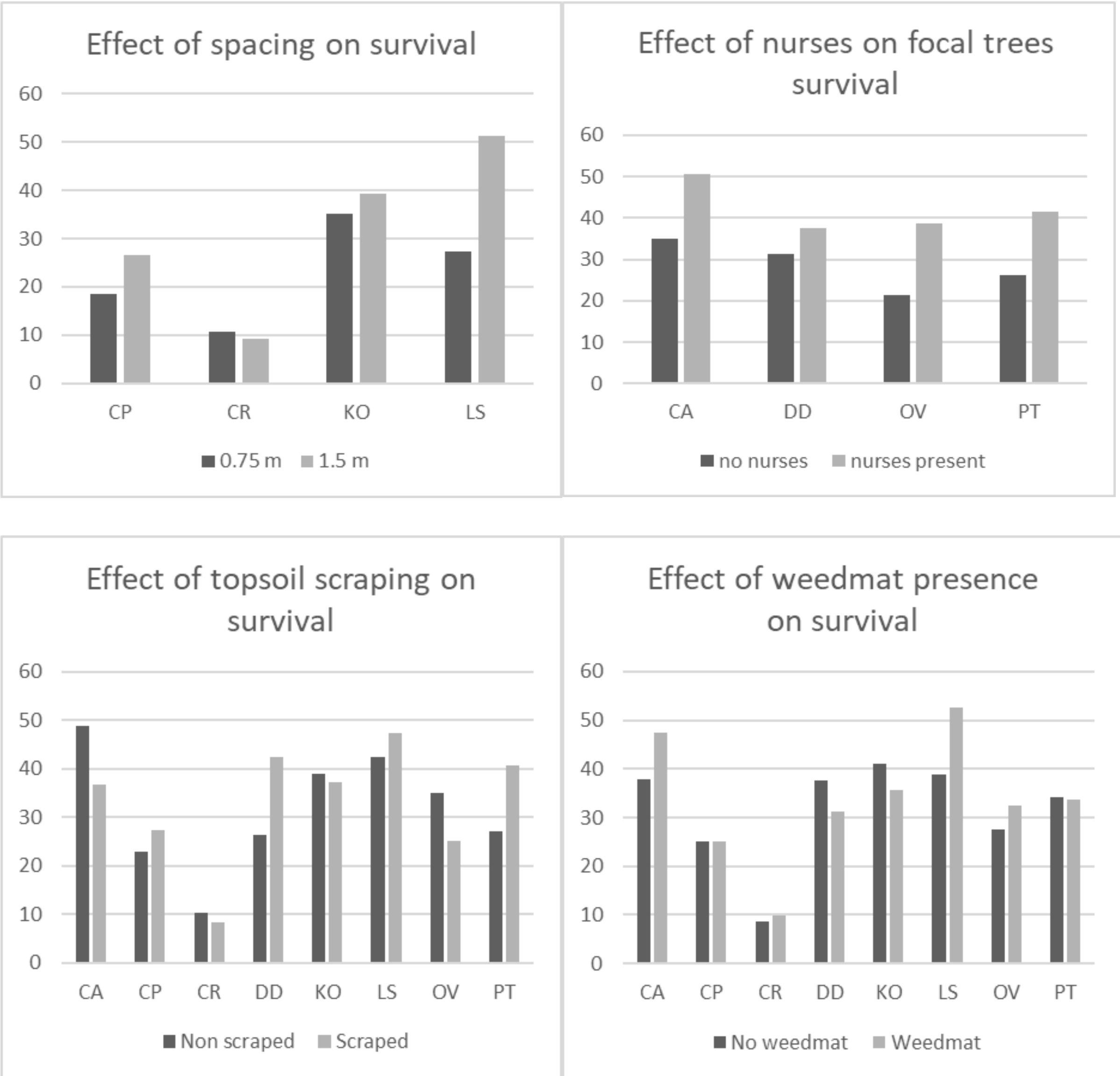

Figure 24: Survival rates 2011-2017 with diverse treatment methods.

Figure 25: "Raw data" graphs - survival from 2016 to 2017 related to elevation. Numbers on the top of the bar represent the number of trees alive in 2016 per category of elevation.

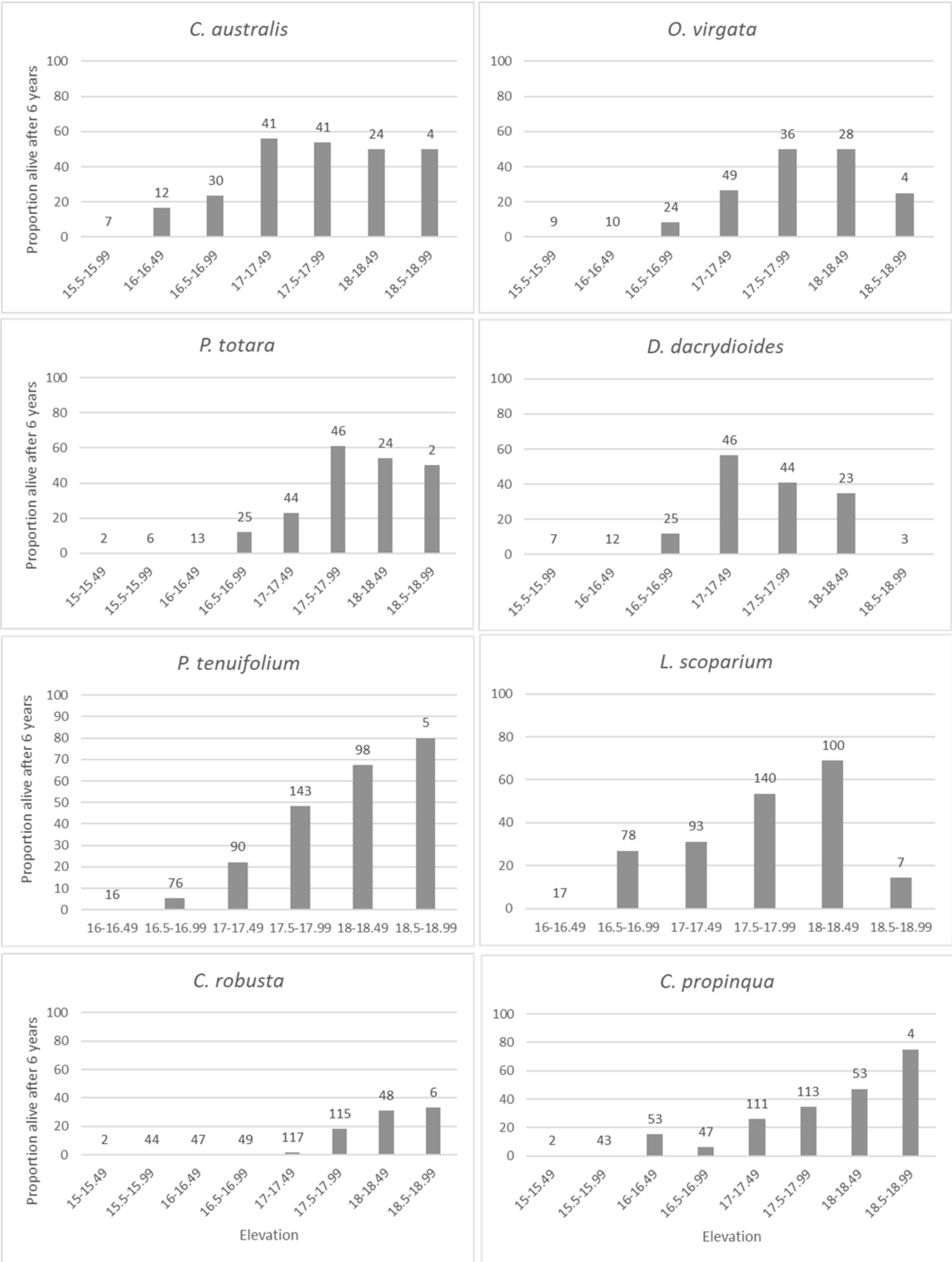

Figure 26: "Raw data" graphs - survival from 2011 to 2017 related to elevation. Numbers on the top of the bar represent the number of trees planted per category of elevation.

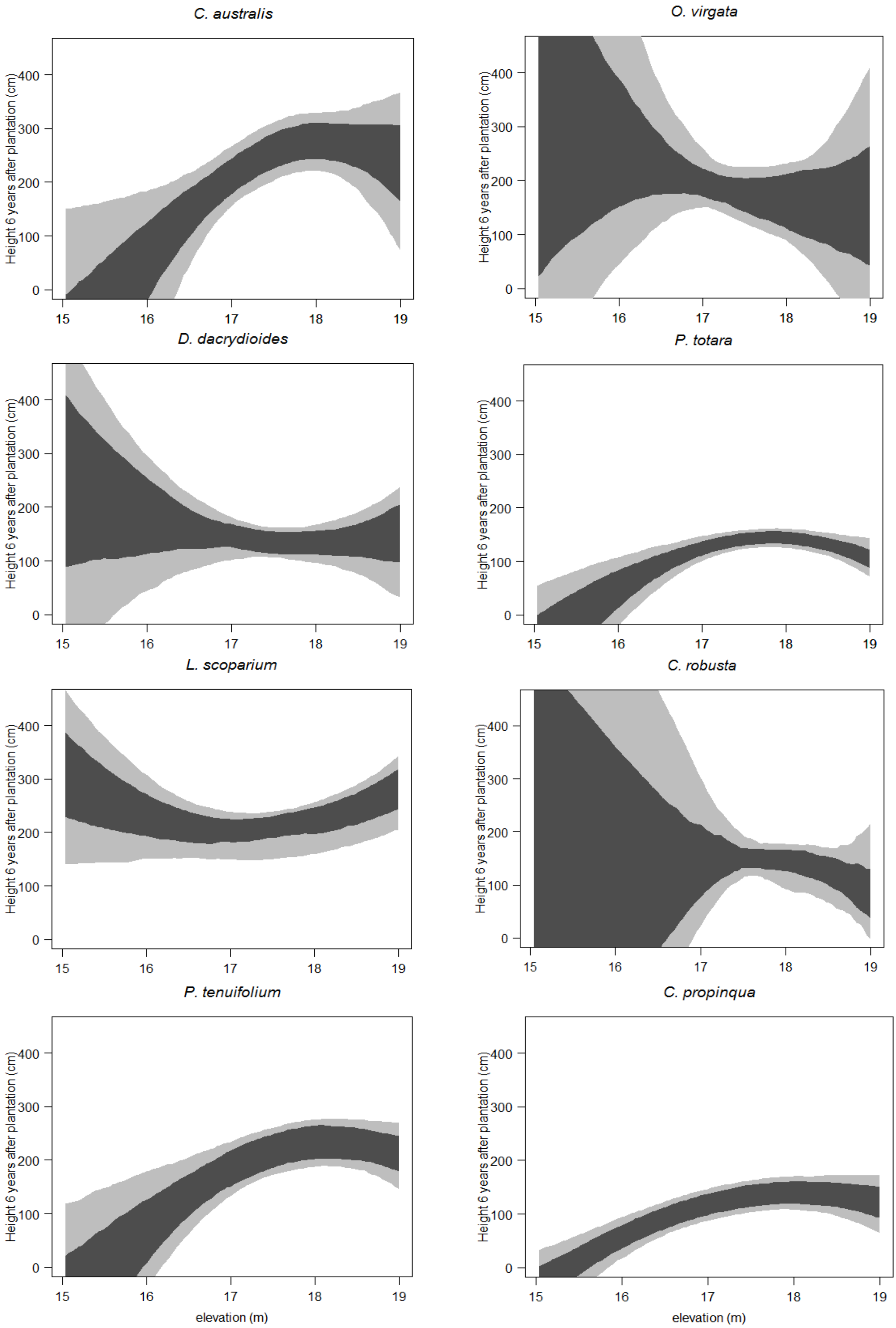

Figure 27: Graphic representation of the effect of elevation on height six years after plantation. Obtained by bootstrapping (n=100) from 2011-2017 growth models (all treatments). Dark grey = 50% confidence interval, light grey = 80%. If the elevation seems to have an important effect on the growth of some species (especially C. australis and P. tenuifolium), the elevation dos not have a significant effect in any of the models.

*Table 16 : Effects of treatments on the survival of nurse species (GLMER) in 2016: beta coefficients and odds ratios values (OR) for significant effects. *, ** and *** respectively significant (p < 0.05) highly significant (p < 0.01) and strongly significant (p < 0.001). ns = non-significant. A slash bar means the variable was not considered in the model.*

Factors	L. scoparium	P. tenuifolium	C. propinqua	C. robusta
Topsoil (S)	ns	46.18 ***	ns	0.694 *
OR		*1.14E+20*		*2.00*
Weedmat present	0.54 *	ns	ns	ns
OR	*1.72*			
Nurse species present	/	/	/	/
OR				
Spacing 1.5	1.32 ***	ns	ns	135 *
OR	*3.74*			*4.26E+58*
Elevation	ns	ns	3.05 *	-21.92 **
OR			*21.12*	*3.02E-10*
Log(elevation)	/	ns	/	517.8 ***
OR				*7.55E+224*
Topsoil * spacing 1.5	/	/	4.86 *	/
OR			*129.02*	
Spacing * elevation	/	/	ns	-7.494 *
OR				*0.0006*
Topsoil * elevation	ns	-2.64 ***	/	/
OR		*0.071*		
Topsoil * weedmat	/	ns	/	/
OR				

*Table 17: Effects of treatments on the survival of focal species (GLMER) in 2016: beta coefficients and odds ratios values (e^{β}) for significant effects. *, ** and *** respectively significant (p < 0.05) highly significant (p < 0.01) and strongly significant (p < 0.001). ns = non-significant. A slash bar means the variable was not considered in the model.*

Factors	C. australis	O. virgata	P. totara	D. dacrydioides
Topsoil (S)	ns	ns	ns	ns
OR				
Weedmat present	ns	ns	ns	ns
OR				
Nurse species present	ns	1.36 *	ns	ns
OR		*3.90*		
Spacing 1.5	ns	ns	ns	ns
OR				
Elevation	ns	-61.84 ***	3.05 ***	ns
OR		*1.39E-27*	*21.20*	
Log(elevation)	ns	1081.37 ***	/	/
OR		*INF*		

*Table 18: Effects of treatments on the 4-years growth (2012-2016) of focal species (GLMER): beta coefficients and odds ratios values (e^β) for significant effects. *, ** and *** respectively significant (p < 0.05) highly significant (p < 0.01) and strongly significant (p < 0.001). ns = non-significant. A slash bar means the variable was not considered in the model.*

Factors	C. australis	O. virgata	P. totara	D. dacrydioides
Topsoil (S)	-47.27	ns	ns	ns
OR	2.96E-21			
Weedmat present	ns	ns	ns	ns
OR				
Nurse species present	36.72	ns	ns	ns
OR	8.86E+15			
Spacing 1.5	ns	ns	ns	ns
OR				
Elevation	ns	ns	ns	ns
OR				
Squared elevation	ns	ns	ns	ns
OR				

*Table 19: Effects of treatments on the 4-years growth (2012-2016) of nurse species (GLMER): beta coefficients and odds ratios values (e^β) for significant effects. *, ** and *** respectively significant (p < 0.05) highly significant (p < 0.01) and strongly significant (p < 0.001). ns = non-significant. A slash bar means the variable was not considered in the model.*

Factors	L. scoparium	P. tenuifolium	C. propinqua	C. robusta
Topsoil (S)	ns	ns	ns	ns
OR				
Weedmat present	ns	-22.045	ns	ns
OR		2.67E-10		
Spacing 1.5	ns	41.682	ns	ns
OR		1.27E+18		
Elevation	ns	ns	ns	ns
OR				
Squared elevation	ns	ns	ns	ns
OR				
Topsoil * spacing 1.5	50.2613	ns		
OR	6.73E+21			
Topsoil * weedmat	/	33.462	/	/
OR		3.41E+14		

Table 20: Height - diameter equations. Different equations were tried and the most accurate ones were chosen from AIC. Height is in cm, resulted basal diameter (BA) in mm.

Species	Equation BA =	a	Std. error	b	Std. error	d.f.	Residual std. error
C. australis	$a * H^2 + b$	0.00114	9.09E-05	42.1	8.20	36	22.67
O. virgata	$a * H^b$	0.0533	0.0616	1.33	0.215	36	16.86
D. dacrydioides	$a * H^2 + b$	0.000459	4.16E-05	3.86	1.01	27	2.61
P. tenuifolium	$a * H^b$	0.0209	0.0230	1.48	0.197	33	15.75
L. scoparium	$a * H^b$	0.0205	0.0271	1.43	0.233	34	13.09
P. totara	$a * H^b$	0.0102	0.0790	1.12	0.155	39	5.285
C. propinqua & C. robusta	$a * H^b$	0.00111	0.00115	2.08	0.198	36	12.66