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Developing design principles for multifunctional carbon mitigation landscape development

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MSc Thesis Landscape Architecture

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Colophon

Photo Forestry
Exploring design principles for multifunctional carbon mitigation landscape development

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Foreword

Dear reader,

You are holding the culmination of over a year's work on landscape design for multifunctional carbon mitigation forests. It has been quite a rough ride, in which most of the work had to be done from home due to coronavirus restrictions. As many activities that could otherwise have served as healthy distractions from this work were cancelled or simply prohibited, the restrictions have been quite hard in keeping proper peace of mind from time to time. Nevertheless, I am happy to share that I have always had friends and family around me (often physically, but mostly digitally) that could keep me on track, or help me in a variety other ways. For that I am very grateful.

I would like to specially thank my supervisor Sven Stremke, for the valuable feedback sessions on the design, the writing process and tips and tricks on keeping my mind in order. I would also like to thank my co-supervisor Igor Sirnik for his help on technical details with regard to photovoltaic systems, as well as the much appreciated feedback on academic writing and the thesis report itself. More words of praise go to the NRG-lab thesis students Joost Andrea and Sanne Glorie, with which I have had some great additional discussions sessions that always gave much welcome direction in my work. I would also like to thank prof. dr. ir. Gert-Jan Nabuurs for the willingness to consult on forestry and forest management and providing me with materials that turned out to be very valuable to my findings.

I hope you find yourself enjoying reading this thesis.

Sam van den Oetelaar

Abstract

It is crucial to reduce global warming by emissions mitigation or through removal of present greenhouse gases from the atmosphere in order to reduce climate impacts on natural systems and societies around the world (IPCC, 2021). Afforestation is becoming politically popular to boost biological carbon sequestration to reduce climate change effects. Similarly, the use of solar panels in the landscape is also getting popular. In densely built and planned countries, multifunctionality of the landscape is a significant factor for the spatial quality of the landscape (Hooimeijer, Kroon & Luttink, 2001). Therefore, with an afforestation challenge that has large spatial implications, there is a need for proper forest design for climate, nature and human activities. A study into a synergy between silviculture and renewable energy production is conducted, in order to find solutions for multifunctional landscapes with regard to climate change mitigation. The airbase of Deelen, nearby Arnhem, the Netherlands, is chosen as the testbed location for this research. Hence, this research is conducted along the following reserach question: *Can the landscape of airbase Deelen provide design prinicples for designing multifunctional carbon mitigation forest landscapes on dry, sandy soils?* The research consists of two parts, [1] the research for design part (RFD) and [2] the research through designing (RTD) part, which is carried out in a pragmatic approach (Lenzholzer, 2013). The RFD part yielded 11 design considerations for the RTD part covering carbon sequestration, forest health, recreation and Forestvoltaics (FV): a promising function combination between photovoltaic (PV) energy production and forest development. The RTD part yielded a landscape design in which an FV system is integrated in a multifunctional carbon mitigation landscape. From this RTD part, 4 generalized design principles are defined that add to the knowledge base of designers on designing multifunctional carbon mitigation landscapes. It is concluded that this testbed area is deemed suitable for creating design principles. However, the proposed concept is novel and conceptual, and practical studies are required to show its true potential.

Contents

List of Abbreviations

Abbreviation	Explanation
AgriPV	Agricultural PV, function combination between crop growth and solar panels
EU	European Union
CCF	Continuous cover forestry
c-Si	Crystalline silicon
FSC	Forest Stewardship Council
FV	Forestvoltaics
GPP	Gross Primary Production, CO_2-uptake for photosynthesis
ha	hectare
IPCC	Intergovernmental Panel on Climate Change
NNN	Natuurnetwerk Nederland (Dutch Nature Network)
NPP	Net Primary Production, GPP minus Ra
PEFC	Programme for the Endorsement of Forest Certification
PV-panel	Photovoltaic panel, or solar panel used to generate electricity
Ra	Plant respiration, CO_2-output
RES	Regionale Energiestrategie (Regional Energy Strategy)
RF	Rotation Forestry
RFD	Research for design
RTD	Research through designing
TWh	Tera Watthours
Wp	Watt peak, measure unit for PV-panel capacity

1. Introduction

It is becoming more and more evident that anthropogenic greenhouse gas emissions are causing global warming. A higher global temperature is expected to increase the frequency and severity of extreme weather events, introduce new water and biodiversity related issues. The combination of these factors contribute to enlarging existing and creating new humanitarian issues. The time for serious climate action is upon us, and as effects are getting more and more extreme already, serious efforts are becoming long overdue. In addition to adapting to the changing climate, i.e. to reduce its impacts on society and ecology, it is also crucial to reduce global warming by emissions mitigation or through removal of present greenhouse gases from the atmosphere (IPCC, 2021).

As greenhouse gas reduction is characterized as a global public good (Stavins, 2011; Barrett, 2003; Nordhaus, 2019), local sequestration methods such as afforestation or reforestation are assumed effective in reducing global warming and thereby reducing climate change effects. Consequently, afforestation is becoming politically popular to boost biological carbon sequestration. The European commission is developing a plan for planting an additional three billion trees by 2030, to not only increase carbon sequestration through the forest carbon cycle, but also increase quantity, quality and resilience of European forests (European Commission, 2020). The Dutch government dedicated a surface area of 37.000 hectares of new forests (Staatsbosbeheer, 2020).

Developing 37.000 hectares of new forest requires changes in land use. Especially in densely built and planned countries such as the Netherlands, multifunctionality of the landscape is a significant factor for the spatial quality of the landscape (Hooimeijer, Kroon & Luttink, 2001). In addition, there are several landscape transitions ongoing or upcoming, such as the energy transition and the agricultural transition. These transitions also require space. Therefore, monofunctional forests are excluded. Hence, increased quality, for both nature and human activities, and increased resilience are important drivers in new forests (Hocks et al., 2018). 18.000 hectares of the forest strategy falls under the responsibility of the government and the provinces, most of which will be found in the Dutch nature network areas (NNN). For the other 19.000 hectares, the focus is on transition zones between nature and agricultural areas. For these areas, function combinations with other land uses (such as agriculture, wind energy, housing) are highly encouraged (Ministerie van Landbouw, Natuur en Voedselkwaliteit, 2021).

With an afforestation challenge that has large spatial implications, there is a need for proper forest design for climate, nature and human activities. Extra thoughts are required in creating these forest landscapes in light of a multifunctional landscape, including productive forest strategies, carbon source removal synergies and recreational values. Regular afforestation through succession or planting for the sake of increasing the level of biodiversity will therefore not suffice. Landscape architects are required to be involved in the development of new forest landscapes. Not only for their expertise on integrating natural processes with land use, but also for their expertise on aesthetics, landscape heritage and cultivating landscapes. This is required to create a variety of experiences, for a multitude of landscape users, thereby creating a true multifunctional landscape.

There is experience with designing forest configurations. The British Forestry Authority (1999) has developed several design principles and considerations for forestation, based on shape, visual force, scale, diversity, unity and the spirit of place, using larger landscape elements to design forest landscapes with percepted experiences in mind. There has also been research on the role of vegetation in carbon mitigation, carbon sequestration rates and storage capacities of various forest types (Hester & Harrison, 2009; Kellomäki, Kilpelaïnen & Alam, 2013), tree species in various contexts and soil types (Conen, et al,. 2005; Sedjo & Songhen, 2013), and undergrowth vegetation (Weissert, Salmond & Schwendenmann, 2017). The knowledge base on carbon mitigation through biological sequestration is therefore quite extensive, but more research is needed for a more complete picture of the various conditions, sequestration rates and storage capacities.

Furthermore, alternative techniques and technologies on renewable energy production (such as photovoltaic panels and wind turbines) and storage options (such as batteries) are advancing rapidly. In line with the Glasgow Climate Pact, the Dutch government aims to reduce greenhouse gas emissions by 48.7 Gt by 2030 and bring it down to zero in 2050. This results in an aim for 50% renewable energy use by 2030, towards 100% in 2050 (Energietransitie Nederland). The manifestation of renewable energy sources in densely built countries' landscapes still causes a lot of heated discussions between, among others, landscape users and governments. Publications on such energy landscapes are emerging (e.g. Stremke & van den Dobbelsteen, 2013; Sijmons, et al., 2017), and some researches focus on creating design principles for energy landscapes (e.g. Vermeer, M. 2018; Yuan, Q. 2019). In parallel, Stremke & Schöbel (2019) demonstrate methods to do so and point towards energy landscapes as a more defined research niche for landscape architects and envrionmental designers. This demonstrates the need for research on energy landscapes. Moreover, no studies or project examples were found that deal with renewable energy methods synergizing with forest design.

1.1. Knowledge gap

Expert knowledge on afforestation or plantation with a focus on biological carbon sequestration is predominantly limited to the urban context (Shafique, Xue & Luo, 2020; Lal & Augustin, 2012). To our knowledge, there are no studies on how to translate and combine these knowledge bases into workable design principles for (large scale) carbon mitigation forests in a rural context. Moreover, to our knowledge, there are no studies or example projects on carbon mitigation forest design strategies in densely built and planned countries. This research attempts to fill this knowledge gap by searching for design principles for multifunctional carbon mitigation forest landscapes on high dry sandy soils. As part of this multifunctional landscape, this research especially focuses on creating a function combination between forest development and solar based renewable energy production. This is done through a research through designing (RTD) process (chapter 6).

1.2. Research approach

This research is approached from a potential transnational landscape problem (afforestation), caused by goals to mitigate climate change. It searches for ways to prevent this landscape problem from manifesting, by RTD at a testbed location. Rather than the source of the design problem, the testbed location is a potential target of the landscape problem and is therefore, instead of the research subject, a place for researching how to design carbon mitigation forests. The approach of this research is therefore problem oriented, rather than location oriented (see Figure 1). The chosen testbed location is Airbase Deelen, a military airfield north of Arnhem, the Netherlands. The location selection and RTD process are discussed further in the methods section starting on page 22.

The scientific novelty that is expected to result from this research are design principles on how to design a multifunctional carbon mitigation forest landscape on high, dry sandy soils. These principles will serve as starting points for designers in climate forest designs. These principles cover how to include nature and increase biodiversity, whether human activities are to be included in the forest landscape, and if other synergies can be implemented, such as energy generation and energy storage.

1.3. Research questions

The objective of this research is to find out how policy makers, land use planners, and above all landscape architects should deal with the spatial impacts and implications of the afforestation challenge that the Netherlands is dealing with the coming years, while focusing on the carbon mitigating function of these forests. This challenge is caused by plans like the forest strategy and the European forest plan. This research focuses on the higher sandy soils of the Netherlands. This objective is translated into the following research questions. An overview of the sub-questions can be found in Table 3.

Main research question

» Can the landscape of airbase Deelen provide design prinicples for designing multifunctional carbon mitigation forest landscapes on dry, sandy soils?

Answering this research question consists of the knowledge part and the design part. In the knowledge part, prerequisite information is studied that is required in the design part of the research. This results in different types of sub-research questions: knowledge questions and design questions.

Figure 1. Research approach. Testing forest design on a testbed location to contribute to a national design problem that derived from the global climate problem of increasing mean temperatures.

Knowledge questions

» Which kinds of forests or forest conditions are most effective in carbon sequestration?
» How do human activites affect conditions for a carbon mitigation forest landscape?

The first knowledge questions serves to find optimal forest ecosystems where the carbon sequestration rate is highest on dry sandy soils. The second knowledge questions serves to find information about different types of human activities and how they interact with the carbon sequestrating function of a forest.

Design questions

» Can synergies between a carbon sequestration forest and alternative (energy) production and storage methods be found on airbase Deelen as a testbed location for dry sandy soils?
» Can synergies between a carbon sequestration forest, nature and recreation be found on airbase Deelen as a testbed location for dry sandy soils?

The part where this research focuses on a landscape design question rather than a landuse problem is inherent to the call against monocultures and for multifunctional landscapes, and expressed through the type of result this research works towards. Therefore, the design questions focus on synergies between different functions from which, among others, the design principles can be retrieved.

1.4. Report structure

This chapter introduced the problem and shows the approach of this research in response to it. The next chapter is the conceptual framework, in which key concepts are discussed that are predominant in this research or in another way important to stress. Next, the methods of this research are discussed (chapter 3). The landscape analysis of the testbed area is conducted in chapter 4. The literature study results are presented in chapter 5, which feed the designing process for the design questions, discussed next (chapter 6). Chapter 7 discusses the methods, results and data of this research. The research is concluded in chapter 8.

2. Conceptual framework

This chapter sets a baseline understanding of the concepts that are worked with by covering the key concepts of this research. The topics are divided in two themes: climate change mitigation [1] and landscape quality and development [2]. The climate change mitigation concepts introduce climate change reponse options and dive into the workings of carbon sequestration in forests and the principles of renewable energy generation. These concepts form the foundation of this research. The second theme discusses the multifuncitonality of the landscape as well as landscape quality: important considerations in any land use change with significant spatial impact.

2.1. Climate change mitigation

2.1.1. Climate change response options

Climate change mitigation and adaptation are ditinguished by the way humanity can respond to the climate change causal chain (see Figure 2). In this sense, adaptation responds to climate change impacts, whereas mitigation responds to the causal factors of climate change. Notwithstanding the desperate need for some adaptation measures, mitigation efforts target the underlying problems, whereas adaptation measures treat the symptoms. Key differences between adaptation and mitigation are spatial and temporal differences. Adaptation efforts are focused on a local, or at most regional scale, since climate change impacts differ strongly per region and result in different local issues (e.g. climate change can impact a river bound city with floods, whereas highland cities may suffer from droughts). Mitigation efforts are focused on the global scale, since climate change is considered as a global public good (Bechtel, Scheve & van Lieshout, 2019). Temporal differences are caused by the response time of measures. Adaptation measures often affect risk reduction and distaster prevention more directly. However, mitigation efforts have to cope with atmospheric residence of greenhouse gases, which can be decades, thereby increasing the temporal effect significantly (Klein, Schipper & Dessai, 2005). Since this thesis focuses on climate forests, and the temporal factor is very significant in forest design, it concentrates on mitigation rather than adaptation.

2.1.2. Carbon mitigation

Two categories of climate change mitigation efforts can be distuinguished: carbon source removal and carbon sink enhancement (Minx, et al, 2018). Carbon source removal deals with preventing carbon (and other greenhouse gases) to be emitted into the atmosphere. An example of carbon source removal is replacing fossil fueled power plants with renewable energy source technologies (such as solar panels and wind turbines). Carbon sink enhancement deals with increasing the active removal of present greenhouse gases in the atmosphere, and/or increasing the storage capacity sinks for greenhouse gases. Removal and storage capacities can overlap within the same measure, depending on the process.

Carbon sink enhancement can be achieved through carbon sequestration. Carbon sequestration is defined as the long-term direct removal of atmospheric carbon in order to reverse global warming or mitigate its effects (The Royal Society, 2009; Sedjo & Sohngen, 2012; Minx, et al., 2018). Carbon can be sequestrated through biological, chemical and physical processes, such as natural sinks and geological storage (Angamuthu, et al., 2010; USGS, n.d.). Afforestation is an example of biolog-

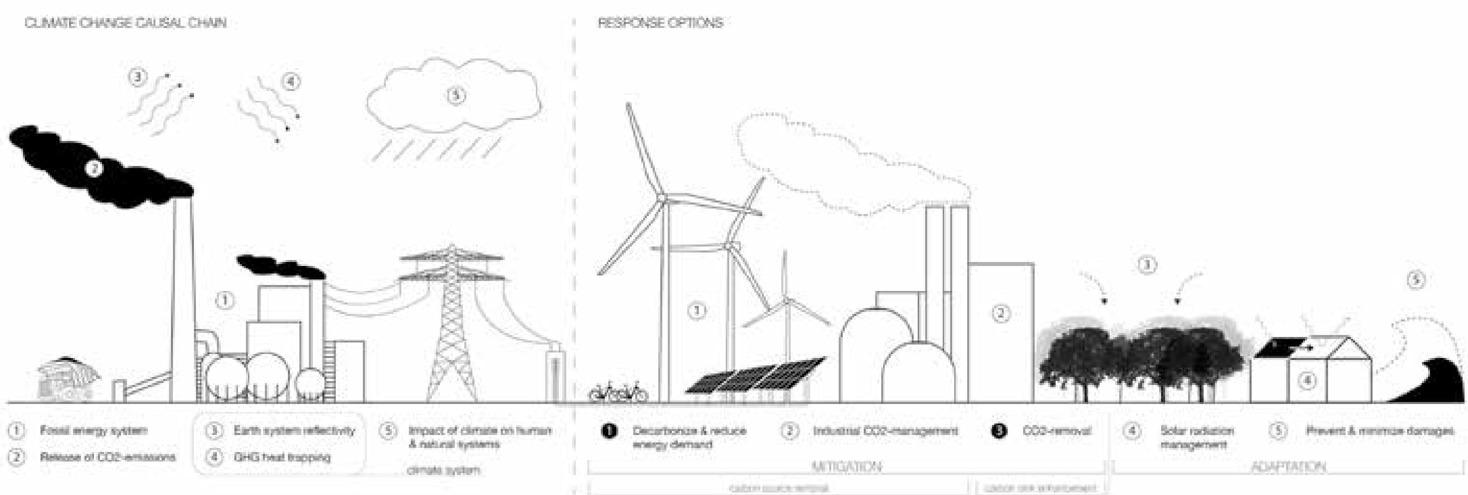


Figure 2. Climate change reponse options (based on Minx, et al., 2018). Human reponses on climate change can target causes of climate change (mitigation) or effects of climate change (adaptation).

ical carbon sequestration, where atmospheric carbon is used by vegetation for growth and stored as biomass.

2.1.3. Biological sequestration through afforestation

As carbon sequestration is part of the forest carbon cycle, it will be discussed in further detail. The photosynthesis process captures CO_2 from the atmosphere, transforming it into sugars using sunlight energy. This is called the Gross Primary Production (GPP). The share of sugars that is used for plant organs rather than respirated (Ra) is called the Net Primary Production (NPP). Net growth can last from decades to centuries, producing a lot of biomass, and collecting and storing a lot of carbon. Eventually, an untouched forest reaches an equilibrium where growth is equaled by degradation and the average NPP reaches zero (Jarvis, Ibrom & Linder, 2005; Lorenz & Lal, 2010). Besides NPP, there are other key system values in the forest carbon cycle (see Figure 3).

2.1.4. Forest succession

Forest succession is the natural development of forests, without human intervention. Forest succession on dry sandy soils consists of several stadia. In the pioneer stadium, pine trees emerge as pioneer species on the poor soil. After several decades, birch and pinus trees dominate. The degradation of the plants in the top soil creates a more nutricious soil, on which deciduoud trees are more comfortable to grow. The final stadium is that of an oak-beech forest. The forest development can take up to 200 years to get to the final stadium. On very poor soils, it can take even longer before the final stadium is reached (Prach, et al., 2021; Berendse, 2012).

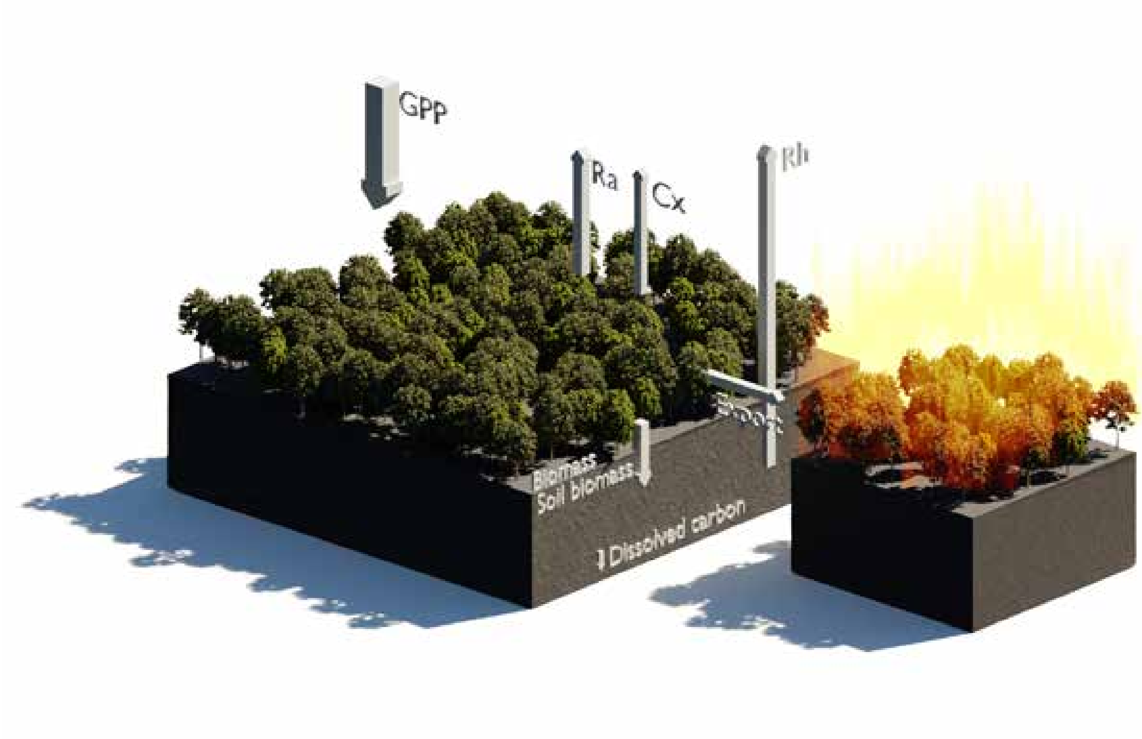
As the climate goals are set for much sooner than 2220, it is considered inevitable to use planted forests over successional development.

2.1.5. Production forest

In the late 18th century and early 19th century, the main focus of forestry was wood production, for which management concepts were developed. Focusing on wood production, management entailed quantification of expected yield. It was therefore crucial to optimize conditions that enhance production (Barreiro, et al., 2017). In the Netherlands, at the lowest forest coverage in the beginning of the nineteenth century (2%), afforestation was initiated by land owners, in order to increase the economic value of unproductive area, predominantly on poor soils. In the twentieth century, the focus was on creating employment and at times of polderization of the landscape, plantations were created to shape the landscape. Probably due to low economic benefits, many private owners sold their forests to the state. Nowadays, nearly half of all forest area is state owned, still a third privately owned and the rest is owned by private nature conservation organizations (Schelhaas & Clerkx, 2017). There is a trend towards forest growth for biomass production (Kellomäki, et al., 2013), intended for sustainable energy production. It is therefore crucial that the production of this biomass is also done sustainably.

The two most prominent international forest certification systems are the international Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC). Several national standards and systems are part of the PEFC (Stupak et al., 2011). Forests products with such certification comply to rules for sustainable development, established in 10 principles (Forest Stewardship Council, 2015).

Figure 3. Forest carbon cycle. Net ecosystem production (NEP), encompassing all carbon fluxes and disturbances of the system; Net ecosystem exchange (NEE) includes all fluxes except disturbances.



The two dominant (production) forest management systems are rotation forestry (RF) and continuous cover forestry (CCF) (Bianchi, et al., 2019). RF is predominantly paired with clearcutting harvesting methods, for practical logistic reasons, or organizational reasons. These practices result in even-aged forest stands, often with single species planting. Questions are raised towards this management method, with regard to sustainable forest management, specifically on ecological concerns. CCF is characterized by stands with an uneven tree age structure, and is maintained through selective removal (either per single tree or in groups of trees). It is worth noting that a CCF forest can be spatially dispersed, dependent on the group size in a group selection removal (Kuuluvainen, Tahvonen & Aakala, 2011).

2.1.6. Climate forest

Balázs et al. (2008) characterize a climate forest as a forest planted or grown on an abandoned field or degraded grassland to reduce atmospheric carbon. However, this definition limits itself to carbon sink enhancement, rather than include other mitigation alternatives that focus on carbon source removal, thereby neglecting the multifunctional landscape potential and synergy potentials with other uses and users. Furthermore, it limits to abandoned fields and degraded grasslands, where it should encompass all kinds of land use transitions into (multifunctional) forest landscapes that result in a net negative carbon balance. Selman (2010) discusses landscapes of carbon-neutrality, in which he points out that energy production and consumption are key drivers of landscape transitions. This notion is critical when thinking of climate forests, as renewable energy production has a potential to be a driver for afforestation. Therefore, a climate forest is defined as a grown or planted forest resulting from land use changes with the goal of reducing atmospheric carbon, either directly (through carbon sink enhancement), or in a combination of direct and indirect reduction (through carbon source removal). When using the term climate, multiple landscape problems can be identiefied. The main driver of this thesis is to reduce carbon in order to reverse global warming or limit its effects, rather than other (climate related) landscape issues, such as biodiversity loss or desiccation. However, other climate change related issues are also addressed as part of the multifunctional climate forest landscape.

2.1.7. Renewable energy

Renewable energy is generally defined as "[...] energy obtained from naturally repetitive and persistent flows of energy occurring in the local environment" (Twidell & Weir, 2015. p3). Energy retrieved from wind, sun, water and plants follow the definition of renewable energy, being naturally repetitive on some time scale with inert variability. The variability of the sun is caused by the rotation and tilt of the earth, which causes the influx of solar energy to show a diurnal and an annual pattern, expressed in different seasons. Seasonal differences also cause variations in biomass production through plant growth. The variability of wind is caused by weather conditions and can vary strongly from day to day.

The key difference between renewable energy and non-renewable energy is that non-renewable energy is not present in the environment as a persistent flow (Twidell & Weir, 2015). In other words, non-renewable energy does not present itself without human interaction. It has to be retrieved from sub-surface reservoirs or mines. Renewable energy is therefore harvested through (partial) interception from these naturally occuring energy flows, rather than retrieved from sub-surface sources. Well-known harvesting technologies are wind-turbines, hydropower dams and solar panels. The term solar panels is overarching and encompasses heat producing panels (solar collectors) and electricity producing panels (photovoltaic panels), although photovoltaic panels are often referred to as solar panels.

A renewable energy source is not necessarily a sustainable energy source. Rather, a renewable energy source is part of a sustainable energy system, which also includes energy-efficiency, social responsibility and environmental responsibility (Golušin, Dodić & Popov, 2013; Hussain, Arif & Aslam, 2017). Golušin, Dodić & Popov (2013) characterize sustainable energy development along several concepts, among which [1] conservation of non-renewable resources, [2] exploitation of renewable resources, [3] intergenerational justice and [4] promotion and education of sustainable development. This research contributes to sustainable development on the exploitation of renewable resources, and also touches upon promotion and education, as will become clear later. It does not aim to fully cover all aspects of sustainable development in its findings. This research focuses on forest development in combination with energy landscapes. Therefore, photovoltaics and their use in the landscape is discussed in more detail.

2.1.7.1. Photovoltaics

A rapidly developing technology in renewable energy production is in photovoltaic panels (PV-panels). In the last two decades, efficiency has doubled, while prices have become 20 times lower. The most predominant PV-technology is crystalline silicon (c-Si) based, which has a market share of ca 93%. Its cost-effective average efficiency is around 21% and the panels have lifetimes of 25-30 years (TNO, n.d.). An upcoming PV-technology is that of thin film solar panels, or perovskite. It is a younger technology, and with an average efficiency of around 18%, it is slightly less efficient than c-Si. However, similar values to c-Si are expected as development continues. (TNO, 2021)

As c-Si-cells are relatively thick, flat surfaces such as roofs or arrays in the landscape are required to operate on. Perovskite cells are much thinner (80x thinner than c-Si) and are therefore intrinsically flexible. Aditionally, Perovskite cells can be made transparent. Its application is therefore wider, and development works towards product integration in windows, roof tiles and more, with possibilities of inkjet printable solar panels. However, perovskite cells are not yet financially competitive with c-Si cells. Nevertheless, it is expected that they will be competitive in the future (TNO, 2021).

Current PV-technologies do not capture all sunlight that hits a panel, but a certain fraction of the light spectrum, which is slightly or very different among types of cells. For example, one type of cell may intercept red and infrared light for its electricity production, whereas another may use blue or ultraviolet light. In addition, each PV-cell has some kind of inert light emitting characteristic. Therefore, the practical efficiency limit of such PV-panels is around 27% (Oberbeck, et al., 2020). In an attempt to overcome such limitations, a relatively new technology is emerging, called tandem-PV cells (Lehr et al., 2018). It is a stack of two different cells that each reacts with a different part of the light spectrum (such as c-Si and a perovskite), thereby reaching efficiencies up to 28% within just a few years of development (Yan, et al., 2019), and aiming for efficiencies of 32% and above in the future. Since it is a very new technology, the costs are still elevated and systems are not yet financially competitive with conventional c-Si systems or perovskite systems. However, TNO (2021) expects to develop a tandem-PV market product by 2023. (TNO, 2021)

An external factor that influences the efficiency of PV-panels is temperature. Too much solar radiation and too high ambient temperatures cause overheating of the panels, which decreases its efficiency significantly (Eldin, Abd-Elhady & Kandil, 2016). Panels should be cooled in these circumstances to keep efficiency levels high, as the efficiency is reduced by 0.5% per degree Celsius over 25 degrees Celsius (Biwole, Eclache & Kuznik, 2013).

2.1.7.2. Photovoltaics in the landscape

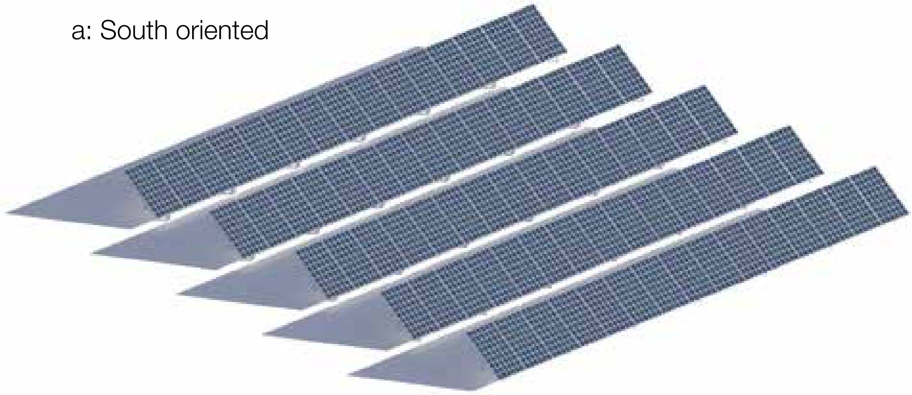
Configurations

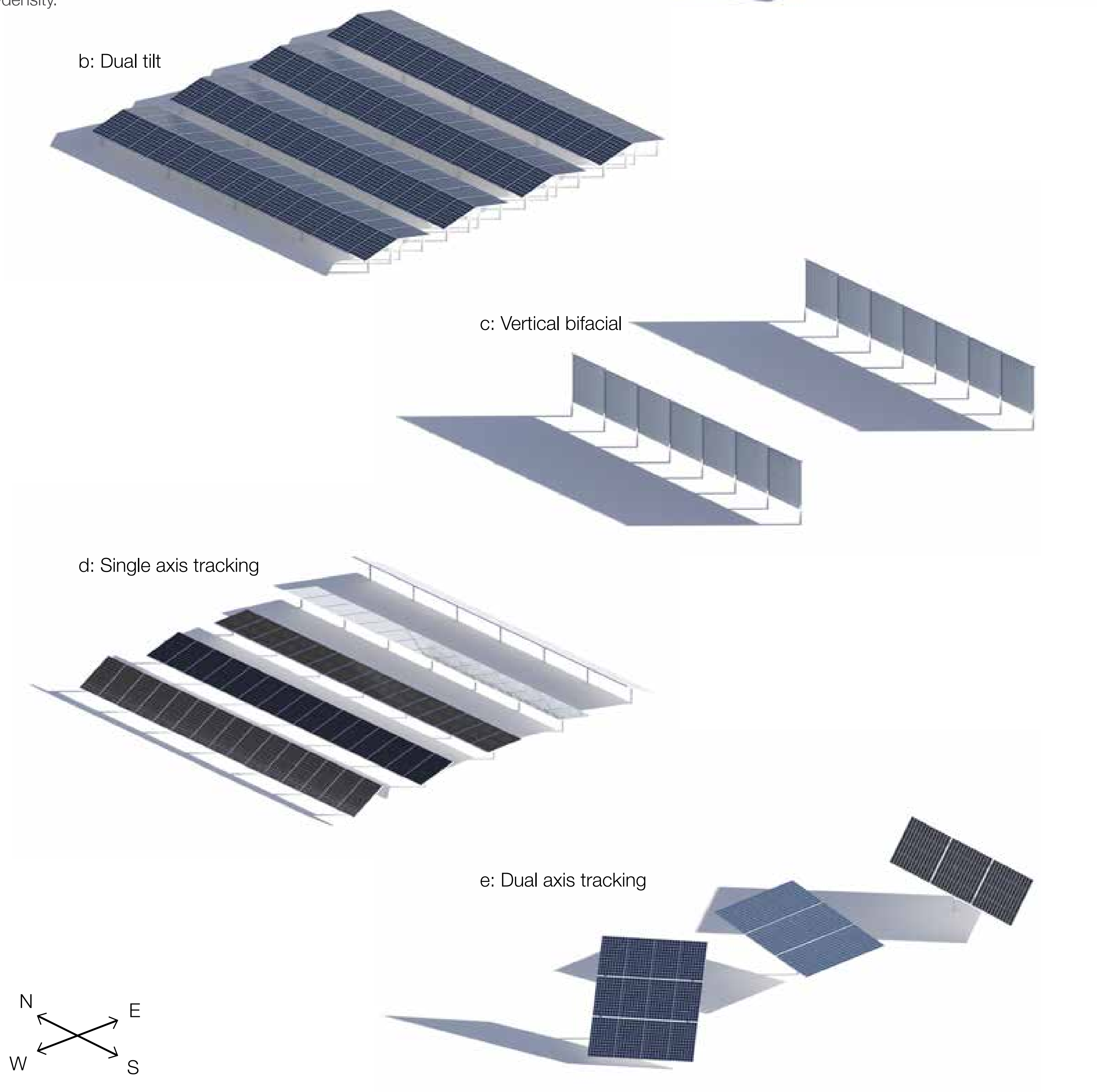
There are several ways to layout a a set of PV-panel arrays, refered to as a PV-system. Depending on the targeted use, one can opt for south facing, east-west facing, bifacing or tracking PV-systems, each with its advantages and drawbacks (see Table 1). In the Netherlands, the most prevailing orientation for PV-systems in the landscape is South oriented. This is done for maximizing electricity output (Litjens, Worrell & Sark, 2017). In an electricity optimized South oriented system (azimuth 180 degrees, see Figure 5 on page 19), the panels are inclined (optimally between 33 and 38 degrees in the Netherlands (Litjens, Worrell & Stark, 2017), generally 37 degrees in the Netherlands). Therefore, drop shadow has to be taken into account

Table 1. PV-system orientation. An overview of several PV-system orientations, with their intended use in the landscape, advantages and drawbacks. This provides insights for design choices with a PV-system. Corresponding model in Figure 4 indicated between brackets.

System Orientation	Intended use	Advantages	Drawbacks	Source
South (a)	Grid power on rooftops, in the landscape	Most optimal static orientation for maximizing electricity production	Not continuously facing the sun optimally throughout a day	
East-West	Produce power for direct use in households, on rooftops or close to households	Balances household electricity supply and demand levels, more PV-coverage (see Figure 4)	22% less efficient (per panel) than South facing systems	Dimish & Silvestre, 2019
Vertical bifacial	AgriPV, meadows	Captures both direct light and reflected light (5-20% more electricity than monofacial panels)	32% less efficient than optimally tilted (bifacial) panels	Appelbaum, 2016
Tracking (single axis)	Grid power in the landscape	Rotates from east to west or changes tilt throughout the day to increase electricity production (20-25% more electricity than fixed system)	More expensive in installation and maintenance than fixed systems due to motors and software to run the tracking operations	Huld et al., 2010
Tracking (dual axis)	Grid power in the landscape	Rotates along azimuthal and inclination angle to optimize light irradiation throughout the day (30% more electricity than fixed system)	More expensive in installation and maintenance than fixed systems due to motors and software to run the tracking operations	Eke & Seturk, 2012 Huld et al., 2010

Figure 4. South oriented PV-system layout at morning (a), and dual tilt system (b) at the same hour (North to the top left of the image). Figure a shows there is a minimum distance required between the rows in a South facing system, minimizing drop shadow from covering the panels at off-peak hours. For dual-tilt systems, this distance is much smaller, demonstrating coverage efficiency: 75 south facing panels, 120 dual-tilt panels on approximately the same area. Figures c, d and e demonstrate the physical appearance of the other systems as described in Table 1, but do not attempt to be comparable to a and b with regard to PV-density.





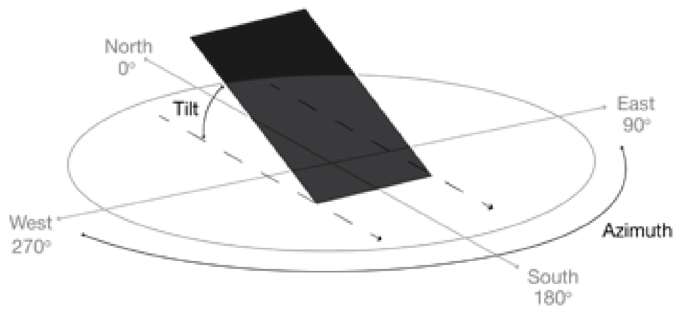


Figure 5. PV-panel orientation, demonstrating tilt and azimuth. This panel is oriented on an azimuth of 180 degrees and a tilt of 35 degrees.

in the layout. Consequenty, around 50% of a surface can be covered with PV-panels (see Figure 4: a, b, c).

Another common orientation setup is East-West oriented (dual tilt-systems). Such a system (see Figure 4: d, e, f) has a lower electricity output, but the electricity output matches demand patterns of households better, where the peak-hours are in the morning and late afternoon. This system is less prone to wind stress, and due to a lower tilt, rows of panels can be placed closer to another, since there is less shade. Therefore, the land coverage can be higher than in a South oriented system. (Litjens, Worrell & Stark, 2017)

Bifacial PV-systems have become financially competitive with monofacial equivalents. They are expected to become the mainstream technology for various applications, for these systems produce 30% more electricity than the monofacial ones, for which they are argued to be "the overall best technology for electricity generation" (Kopecek & Libal, 2021, p1).

Single axis tracking PV systems typically rotate along their tilt axis throughout the day to follow the path of the sun (see Figure 4d). Thereby, it can receive more sunlight than a static system, be it at the cost (of both energy and investment) of a rotating system. A dual axis tracking system rotates along both its tilt annd azimuth, further optimalizing sunlight sollection. These systems take more space, due to the long shadows they can cast at morning and in the evening. They also have higher operating and investment costs due to the moving parts Figure 4e).

Litjens, Worrell & Stark (2017) argue against focusing on maximizing electricity output for PV-systems. Rather, they argue to include demand patterns and market prices. Due to a lack of significant energy consumers around the design site (see chapter 4 starting on page 34), a system that focuses on supplying to the main grid, rather than a self-consumption focused system, would be most sensible. Therefore, this thesis focuses on maximizing electricity output.

AgriPV

AgriPV (also known as Agriphotovoltaics or Agrivoltaics) is the landuse combination of crop growth and renewable energy generation through PV-panels. Gafford et al. (2019) show that there are several additive as well as synergistic benefits resulting from an AgriPV system, such as reduced drought stress, increased food production and reduced PV-panel heat stress. Several studies are looking closely into the effects of an AgriPV system with various crops, with results ranging from where the PV does not show negative effects (Cho et al., 2020), to systems where there are positive effects in food production, predominantly increased yield (Gafford, et al., 2019; Dupraz, et al., 2011; Marrou et al., 2011). In addition to food production benefits, farmers can also achieve energy cost reduction benefits and an extra source of income from energy production sales (Majumdar & Pasqualetti, 2018).

Forestvoltaics: an exploration

Function combinations such as AgriPV are essenitial when creating multifunctional landscapes, and especially in the context of multifunctional carbon mitigation landscape design. In relation to forest development for biological carbon sequestration, and with carbon source removal in mind, an exploration of a function combination between forest development and an AgriPV-like system could be very promising. Synergies between plant growth and photovoltaics are not new, as presented in the previous section. Furthermore, research has been done in synergies between wet ecological succession and PV-panels (de Boer, 2020). Inspired by these examples, and due to lack of existing knowledge on the following concept, research into a synergy between silviculture and renewable energy production is conducted. With such a concept, a piece of land can have both a carbon sequestration function, a carbon source removal function, as well as a productive function for both timber and renewable energy. This way of exploitation would also be economically more interesting than just a production forest. However, apart from timber production, forests serve plenty other roles, which need to be looked into when considering such function combination. This concept has two dimensions: the conceptual dimension and the design dimension. The conceptual dimension encompasses the theoretical basis on the workings of the function combination. The design dimension encompasses spatial expression of such a system in the landscape, its configuration and intended lifetime. The latter also has a strong temporal parameter. The conceptual dimension is discussed in section 5.3.3.1. The design dimension is discussed in section 6.1. The concept will be further referred to as Forestvoltaics, or FV.

Society

Developments of new PV-systems in the landscape are fuel for heated discussions. Local residents often protest against this type of land use with landscape quality rooted arguments (Kruijff & Unen, 2021). More about landscape quality in section 2.2.1. Challenges in public acceptance are linked to citizen integration in the process, about which there does not seem to be consensus. Assessment of public values should help in creating public support for solar panels in the landscape (Pasqualetti, 2011).

2.2. Landscape development

2.2.1. Landscape quality

There has been a call to have landscape quality only be determined through the subjectivistic approach; through the eyes of the beholder (Lothian, 1999; Daniel, 2001). This shows that experience valuation is highly dependent on the observer, which makes it difficult, if not impossible, to quantify. In addition, there is an important difference between the expert/designer valuation of landscape quality and the public perception based valuation. The public perception valuation is based on biophysical landscape elements as stimuli that trigger psychological responses in the observer. Such responses can be direct sensory perception (see, feel, touch, taste, smell) or cognitive perception constructs, such as prospect-refuge. The expert (e.g. trained observers with knowledge of landscape processes, systems and designing) uses its knowledge of landscape and design to break down the biophysical features into design parameters and values the landscape quality based on the assumption that these parameters are universal indicators for landscape quality (Daniels, 2001). Nevertheless, Selman (2010) states that we may be able to learn to love new landscapes, in which narratives of endeavour, solidarity, enterprise, community and purpose are experienceable. He states that the landscape as the object can influence the way the subject experiences that landscape. The landscape then serves as a tool for shaping the subjectivistic approach.

This thesis, with regard to research validity, approaches landscape quality objectivisticly, using Hooimeijer, Kroon & Luttik's (2001) objectivitic model, based on the Vitruvius triplet utilitas, firmitas, venustas. They translate these concepts to respectively user value, experiential value, and future value, thereby operationalising these concepts into design criteria. They further identify economic, societal, ecological and cultural interests as crucial elements in determining landscape quality from differetent societal perspectives, which are used in combination with the design criteria to identify and value aspects of landscape quality (see Table 2). For the operationalisation of the value/interest combinations, the definitions by Hooijmeijer, Kroon & Luttik (2001) are used (see Table 2). The operationalisations of user value and future value are strongly linked to the multifunctional landscape, discussed earlier. However, a multifunctional landscape is not necessarily a landscape with high quality. Therefore, the experience value differentiaties a multifunctional, durable landscape from a landscape with high quality.

Relevant for this thesis is landscape quality for large scale energy landscape transformations. Oudes & Stremke (2020) point out that quality assessment of such landscapes are often limited to experience values, and that little is known about the user value and future value of these landscapes. They find that landscape quality operates on different scale levels. Trade-offs between landscape quality interests are often supported economically, as some decisions are made, changed or rejected due to financial reasons. Although, such trade-offs were not found often (Oudes & Stremke, 2020). Oudes & Stremke further find that governmentally appointed quality teams generally improve landscape quality. In addition, a participatory planning and design process for such landscape transformations increases acceptance of the landscape transformation. This in turn increases the experience value of the landscape.

Another important consideration in the experience value of a landscape is its aesthetic and user perception. An aesthetic experience is the pleasing or displeasing result of a perceived scene or object, where it is debated if the observers history,

Table 2. Landscape quality valuation matrix. The Vitrivius triplet is operationalised into design criteria to value landscape quality. Scores are given for each value/interest combination to determine landscape quality. (Hooijmeijer, Kroon & Luttink (2001)

	Economic interest	Societal interest	Ecological interest	Cultural interest
User value	Allocation efficiency	Access	Safety, disturbance	Liberty of choice
	Accessibility	Division	Pollution	Variety
	External effects	Participation	Desiccation	Encounter
	Multi-purpose	Choice	Fragmentation	
Experience value	Image	Disparity	Space, rest	Uniqueness
	Attractiveness	Connectedness	Beauty	Beauty
		Safety	Health	Contrast
Future value	Stability/flexibility	Inclusion	Stocks	Cultural heritage
	Agglomeration	Cultures of poverty	Ecosystems	Ingration
	Cumulative attraction			Renewal

culture, social class, and personality influences the experience. Enrichment of the landscape is inherent to landscape design and can to a large degree be provided by pleasurable experiences through sensory emersion of the landscape. Since an aesthetic experience is not necessarily a pleasurable one, extra consideration is required on pleasurable experiences in the designing process. (Bell, 1999)

2.2.2. Multifunctional landscape

Brandt & Vejre (2004) distinguish four different interpretations of the term multifunctional landscape: [1] as an expression of the many different functions of the combination and unity of natural ecological systems; [2] as society's material-sociological links between different types of land uses; [3] as the policy-scene for mutually inclusive or exclusive land uses; and [4] culturally, as a theatre for aesthetics, social communication, conflicts, and cultural interpretation, primarily based on landscape architectural traditions. The first interpretation accords with afforestation efforts for carbon sink enhancement, by which the natural processes result in removal of atmospheric carbon. However, in a country where every square metre has at least one owner and often multiple actors, a truly multifunctional landscape cannot be defined through natural processes alone, and needs its social and societal counterparts. Oudes & Stremke (2021) refer to landscape multifunctionality as "the capacity of a certain area of land to serve mulitple purposes and fulfill several needs at the same time" (p.2). They further specify different types of solar power landscape multifunctionalities, which are relevant in light of the forestvoltaic concept. These types are array multifunctionality (beneath arrays), patch multifunctionality (on the patch area in between arrays) and adjacent multifunctionality (in between or next to patches). These multifunctionalities are operationalized by using the number of functions on a surface area as an indicator. The first two types encourage interactivity between different functions (e.g. by usage of the shade cast by the PV-arrays), and thus demonstrate potential for synergies between landscape functions.

3. Methods

The research methods are distinguished in two phases, which partly overlap. The first phase is identified as 'research for design' (RFD). The knowledge gained from this research informs the designing phase, but does not yet entail the practice of designing itself. Answering the knowledge questions prepares for the designing phase as it yields informed considerations and some design decisions for model development. The results from the first phase are applied in the second phase, the RTD phase, where the designing process itself is the research method (Lenzholzer et al., 2013; Lenzholzer, Duchhart, & Koh, 2013). It is iteratively processed and tested in different models, to result in a master plan design (see Figure 6 on page 25).

Both the knowledge questions and the design questions guide in finding an answer to the main research question. An overview of the research questions and the accompanying methods is shown in Table 3.

3.1. RFD

First, the knowledge required to answer the knowledge questions will be obtained through literature study. For the first knowledge question

> *Which forest types contribute most effectively to carbon sequestration and storage?*

and its sub-questions (see Table 3), the focus of the literature study will be on forest carbon cycles and carbon sequestration by tree species and forest soils, and the impact of change in land use on carbon sequestration.

The expected outcome is knowledge on carbon seqeustration rates for various tree species. It is expected that this data can be used to compare sequestration rates between both various existing forest compositions, and spatial composition of new forests. For the second knowledge question:

> *How is nature quality ensured in a new carbon mitigation forest?*

and its sub-questions literature is studied concerning nature development, the meaning and role of biodiversity to landscape processes, and differences in biodiversity in different landscape types. This is done in order to gain the proper knowledge on how to include and increase the role of the natural landscape in the new climate forest design. The third knowledge question:

> *How does a carbon mitigation forest landscape affect forest-oriented human activites?*

and its sub-questions are answered by inventorizing various activities that depend on forests, that are stongly linked to forests or can be present in forests. Whereas the second knowledge question lays the foundation for a multifunctional landscape in terms of natural processes, answering this question forms a crucial baseline for the human aspect of the multifunctional landscape, with a variety of land uses and landscape users.

3.2. RTD

This research does not solely result in objective quantifiable knowledge, but does intent to find somewhat generalizable principles, in reaction to relevant and contemporary landscape transitions. Hence, this research will be conducted through a pragmatic RTD process (Lenzholzer, 2013). The new design knowledge is represented as design principles or design principles, established through an iterative designing process in which different designs are tested and evaluated according to initially defined criteria. The used criteria take high consideration of objectivity, validity, reliability and generalizability (Lenzholzer et al., 2013). Generalizable design principles serve as a tool to inform design practice, as easily applicable, pre-processed scientific knowledge that can be applied in different contexts (Klemm, 2018). These generalizable principles are tested at one testbed location, which means that in order to apply them elsewhere, adaptations are often necessary (Lenzholzer et al., 2013).

Location

The testbed location of the RTD case is determined by several criteria and is chosen in the Netherlands, due to its land-use density, the topicality of afforestation and also the availability of travel options during covid-19 restrictions within national borders. The main emphasis of the location selection is that the location serves as a testing ground for iterative climate forest design, rather than an exploration of possible futures for the chosen area. Therefore, the location is selected through a multi-criteria analysis.

Several primary criteria were established: the location had to be losing its current function within the coming years, the climate potential had to be significant, as well as the natural potential and the potential multifunctionality of the landscape. Potential locations that resulted from this criterium were, among others, airfields, farm plots and wastelands. Airfields were chosen to continue with, from personal interest in aviation, as well as the large areas that they cover, which has a larger absolute climate potential, contributing more to the Dutch 100.000 hectares of forest plan than other areas. It is expected that at least some of the design principles that result from this area are also applicable to smaller scale areas. Although the total area of farm plots that are losing their function is large, the exact areas are very

Table 3. Methods per research question. Sub-questions are defined for each knowledge question in order to get to an answer. Various methods are presented and used to be able to answer the knowledge questions. Additionally, expected data and the expected outcome are presented for each knowledge question.

Research question	Sub-questions	Method	Data	Expected outcome
Main research question				
Can the landscape of airbase Deelen provide design prinicples for designing multifunctional carbon mitigation forest landscapes on dry, sandy soils?				
Knowledge questions				
Which forest types contribute most effectively to carbon sequestration and storage?	Which forest types have the highest carbon sequestration rate and carbon storage capacity? What forest conditions are beneficial for increasing carbon sequestration?	Literature study	Forest carbon cycle and biological carbon sequestration literature. Expert consultancy	Forest typologies for optimal C-sequestration. Conditions for optimal C-sequestration
How is nature quality ensured in a new carbon mitigation forest?	What defines nature quality in forests? How is biodiversity optimized in an afforested landscape?	Literature study	Forest succession and biodiversity of various landscapes	Forest typologies with high biodiversity potential Forest typologies with suitable conditions for red list species
How does a carbon mitigation forest landscape affect forest-oriented human activites?	Which human activities are dependent on or strongly linked to forests? How does deforestation affect the forest ecosystem? Do renewable energy production or storage alternatives provide beneficial conditions for forest growth or carbon sequestration?	Inventorize and analyse forest dependent human activities.	Map analysis. Study into human-forest synergies.	Forest dependent recreation activities Forest dependent production activities
Design questions				
Does designing the landscape of airbase Deelen provide principles for synergies between a carbon sequestration forest and renewable energy production and storage methods?		Research through designing	Informed by knowledge questions, drawings, peer discussions	Landscape design with focus on carbon sink enhancement and carbon source removal.
Does designing the landscape of airbase Deelen provide principles for synergies between for a carbon mitigation forest, nature and recreation?		Research through designing	Informed by knowledge questions, drawings, peer discussions	

difficult to locate, as one does not know exactly which farmers are going out of business within the next decades. Wastelands are rejected due to the many design limitations they entail, caused by health and safety regulations of these areas, limiting the multifunctional potential of the landscape design.

For the site selection, several airfields in the Netherlands that are losing their current function, or have recently lost their current function are found: Military Airbase Valkenburg (Katwijk), Military Airbase Soesterberg, Den Helder Airport and Military Airbase Deelen (near Arnhem) (Gordijn et al., 2005). Another multi-criteria analysis is executed to choose the most suitable location for this research. Airbase Soesterberg is not considered in this analysis, as its use has already been redefined in the last couple of years (hosting a military museum and a landscape park). Following from the multi-criteria analysis, airbase Deelen was chosen as the testbed location for this research. This result also set the direction of the research towards high, dry sandy soils. In addition to the suitability of the landscape, airport Deelen is now under review by the municipality (Sven Stremke, 2020, personal communication) for its next function. Hence, now is the time to act on this large area, so this research can serve as a starting point for the municipality on climate forest design in the test area itself. Consequently, this landscape can contribute to the 37.000 hectares of new forest, and move further towards carbon neutrality. The site is further analyzed in chapter 4 starting on page 34).

Design questions
The RTD part of this thesis is guided by the following design questions:

> *Does designing the landscape of airbase Deelen provide guidelines guidelines for synergies between a carbon sequestration forest and renewable energy production and storage methods?*

This question guides the designing process in search for mutually beneficial function combinations between carbon mitigation forests and renewable energy production using photovoltaic (PV) panels.

> *Does designing the landscape of airbase Deelen provide guidelines for synergies between a carbon mitigation forest, nature and recreation?*

This question guides the designing process in search for mutually beneficial function combinations between carbon mitigation forests, biodiversity and recreational activities. Both design questions also influence each other, as both carbon sequestration and renewable energy production are part of a carbon mitigation landscape.

Design evaluation
The model development is evaluated through several criteria: carbon sequestration rate, energy production and landscape quality. Landscape quality is operationalised through the criteria user value, experience value and future value (see section 2.2.1). This valuation makes sure that results from all knowledge questions find their way to the landscape design.

The landscape design evaluation is conducted against two other models: maximizing carbon sequestration and maximizing carbon source removal, i.e. a model that maximizes forest coverage and a model that maximizes PV-panel coverage. These models are chosen as they represent the binary attitude towards creating energy landscapes (as most PV-parks have been in the past years) and reforestation. It is expected that these models score high on their respective targets (carbon sequestration and energy production) but very low on the other valuation criteria. The landscape design searches for arguments for multifunctionality in a qualitative landscape.

3.3. Materials

Materials for the research will consist mostly of peer reviewed scientific literature (predominantly journal papers and books), spatial (GIS) data on various scales, the designing process (see chapter 6 starting on page 58) and grey litareture. See Table 3 for an overview of the usage of the data for each research question.

3.4. Validity and reliability

The position of the designer executing the RTD process is undoubtedly subject to bias, since the creative, iterative RTD process relies on the design experience, conceptual capabilities and a multitude of other skills (such as graphical translation and representation) and experiences of the researcher. Therefore, extra validation techniques are applied in this research, such as consultancy with forestry experts and thesis supervisors, peer briefing and discussion sessions with other thesis students, and project reviews for inspiration on contents and visualisations. Reliability of the designing process is strengthened by the RFD part (Lenzholzer, Duchhart & Koh, 2013), as well as the valuation of the design.

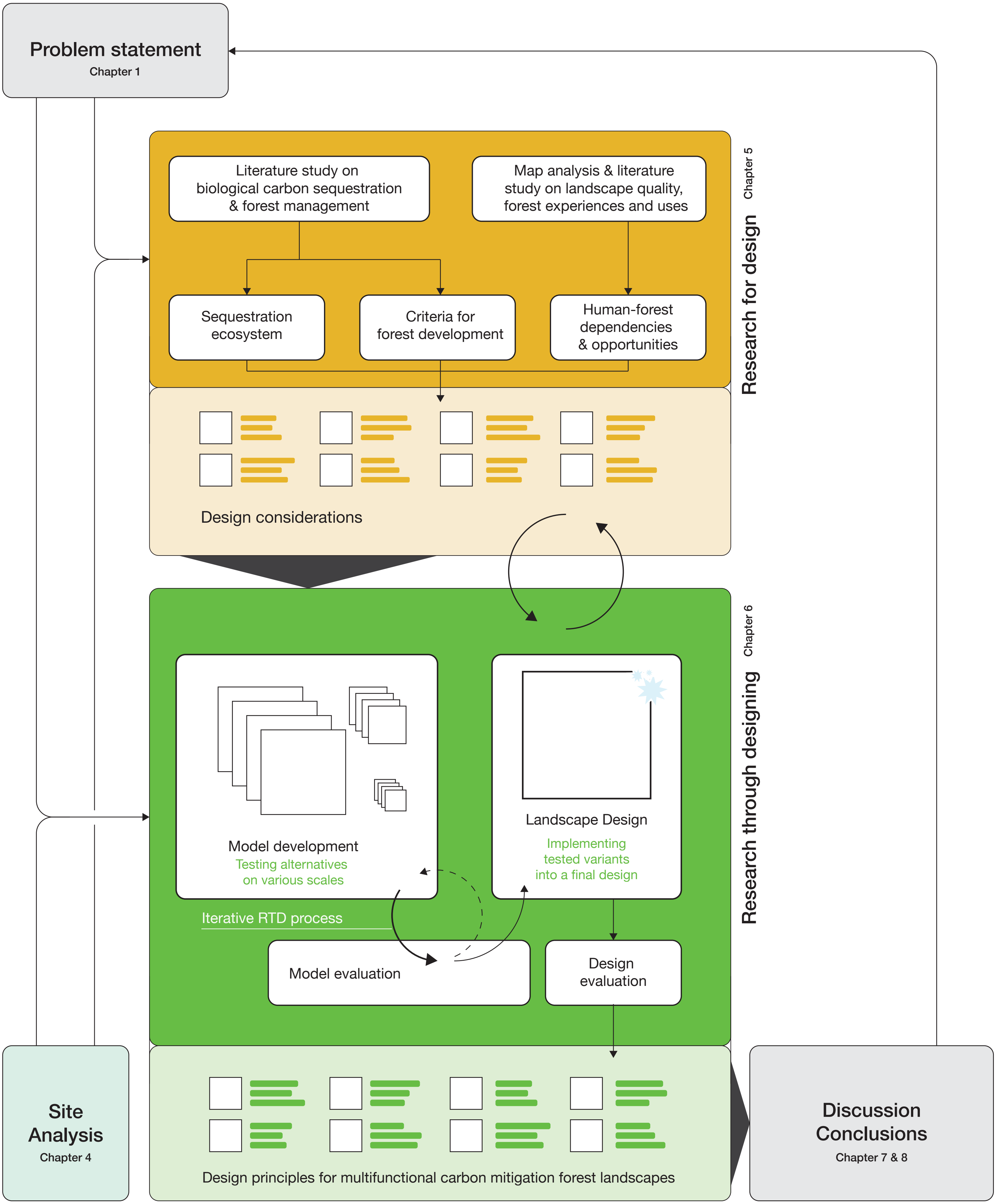


Figure 6. Research design flowchart. The problem statement and the site analysis feed into the RFD part (yellow), in which design consideratinos for the RTD part are developed (green). The circular arrows between the RFD and the RTD parts indicate the iterative process of researching and designing. The RTD part yields design principles, atfter which the thesis is concluded.

Figure 7. Eastern border of the airfield. facing South. The vastness and openness shows the aesthetic quality of the landscape.

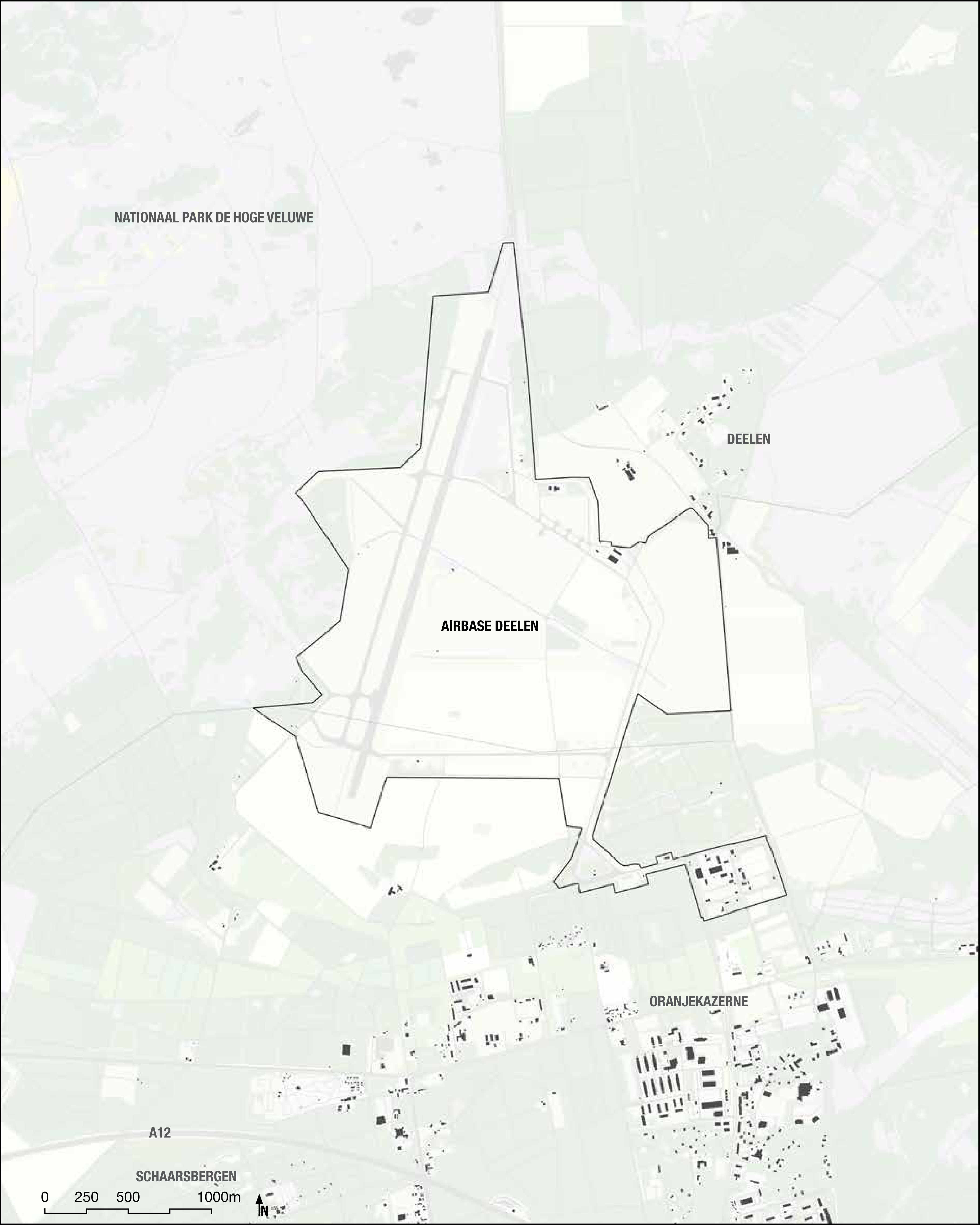
Figure 8. Northern border of the airfield, facing South. Vegetation changes along with the elevation. A unique 4km view to the forest edge South of the airfield exe

emplifies the vastness and scale of the landscape.

Figure 9. Southern approach towards the airfield through forested areas and open pockets makes for a varied landscape experience.

Figure 10. Southern border of the airfield, facing North. ‘No entry’ signs placed even at longer distances from the fence to keep people clear from the area.

Figure 11. Location of the airbase


NATIONAAL PARK DE HOGE VELUWE
DEELEN
AIRBASE DEELEN
ORANJEKAZERNE
A12
SCHAARSBERGEN
0 250 500 1000m
N

4. Site analysis

This chapter describes the analysis of the landscape of airbase Deelen, in order to set a baseline understanding of the landscape. This is crucial for the landscape designing phase. First, the situation and context of the landscape are inventorized and analysed, resulting in predominantly general conclusions, or, non-specified to a particular theme. Then, this information is used for drawing conclusions on finding potentials and challenges of the landscape, specified to a multifunctional carbon mitigation forest landscape.

4.1. Landscape

The Deelen airfield landscape is located on the Veluwe, one of the moraines in the Netherlands. It is characterized as a forested area with heather fields and drift sand dunes. The airfield area is quite unique in its context. Not necessarily in its openness and vastness, but rather in its lack of height differences, the vegetation and the way the landscape is managed. The lack of height differences is worth pointing out, but also explains the location choice of the airfield. The landscape analysis is divided into two parts: the Earth part, consisting of the natural layers and systems of the landscapes; and the Society part, consisting of the societal layers, how people use and move through the landsape.

4.1.1. Natural domain

Different tree species have different preferences, with regard to soil types, soil acidity, the hydrological situation and in relation to other species in terms of ecological competition. It is demonstrated that a healthy, well growing forest is a prerequisite for proper carbon sequestration through afforestation (see section 5.1 starting on page 48). Therefore, the landscape characterizations mentioned before are important in designing carbon mitigation landscapes.

4.1.1.1. Geomorphology

Airbase Deelen is located on top of the Veluwe moraine, which was formed by glaciers during the Saale glaciation. The soils on the airbase are predominantly identified as humus podzols and brown forest soils. Humus podzols are formed through physical and chemical soil processes that lead to downwash, movement and precipitation of soil organic compounds, iron an aluminium. They are characterized as chemically poor, acidic soils. Brown forest soils contain a humus layer, which is important in sandy soils, as it has a moisturizing effect, as well as the capacity to bind nutrients that originate from the litter layer. The fertility of these soils is therefore relatively high for dry sandy soils (Jongmans, et al., 2013).

In the surrounding area, some anthropogenic soils are identified, called Enkeerd soils. These soils are created in the Middle Ages, through long-term turfing and fertilization of the soils, in order to create more fertile soils for cultivation. These soils are therefore very fertile. The drift-sand soils to the North and Northwest are identified as Duinvaag soils, Relatively homogenous soils (pdok, n.d.; Jongmans, et al., 2013). Geomorphologically, this area is exemplary for moraine landscapes. These landscapes are present in other parts of the Netherlands (Utrechtse Heuvelrug, Sallandse Heuvelrug), as well as in western parts of Germany.

The lack of height difference and relief at the airfield is magnified by the height differences in the surrounding area. The area itself is already quite flat, and although the sources describing the development of the airbase (Peters, 1996; MijnGelderland, n.d.; 75 jaar vrijheid, 2018) do not mention major groundwork changes, elevation map reveals the lack of relief compared to its surroundings, which may suggest that the area was further egalized when the airbase was built (see Figure 14).

4.1.1.2. Hydrology

A moraine is a water infiltration landscape with low groundwater tables. Elevation maps show traces of old stream valleys running predominanyly South of the airbase, going furthers Southwest. At the Veluwe, dessication concerns are raised (Schuttenhelm, 2020), and strengthened by climate change, which causes hotter and drier summers. Paired with too high nitrogen levels, it causes acidification of the soils, as well as mineral shortage and nitrogen surplus in deciduous trees (especially oak trees), impacting the entire food chain (Schuttenhelm, 2021). Furthermore, downstream reduction of water availability due to forest afforestation is warned for (Bentley & Coomes, 2020). With regard to water interception, little impact as a result from afforestation is expected, as it is already a very forested area (Nabuurs, personal communication, 14 December, 2020).

4.1.1.3. Ecology

Typical vegetation types in the moraine landscape and around the airbase are mixed forests, evergreen forests, heather and pioneer species on the sand drifts. Mixed forests consist of evergreen trees and deciduous trees. This is often a further developed succession stage, in which *Fagus sylvatica* and *Quercus robur* are slowly taking over dominance from *Pinus sylvestris* and *Betula pendula*. Dry pinus forests are dominated

Figure 12. Elevation map of the testbed area (outlined)

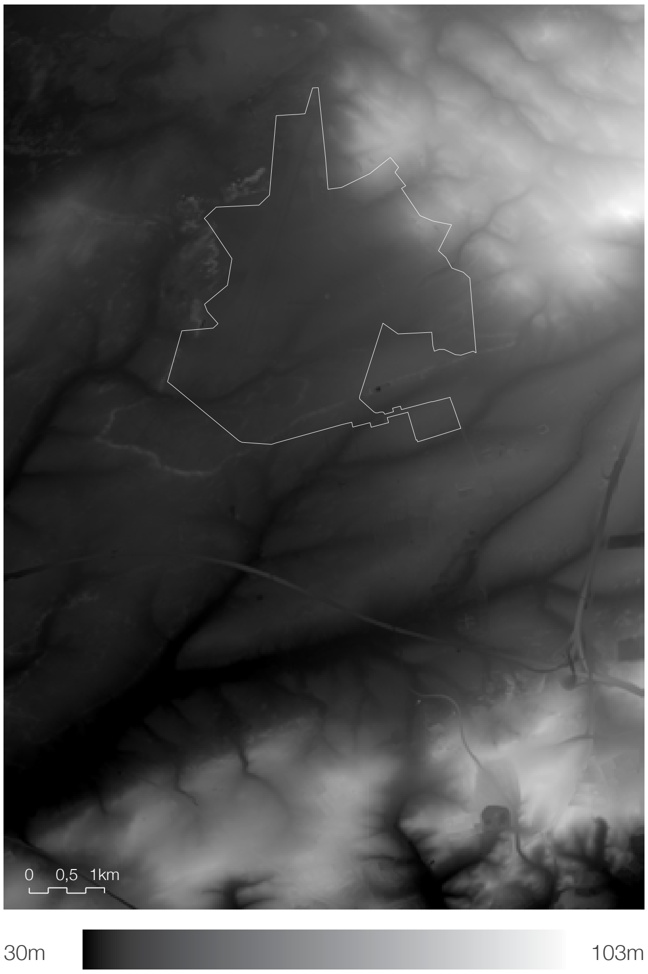


Figure 13. Nature networks in and around the testbed area (outlined)

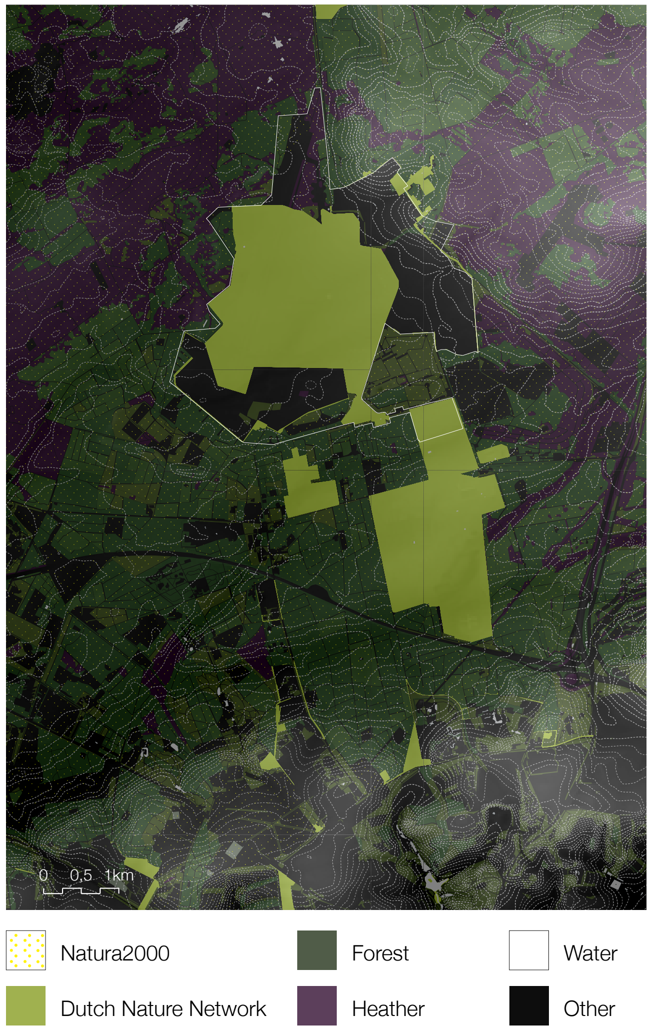


Figure 14. Geomorphology of the airbase. Old brooks are clearly visible. Testbed area outlined

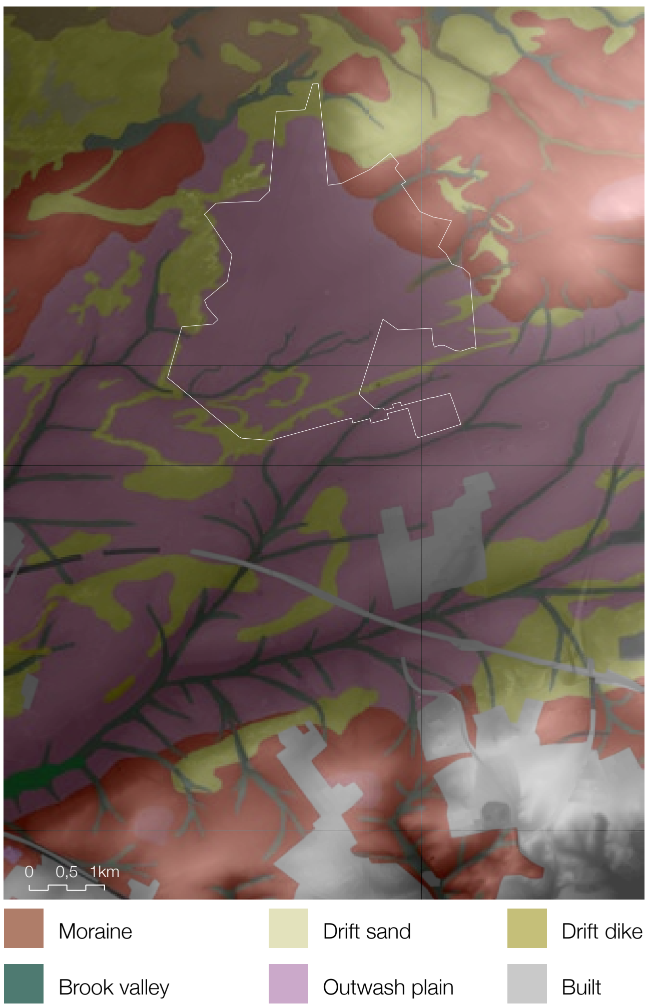
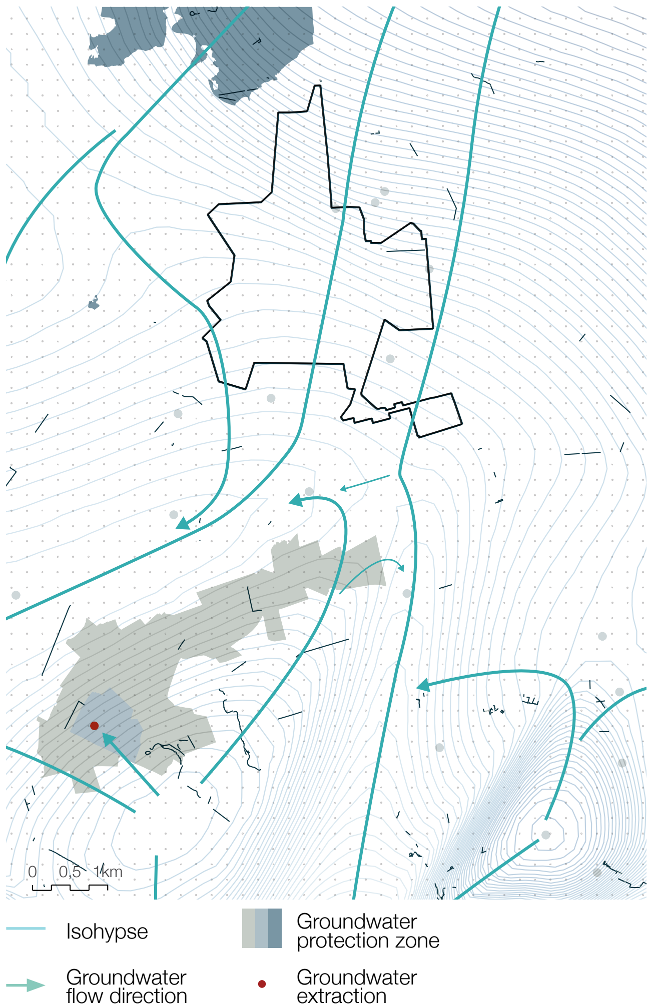


Figure 15. Groundwater system around the airbase (outlined)



by grasses and mosses (*Corynephorus canescens, Festuca ovina, Cladina portentosa, C. arbuscula, Cladonia coccifera*). In more mature parts, blueberries (*Vaccinium myrtillus*) and redberries (*V. vitis-idaea*) are present as well, and undergrowth of *Fagus sylvatica* is increasing. On the podzol soils, mycorrhiza fungi live in symbiosis with *Betula pendula* and *Pinus sylvestris*. Many other fungi are present as well in the late symmer and autumn (*Leccinum scabrum, Amanita muscaria, Lactarius rufus, Suillus bovinus*). In mixed forests and deciduous forests, undergrowth consists predominantly of *Dryopteris dilatata* (a fern) and *Ceratocapnos claviculata*. *Cantharellus cibarius* and *Amanita fulva* are found living in symbiosis with oak roots. Autumn fungi growth is dominated by *Collybia maculata* and *Mycena galopus* (Berendse, 2012).

The dry sandy soils are home to three of the Dutch “big five” animals: the red deer (*Cervus elaphus*), the deer (*Capreolus capreolus*) and the wild boar (*Sus scrofa*). The habitat of these animals is in and around these forests and drift sand landscapes. There is no abundance of birds in the pine forests and mixed forests. In pine forests, *Parus cristatus*, *Fringilla coeleps*, *Phylloscopus trochilus*, *Erithacus rubecula* and few *Turdus merula* find their way. *Regulus regulus* and *Parus ater* are found in older pine forests as well. Beech forests are a much more attractive habitat for many birds, with presence of *Sylvia atricapilla*, *Ficedula hypoleuca*, *Columba oenas*, *Parus palustris*, *Sitta europaea*, *Certhia brachydactyla*, *Dendrocopos major* and *Dryocopus martinus*. Owls (*Strix aluco*) nests in woodpecker holes, so do bats (*Nyctalus noctula*).

4.1.2. Social domain

4.1.2.1. Context

Airbase Deelen is named after and located to the Southeast of the small township Deelen, located approximately 6.5 kilometres north of Arnhem. The township counts 60 habitants at the start of 2020 (Allecijfers.nl, 2020). The Southern third of the area is part of the municipality of Arnhem, the northern two thirds, including the township, is part of the municipality of Ede. The current terrain of the airbase covers approximately 645 hectares in area and is in use by the National Army for trainings with helicopters, the Air Manouvre Brigade and special forces (Koninklijke Luchtmacht, n.d.). The airbase is therefore closed for public (see Figure 16). Adjacent to the South of the airbase, the ‘Oranjekazerne’ (*Orange military base*) serves as one of two main locations of the Air Manouvre Brigade (Koninklijke Landmacht, n.d.). More aviation activities are found to the East of the airbase, where the glider airfield Terlet is located.

Adjacent to the West of the airbase lies National Park ‘de Hoge Veluwe’. The 5500 ha nature reserve is covered with 3.200 hectares of forest, 2.100 hectares of heather and 60 hectares of drift-sand and hosts a museum, a villa by architect Berlage and several food and drinks establishments. The park attracts hundreds of thousands of visitors anually (500.000 visitors in 2020) and preserves living conditions for over one hundred Red List species (Stichting het Nationale Park de Hoge Veluwe, n.d.). The Park is accessible by paying an entrance fee only.

4.1.2.2. Landscape accessibility

When moving from the city centre of Arnhem (the largest city in close proximity) into the landscape to the North, one moves through a sequence of historic estates (such as Sons-

Figure 16. Signs along the entire perimeter of the airbase “No access, DANGEROUS, guarded by dogs”, make clear visitors are not welcome.

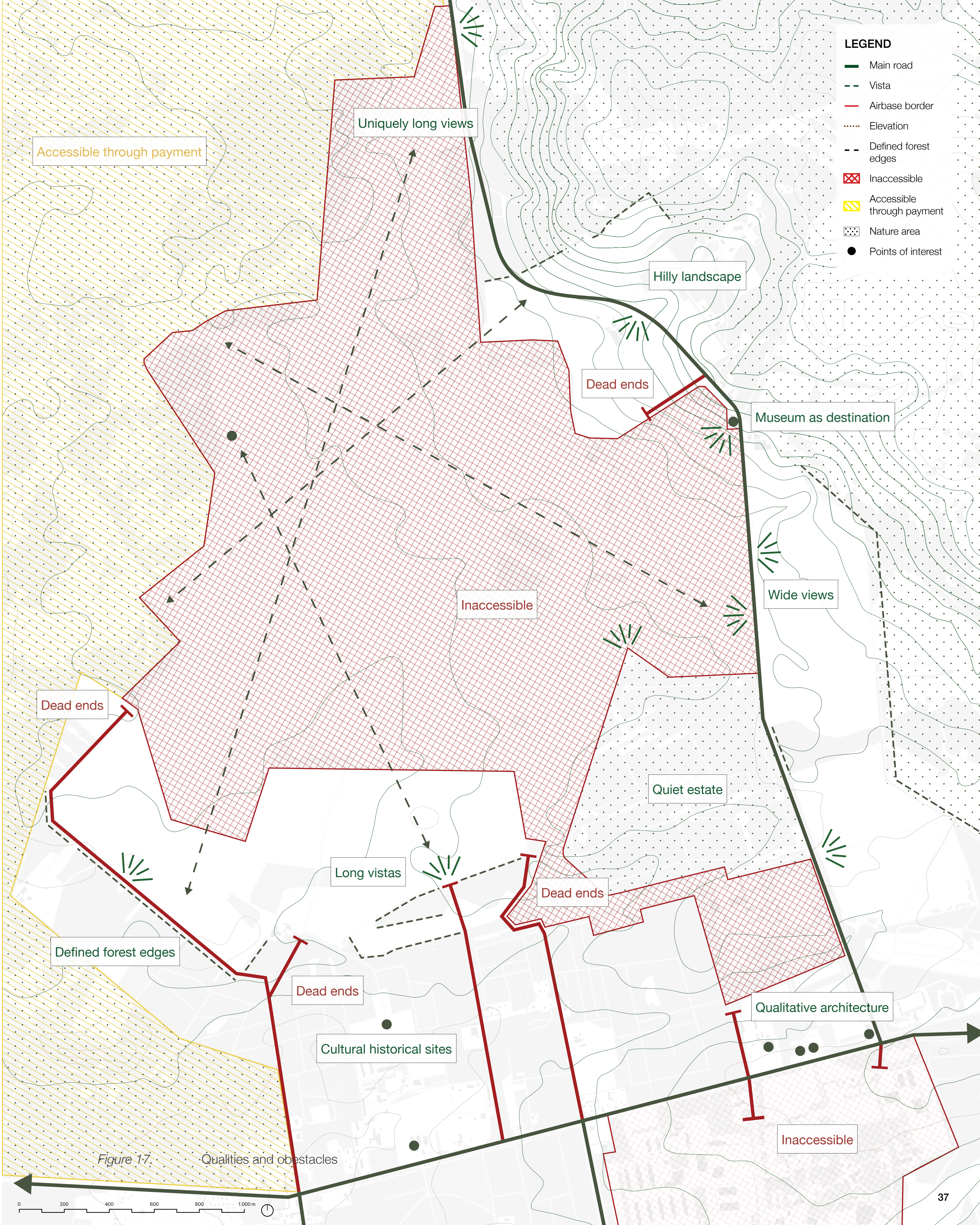


Figure 1-7. Qualities and obstacles

beek, Zypendaal, Groot Warnsborn, Schaarsbergen), which is a great recipe for interesting, experiential recreational routes with cultural value. These landscape style estates are part of an area nicknamed 'Gelders Arcadië' (Visit Arnhem, 2021). The Gelders Arcadië spans from the village of Rheden to Wageningen. However, when moving North along the Schaarsbergen estate, there are several landscape barriers (see Figure 11 and Figure 17), the first of which is the highway A12. Although several bridges and tunnels provide access across, the estate is cut into two. One that finds its way North of Schaarsbergen enters an old production forest landscape, and soon sumbles upon the second major barrier: the airbase, or, to the west, the semi-permeable barrier of the paid entrance of the National Park (see Figure 17). The zone North of Arnhem is therefore a fragmented, illegible area. It is an area where one does not need to go. An area where one must find a way through to reach the Veluwe, instead of the area being a part of the Veluwe (Jong & Seumeren, 2017).

4.1.2.3. Recreation

As the airbase itself is completely closed for public (see Figure 16 on page 36), there are no recreational values to find there at this time. Planned recreational routes around the airbase are limited to a few walking routes and some bicycle routes. However, the surrounding areas are used a lot in non-planned routes, by runners and cyclists. Then again, the airbase itself is a black spot between the city of Arnhem and the National Park. It is worth noting that several south-north routes coming from Arnhem have to detour around the airfield. This indicates potentials for new routing through the new landscape.

There are some notable destinations surrounding the airbase. Most notable is the National Park 'de Hoge Veluwe'. Three kilometres to the East, across the highway A50, there is another National Park; Veluwezoom, which is freely accessible and includes a visitors centre and some food and drinks establishments. North-east of the airbase, close to the township of Deelen there is a museum about the airfield itself, which focuses strongly on the military history during the second world war. Furthermore, the 'Gelders Arcadië' landscape is a series of landscape destinations around Arnhem. In addition, tourist attractions in Arnhem include Burgers' Zoo, the Dutch Open Air Museum, as well as the city centre itself.

4.1.3. Future plans

In the vision document for 2040 of the municipality of Arnhem (Gemeente Arnhem, 2020), the airbase is appointed as an energy landscape. Not much further details are revealed about the area, but this could suggest that the military activities are going to moved elsewhere in the Netherlands. With highly valued landscapes to the East and West of Arnhem, the lack of permeability to the North is noteworthy, and there are opportunities for change and creating more destinations to the North once the military activites find a new place.

4.2. Carbon sequestration potentials

This section looks into the carbon sequestration potentials of the landscapes. It also forms the comparative model that maximizes the carbon sequestration rate. It serves as a check to see what is practically possible in terms of carbon sequestration. It is not intended as a desirable landscape design.

The current land use of the area consists of predominantly heathery grasslands, as well as some agricultural land. The current total carbon sequestration rate is therefore estimated on 305 tCO_2 per year. Afforestation of the entire area can increase the carbon sequestration rate to 2424 tCO_2 per year during the first ten years, and 4795 tCO_2 per year thereafter (see Table 5, Figure 20).

4.3. Energy potentials

This section looks into the energy potentials of the landscapes, and puts it in perspective of existing plans and strategies. It also forms the comparative model that maximizes renewable electricity production through PV-systems. It serves as a check to see what is practically possible in terms of electricity production and mirrors itself to many PV-park projects, where reaching practical limits to maximize production are often the target. It is not intended as a desirable landscape design. There are currently no large scale energy production systems at the site. However, concrete plans with regard to renewable electricity production are in development, discussed next.

4.3.1. Regional Energy Strategies

In compliance with the Glasgow Climate Pact targets (see United Nations, 2021), 30 clusters of municipalities are formed throughout the country as Regional Energy Strategy (RES) regions. Governmental bodies, citizens, businesses, utiliy managers and societal organizations are enabled to investigate suitable locations for sustainable electricity production through wind and solar electricity production. The National Program RES has a facilitating role in these processes for developing sustainable energy systems (Nationaal Programma Regionale Energiestrategie, n.d.b). The national target is to achieve 35 Tera Watthours (TWh) of renewable electricity production on land in 2030. This is a target in addition to electricity production from wind turbines on sea, which on itself will not suffice for the Climate Agreement (Nationaal Programma Regionale Energiestrategie, n.d.a). Each RES-region formulates a substantiated bid to commit to the national 35TWh target, presented in RES-reports.

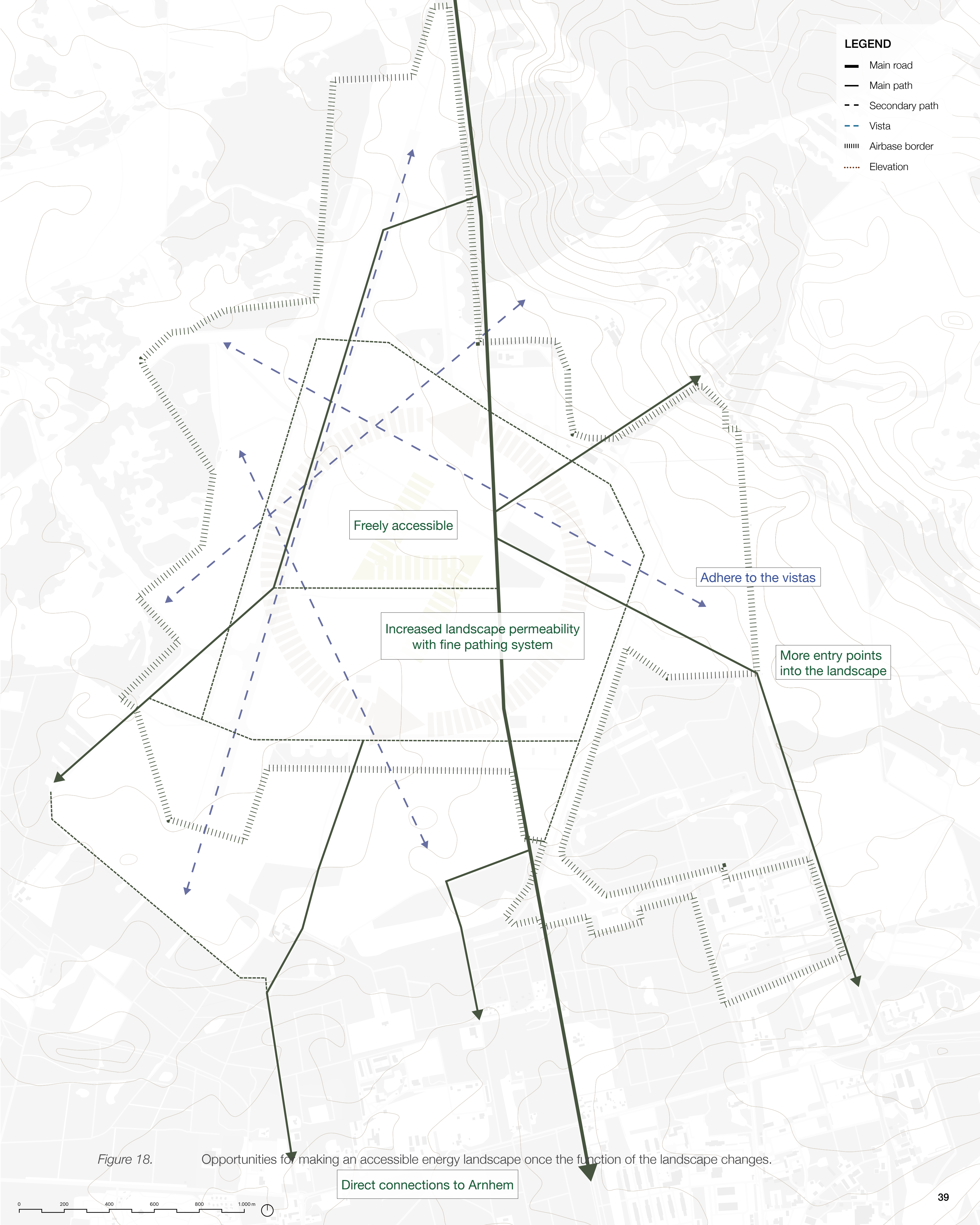


Figure 18. Opportunities for making an accessible energy landscape once the function of the landscape changes.

The airbase is spans its borders across municipal borders (Ede and Arnhem). These municipalities are part of a different RES-region. The municipality of Arnhem is part of the RES-region Arnhem-Nijmegen, whereas the municipality of Ede is part of the RES-area Foodvalley. The energy targets of both RES-region are discussed briefly.

4.3.1.1. RES-region Foodvalley

The bid for RES-region Foodvalley is 0,75 TWh, of which 0,17 TWh has been realised or is in the pipeline. This region expects to yield 0,21 TWh from PV-systems on rooftops, 0,26 TWh from PV-systems on land and 0,25 TWh from wind turbines (and the remaining 0,03 TWh from 'other' PV-systems) (RES Foodvalley, 2021). For the municipality of Ede, the development of larger solar parks is left to non-governmental initiatives. Airbase Deelen is appointed as a 'yes, provided that...' area for medium sized solar parks, and 'no, unless...' area for large solar parks, with regard to willingness of development (Gemeente Ede, 2020). Furthermore, RES Foodvalley (2021) prioritizes function combinations with PV-systems above regular field systems. In this bid, the area of the airbase is excluded in the search for wind turbines.

4.3.1.2. RES-region Arnhem-Nijmegen

The bid for RES-region Arnhem-Nijmegen is 1,62 TWh, of which 0,12 TWh has already been realised (as of february 2021). This region expects 0,49TWh from solar panels on rooftops. The remaining 1,13 TWh has to come from wind turbines and solar parks in a 11-89% ratio respectively (RES Regio Arnhem Nijmegen, 2021). The part of Airbase Deelen in this region is appointed as search area for a solar park, not for wind turbines.

4.3.2. Solar landscape

Turning the landscape into a solar landscape, aiming for maximizing electricity production, it is estimated that 347 hectares of the area can be covered with PV-systems. This would be the largest solar power plant in size and power output in the Netherlands (Essent, 2020; Wikipedia, 2021) (see Table 4).

Table 4. Electricity maximisation, covering the entire airbase with PV-systems, in 2021 and 2050. Technological advances for 2050 are based on current prospects (see section 2.1.7.1). System kWp = Area (m^2) * PV-efficiency * Coverage (EU Science Hub, 2021).

Year	2021	2050
Technology	c-Si	Perovskite, c-Si tandem
PV-efficiency	22%	36%
Wp-factor Netherlands (Essent, 2019)	0.88	0.88
Area covered (ha)	347	347
Coverage	50% South oriented	50% South oriented
System kWp	381,700	624,600
Electricity Production (TWh/y)	0.335	0.550
Households (average Dutch concumption per year)	~ 93.300	~ 152.600
% households of Arnhem	116%	190%

Table 5. Carbon sequestration maximisation when transforming the entire airbase (excluding existing forests and buildings) into a mixed forest. Superscripted numbers,1: Boosten et al., 2020, 2: Farage, et al., 2010, 3: Lal, 2008, 4: Yang et al., 2019.

Land cover	Carbon sequestration rate (Mg C ha^{-1}y^{-1})	Coverage (ha, 2021)	Sequestration (Mg C, 2021)	Coverage (ha, 2030)	Sequestration (Mg C, 2030)	Coverage (ha, 2050)	Sequestration (Mg C, 2050)
Mixed forest	4.6 in the first decade, then 9.1[1]	0	0	527	2424	527	4796
Heathery grassland	1.1[3, 4]	186	205	0	0	0	0
Cropland	0.4[3]	137	55	0	0	0	0
Heather	1.5[2]	32	47	0	0	0	0
Total		355	306	527	2424	527	4796

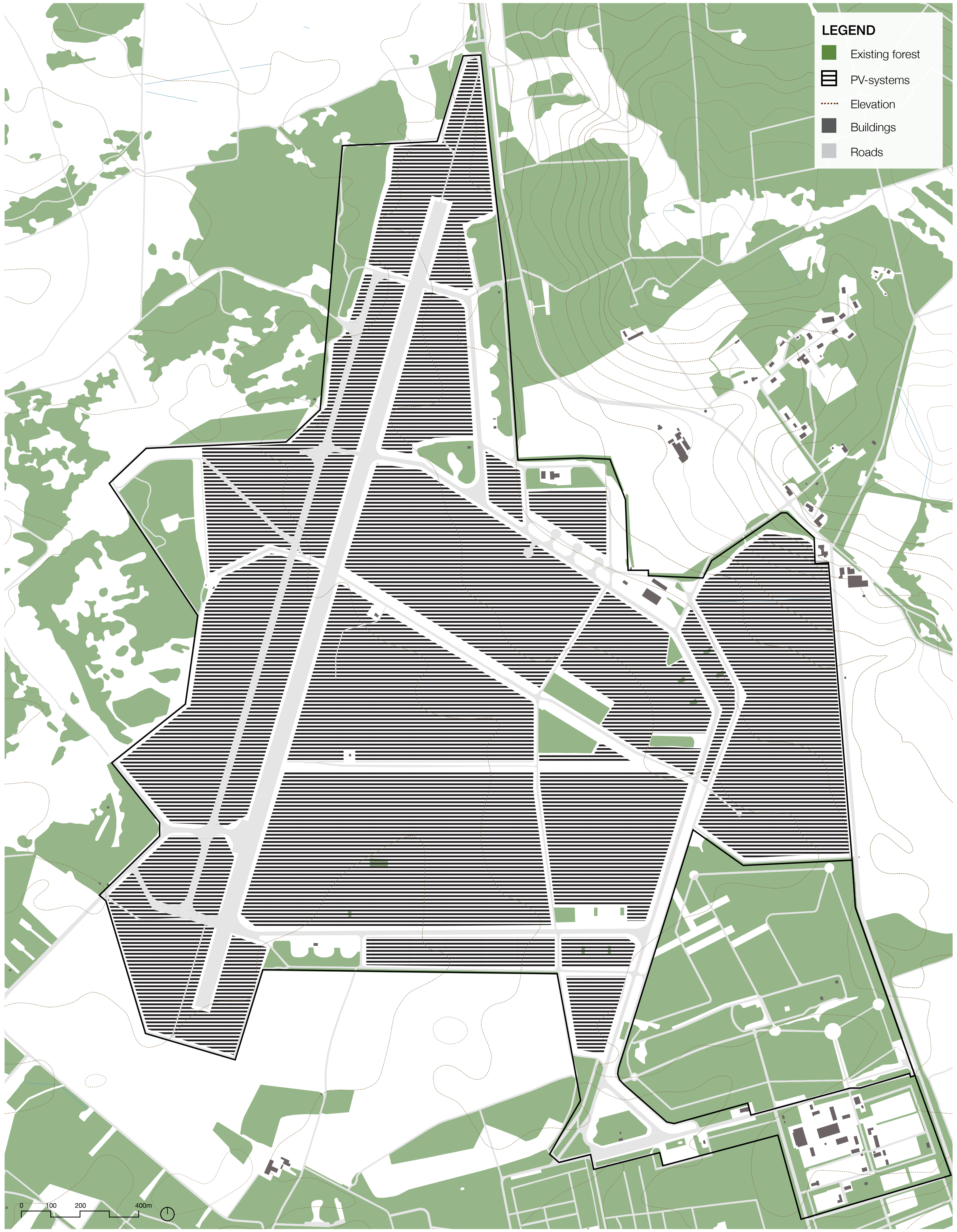


Figure 19. Visual representation of the monofunctional energy maximisation model, approached pragmatically, as all concrete is kept for easy access across the whole airfield landscape for maintenance purposes to the PV-systems. Approximately 347 hectares of PV can be placed in this model

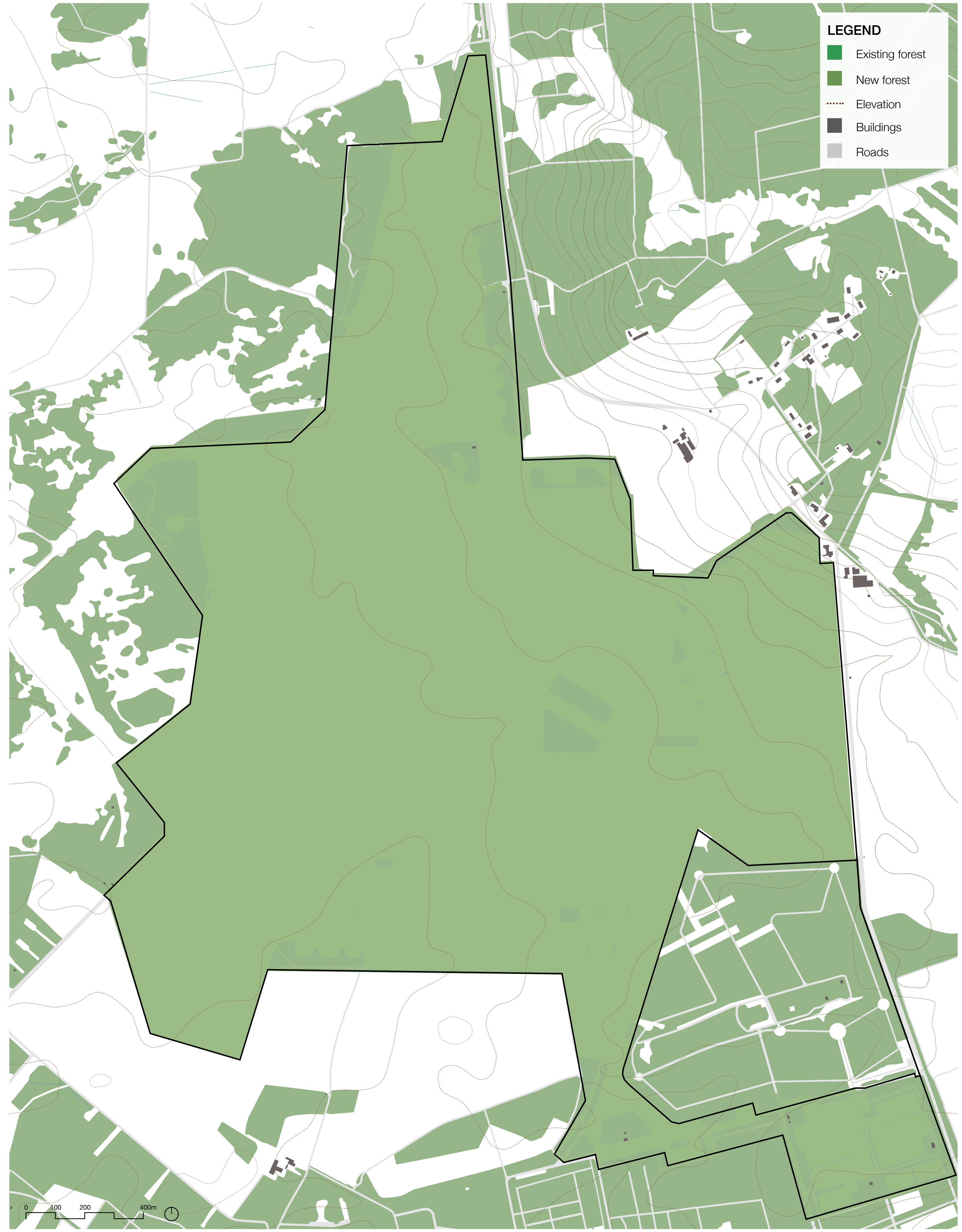


Figure 20. Visual representation of the monofunctional carbon sequestration maximisation model. The entire landscape is transformed into a new forest landscape. This model contains approximately 527 hectares of new forest development.

Figure 21. Northeastern border of the airfield. At a higher elevation than the airfield, there is a top-down view on the airfield, revealing a layered landscape


with patches of land grown with trees.

Figure 22. Southern border. View over the former taxiways for the aircraft. The rigidity and harshness of the airfield elements are contrasted by the patches

s in between that are overgrown with trees.

Figure 23. The landscape South of the airfield shows similar characteristics in its kilometre long views and its openness, but is clearly dominated by agricu


ultural practices.

5. Research for design

This section provides answers to the knowledge questions (as stated in Table 3, reiterated in the sections below). Its answers are used in the form of design considerations, which are applied in the RTD part of this research (see chapter 6 starting on page 58).

5.1. Knowledge question 1: Which forest types contribute most effectively to carbon sequestration and storage?

This knowledge question is answered through answering the sub-questions (see Table 3). Conclusions are drawn in section 5.4, where they are translated into design considerations.

5.1.1. Sub-research question 1.1: Which forest types have the highest carbon sequestration rate and carbon storage capacity.

In order to find out which forest types generally have higher CO_2-sequestration, various forest types are distinguished and their components extracted into smaller parts with quantifiable carbon sequestration rates. European forests are classified in 14 categories, with a total of 72 identified forest types (see Annex A). These categories and types are differentiated along the following indicators: naturalness, number of forest occurring spedies, growing stock, age/diameter distribution and deadwood amount (European Environment Agency, 2007). Nine of these 72 forest types are found to be present in the Netherlands (Barbati et al., 2014; European Environment Agency, 2007; van der Sluis et al., 2019). The ashwood and oak-ash forest type (see Annex A) is found to be able to grow in the Netherlands, but has probably been cut to make room for agricultural practices (European Environment Agency, 2007). Forests that are suitable for growth on humus podzols and brown forest soils are further specified, as these soils are prominently present in the study area (Table 6). Recurring tree species that are naturally present in these forests are *Quercus robur, Quercus petrea, Fagus Sylvatica* and *Pinus sylvestris.* It is therefore no surprise these are native species. These species are further analyzed in order to find carbon sequestration rates. Other tree species are also added in this research, since this thesis studies ways in which the carbon sequestration rates of new forests can be maximized. Therefore, it is necessary to think beyond naturally occuring forest types and include non-native species. Among the studied species, *Pseudotsuga menziesii, Fagus sylvatica* and *Fraxinus excelsior* are relatively high carbon sequesters (see Table 7 on page 50). These species are therefore logical to start reasoning from when designing new forests that focus strongly on carbon sequestration. However, *Picea abies, Quercus, Acer, Alnus* and *Pinus nigra* are running up. With the first baseline principle in mind, and taking into account forest compositions (see Table 6), these tree species are to be taken into consideration as well to be used in carbon mitigation forests.

The carbon sequestration rates of afforested areas range between 2.6 and 4.6 Mg C $ha^{-1}y^{-1}$ (Mega grams (tonnes) per hectare per year) for young stands (Vesterdal et al., 2007; Boosten et al., 2020). Older stands' sequestration rates are around 9.1 Mg C $ha^{-1}y^{-1}$ (Boosten et al., 2020). Afforestation on nutrient-poor sandy soils have shown to result in higher carbon sequestration rates in forest floors compared to nutrient-rich clayey soils. For calculations later in this research, a sequestration rate of 4.6 Mg C $ha^{-1}y^{-1}$ is used for forests up to 10 years after planting. For forests older than 10 years, a sequestration rate of 9.1 C $ha^{-1}y^{-1}$ is used. Pre-forest conditions (see Chapter 4) are also relevant with regard to afforestation with carbon sequestration as main purpose. Not all forest types will increase carbon sequestration, depending on the current land-use and the forest type to which the landscape is transformed (Friggens et al., 2020).

5.1.2. Sub-research question 1.2: What forest conditions are beneficial for increasing carbon sequestration?

Lerink et al (2020) identify some principles to maximize biological CO_2-sequestration through afforestation: [1] Develop healthy, well-growing forests. The principle of carbon sequestration is nested in carbon assimilation for plant growth. The primary condition for good carbon sequestration is therefore a forest with good growth conditions. These conditions are dependent on the forest type, and therefore dependent on the soil and climate conditions of the forest. However, generally, high biodiversity helps to keep keeping forests healthy (Den Ouden et al., 2011). This topic is further developed in section 5.2.

[2] Extend sequestrated carbon storage time for as long as possible. Biological carbon sequestration does not occur in the same rate throughout the lifetime of a plant or tree. Rather, there is an optimum curve for the sequestration rate, linked to the growth rate. These curves vary for different tree species. Generally, young trees have a lower sequestration rate, much optimal sequestration rates happen around 50-60 years, after which the sequestration rate declined (see Figure 25 on page 52). The longer trees live, the more carbon can be assimilated. The stored carbon thereby increases. Natural forests reach a sequestration/emission equilibrium after some time (Lerink et al., 2020). Biomass removal (wood harvest) can therefore increase the sequestration rate, while yielding usable products.

Table 6. Dominant tree and undergrowth species per forest type that prevails on European humus podzols and/or brown forest soils (European Environmental Agency, 2007).

Forest type (dry sandy soils)	Prevailing tree species (Netherlands)	Notes
2.2. Nemoral Scots pine-birch forest	*Pinus sylvestris spp sylvestris* On most fertile soils: *Fraxinus excelsior* *Ulmus glabra* *Tilia cordata* *Quercus robur* On poor soils: Boreal conifers	
4.1. Acidophilous oakwood	*Quercus robur* *Quercus petrea* *Betula pendula* (regeneration phase) *Betula pubescens* (regeneration phase)	60-90% canopy closure acidophyte shrub and herb layer
4.2. Oak-birch forest	*Quercus robur* *Betula pendula* *Betula pubescens* *Sorbus aucuparia* *Populus tremula*	
6.2 Atlantic and subatlantic lowland beech forest	*Fagus sylvatica L.* Acidic soils: *Quercus patrea* *Quercus robur* *Castanea sativa* More fertile soils: *Carpinus betulus* *Tilia cordata* *Fraxinus excelsior*	Understorey species: *Ilex aquifolium* *Taxus baccata* *Hyacinthoides non-scripta* *Primula acaulis* *Digitalis purpurea* *Ruscus aculeatus* *Buxus sempervirens* *Daphne laureola* *Arum maculatum*
13.4. Other birch forest	*Betula pendula*	
14.1. Plantations of site-native species	*Quercus robur* *Fagus sylvatica* *Pinus sylvestris* On more fertile parts: *Tilia cordata* *Acer pseudoplatanus* *Acer platanoides*	(Nabuurs, personal communication, 14 December 2020)
14.2. Plantation of non-site-native species and self-sown exotic forest	*Pseudotsuga menziesii* *Picea abies* *Larix*	(Nabuurs & Mohren, 1993)

Deforestation effects on the carbon balance and sequestration rates are discussed in section 5.3.2.

[3] Protect soil and litter carbon by minimizing soil tillage. Soil tillage temporarily increases soil carbon respiration, disturbing the soil carbon balance.

[4] Consider climate change effects on tree species' sequestration capacity. Some expected climate change effects, such as increased droughts, affect carbon sequestration rates of some tree species, as they are no longer living in good conditions. Planting tree species with these changes in mind may cause the carbon sequestration rate to be lower initially, but higher in the long term (Lerink et al., 2020). In a rotation forest, these changes can also be applied later, although careful considerations have to be made with regard to growth competition between species. This may cause more intensive management.

5.2. Knowledge question 2: How is nature quality ensured in a new carbon mitigation forest?

5.2.1. Sub-research question 2.1: What defines nature quality in forests?

Healthy, well-growing, healthy forests are a prerequisite for maximizing carbon sequestration. Yet, how does one determine forest health? In general, forest health can be defined along its capacity to recover after disturbance or under influence of stresses (Trumbore, Brando & Hartmann, 2015). Ecosystem resilience is one of the functional components of biodiversity and is therefore closely related, or rather overarching with regard to this definition (Muys, den Ouden & Verheyen, 2011b). In addition, similarly to how a person's health is determined through indicators (e.g. blood pressure, temperature), forest health and thus biodiversity can be determined by indicators (McCune, 2000).

Biodiversity is regarded as the key factor of ecosystem functioning (Muys, den Ouden & Verheyen, 2011b). It is defined as "the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems" (UNEP, 1992, p.3). Biodiversity is guided by three key components: ecosystem composition, structure and functional processes. Ecosystem composition is the identity of an ecosystem and the variety of its species and populations. Ecosystem structure is how the forest is organized spatially.

Table 7. Carbon sequestration rates for tree species with high sequestration rates. Full table in Annex B.

Tree species	Carbon sequestration rate ($MgCO_2$/ha/y)	Source
Deciduous		
Acer platanoides		
Acer pseudoplatanus	9.0	Lerink, et al., 2020
Alnus glutinosa	7.3	Lerink, et al., 2020
Betula pubescens		
Carpinus betulus		
Castanea sativa		
Fagus sylvatica	11.8	Lerink, et al., 2020
Fraxinus excelsior	10.9	Lerink, et al., 2020
Quercus petrea		
Quercus robur	7.5	Lerink, et al., 2020
Quercus rubra	8.0	Lerink, et al., 2020
Sorbus aucuparia		
Tilia cordata		
Conifers		
Picea abies	8.1	Lerink, et al., 2020
Pinus nigra	6.3	Lerink, et al., 2020
Pseudotsuga menziesii	12.0	Lerink, et al., 2020

Functional processes are ecological and evolutionary processes, such as nutrient cycle, water cycle and energy cycle, species development and extinction. Biodiversity is determinant for biomass production, resource cycles and the resilience of a forest (Muys, den Ouden & Verheyen, 2011b). Consequently, pursuing high biodiversity will ensure forest health and in turn create natural quality while maximizing carbon sequestration. How biodiversity is managed is discussed in section 5.2.2.

Several indicators through which biodiversity can be determined are dead wood (presence and type), canopy closure, presence of specifically-shaped trees (forked, crooked, damaged), presence of lichen communities and biomass productivity (McCune, 2000; Liira & Sepp, 2009; Trumbore, Brando & Hartmann, 2015). Dead wood has a key ecological role in a forest ecosystem. It stores water and nutrients and many organisms are somehow related to dead wood. The type of dead wood (tree type, standing or fallen down), and thereby the conditions it provides is determinant for the development of organism communities (Wijdeven, Moraal & Veerkamp, 2011). Canopy closure is determined by the amount of light the forest canopy lets through and that reaches the forest floor. This impacts inter specific and intra specific competition and therefore impacts the biodiversity potential of a stand (Verheyen et al., 2011). Biomass productivity is the volumetric growth of biomass in a forest over a certain time period (generally $m^3ha^{-1}y^{-1}$). This is closely related to carbon sequestration, as photosynthesis is the main driver behind plant growth (Muys, den Ouden & Verheyen, 2011a). High biomass production therefore indicates both a healthy forest, as well as high carbon sequestration.

5.2.2. Sub-research question 2.2: How is biodiversity optimized in an afforested landscape?

The importance of managing biodiversity in new forests was demonstrated in section 5.2.1. Through afforestation, plantations will take up an increasing proportion in future landscapes. Fortunately, plantation forests can contribute in forest biodiversity conservation (Hartley, 2002). This section dicusses ways in which biodiversity development and preservation can be achieved in afforested areas with a focus on dry sandy soils. Several management principles and practices are found in order to optimize forest biodiversity.

Lindenmayer, Franklin & Fisher (2006) describe five principles for managing forest biodiversity. (1) The maintenance of connectivity. (2) The maintenance of the integrity of aquatic systems by sustaining hydrological and geomorphological processes. (3) The maintenance of stand structural complexity. (4) The maintenance of landscape heterogeneity. (5) The use of knowledge of natural disturbance regimes in natural forests to guide off-reserve forest management practices. These five principles operate on different scales. The first, second and

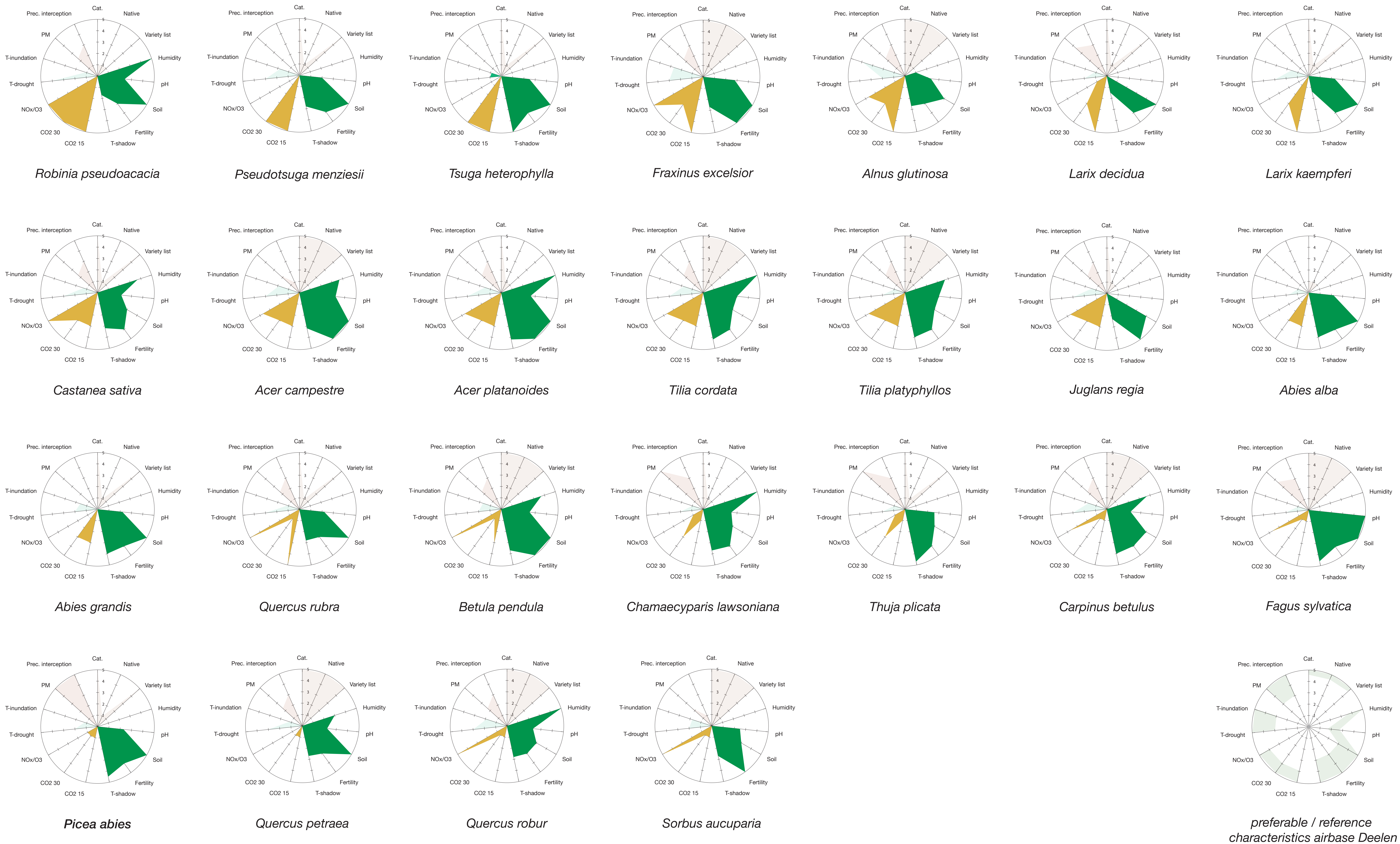


Figure 24. Dry sandy soil tree species (green area) with their relative carbon sequestration rates (based on Lerink, et al., 2020), sorted by relative carbon sequestration (yellow area). Combined with the numbers from Table 7, these relative sequestration rates give insight into tree species choice for maximizing carbon sequestration. See Annex C for explanation of the labels and Annex D for the full comparitive overview of these and more tree species.

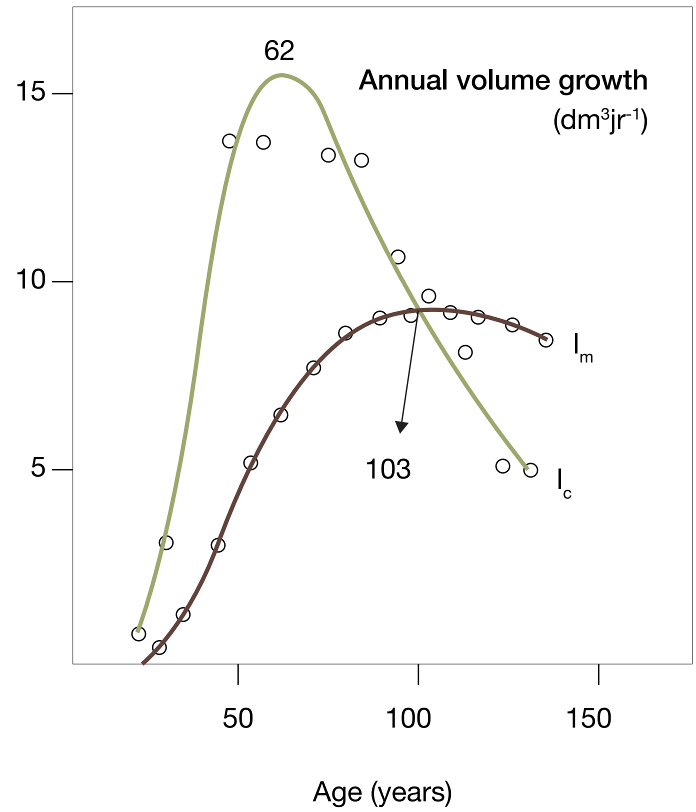


Figure 25. Annual volume growth of *Picea abies.* Numbers indicate age at which the growth culminates. Im = average annual growth, Ic = ongoing annual growth (from Muys, den Ouden & Verheyen, 2011a). As volumetric growth is related to carbon sequestration, it is an indicator of the annual carbon sequestration rate as well.

fourth principles operate on the landscape scale, in its systems and interactions between different land-uses. The third and fifth principles operate predominantly on a stand scale, and between different stands, as they focus on variety within and between stands and forest resilience. In relation to the first principle, Hermy & Bijlsma (2011) state that forest areal is a very important factor for species variety.

Functional characteristics of forests are used to explain and direct ecosystem community behaviour (Muys, den Ouden & Verheyen, 2011b). These characteristics are morphological or fysiological and are deemed near infinite (Muys, den Ouden & Verheyen, 2011b). Examples are differences in shade tolerance, leaf characteristics, canopy structure, nitrogen assimilation, et cetera. In monoculture forests and forests with low species variety, these characteristics can be predictive for the direction in which the forest develops. The higher the variety, the more differences in characteristics, the more unpredictable the development gets (Muys, den Ouden & Verheyen, 2011b).

Forest stands of different ages and stages of succession are distuinguished by different species and species varieties. In a forest, presence of stands in the full range of succesion is beneficial for the resilience of the ecosystem, as new species are present in the ecosystem to take over if some form of disturbance eliminates a stand (Verheyen et al., 2011; Trumbore, Brando & Hartmann, 2015). Presence and variety of dead wood is important. Dead wood occurs as standing or fallen dead trees, as fallen brances and bark, dead root systems and as tree cavities. These different types of dead wood create different conditions that are interesting for a variety of organism communities. Optimally, a variety of these types is preserved to attract more diverse communities (such as different lichen communities) (Wijdeven, Moraal & Veerkamp, 2011). Canopy closure can be managed through tree species selection, but most predominantly through thinning of stands. This opens up the canopy (temporarily), in order to let more light reach the forest floor and allow for light tolerant undergrowth the opportunity to develop (Verheyen et al., 2011).

5.3. Knowledge question 3: "How do human activites affect conditions for a carbon mitigation forest landscape?"

This question is answered through its sub-questions. Sub-question one displays the results of an inventorization of human activities related to forests. Sub-question two addresses the impact of deforestation on an ecosystem. Sub-question three develops further on the forestvoltaic principle.

5.3.1. Sub-research question 3.1: Which human activities are dependent on or stronly linked to forests?

Smink (2011) identifies three aspects along which afforestation can be discussed: societal, economic and environmental. The environmental aspect is discussed in section 5.2. This section covers the societal and economical aspects. The economical aspect is approached from a business viewpoint, where the forest is in some way exploited for financial profit. The societal aspect is approached from the visitors standpoint. Visitors are people using the landscape without economic interest. Although visitors may use the landscape economically, by making use of offered services and/or products, they do not offer services or products themselves. This is what differentiates the economical from the societal aspect.

5.3.1.1. Economical forests

In terms of economical activities in forests, a distinction can be made between activities that yield wood products and activities that yield non-wood products or provide services. The most obvious human activity that is dependent on forests is forestry. In fact, forestry shaped the Dutch landscape in the 20th century (Schelhaas & Clerkx, 2017).

Activities that yield non-wood products or provide services prevail in the recreation & tourism industry. Spatial inventorization identified several types of such activities in and around forests. Four categories with a depency with forests can be distinguished: [1] not dependent, [2] somewhat dependent, [3] strongly dependent and [4] inherently dependent. Examples of activities that are not dependent on forests [1], yet can be found in or around forests are observation towers, information centres, cafés, restaurants and overnight accomodations, such as bed & breakfasts and hotels. These places supply recreational demand in forested areas, provide information about an area or facilitate multiple-day trips towards a (forested) area. Activities that are somewhat dependent [2] can exist in non-forested landscapes, but would suffer somewhat from the lack of trees or forest landscape characteritics. For example a paintball course. Strongly dependent activities [3] could theoretically exist outside forests, or exist partially outside forests, but would practically not comply to people's expectations if offered elsewhere, or if forests are not part of the experience. An example is a mountainbiking route or a hiking route through nature. Activities in the last category are inherently dependent on forests [4], and cannot exist elsewhere. For example, a climbing forest.

5.3.1.2. Societal forests

It is demonstrated that green spaces positively affect human health and reduce stress levels (Ulrich, 1986; Maas et al., 2006; Nielsen & Hansen, 2006; Maas & Verheij, 2007; Shin, 2007; Smink, 2011). Recreational activities in forest environments, oases of vegetation and natural features, have a strong positive effect on human well-being, compared to urban environments (Lee et al., 2009). Smink (2011) identifies the main reasons for people to visit a forest. In order from most popular to less popular, these reasons can be grouped into [1] multi-sensory appreciation of the natural landscape, [2] social trips with friends and/or relatives, [3] stress reduction and escapement from daily routines, [4] work on active health, and [5] to do research. Apart from the fifth, these are all considered recreational reasons to visit a forest.

Moving through a forest for recreational purposes can be done in several ways. People can walk, run, cycle, and sometimes drive a car through a forest. Or, at some places, people can use alternative transport means offered for rent to day tourists, such as mountainbikes, segways, scooters, mopeds or racing bikes. Additionally to means of transportation, places to stay can be found often as well, ranging in stay duration between minutes and days. These destinations provide resting points from long walks or cycle tours, but can also be places people go to prior to the whichever reason they have to visit a forest landscape. Despite many possibilities, the research site tremendously lacks means of recreational activities or destinations. It is limited to nature appreciation in the area surrounding the airbase and the estate Vrijland. There is a very high potential to create places where people move through, go and stay, with regard to the size of the area,

5.3.2. Sub-research question 3.2: How does deforestation affect the forest ecosystem?

There a various forest management options. In relation to the forestvoltaic concepts (dicussed in section 5.3.3), (temporary) deforestation effects are relevant with regard to clearcutting forestry. Deforestation with heavy machinery can change the soil through damaging, compaction and rutting. First, this can create changes in the hydrological characteristics of the soil, as well as in soil respiration processes. Soil recovery depends on soil type and biological activity. Sandy soils are generally less sensitive to these soil alterations, but the lack of water and nutrients and high acidity in these soils limit biological activity. The recovery potential of these soils is therefore low. Second, Root growth is also affected by compaction, as roots have less, or much smaller pores to grow their way through. Nevertheless, in dry sandy soils, where pores are generally large, compaction can be beneficial for the water-retention capacity of the soil. Third, transportation of the harvested trees is often paired with damaging of other trees. Furthermore, rejuvenation seedlings are often destroyed in large quantities as a result of mechanical wood harvesting (Ampoorter, Goris & Verheyen, 2011).

In addition to soil changes, with its consequences to plant growth, deforestation also causes changes in the forest carbon cycle. This is relevant in relation to the carbon sequestration function of the forests in this design research. On bare soil, the soil respiration is much higher. In addition, young trees have a low NPP. Therefore, for several years after harvest, the stand has a negative NEP (Lorenz & Lal, 2010).

5.3.3. Sub research question 3.3: Do renewable energy production or storage alternatives provide beneficial conditions for forest growth or carbon sequestration?

When considering renewable energy production alternatives that combine with forest land uses, the obvious principle would be to use the forestry products as biomass energy. Biomass energy is heavily subsidized for its renewable energy potential (Field, Campbell & Lobell, 2008). Nevertheless, using forestry products for biomass conflicts with the general principles for carbon sequestration forests and its products' lifetimes (see section 5.1.2). There are three ways to convert biomass into a usable energy source: combustion for electricity and heat production, changed into gas-like fuels or changed into liquid fuels (Demirbas, 2007). Since combustion of biomass releases a lot of the stored carbon back into the atmosphere, this kind of energy production is inconsistent with the principle to use afforestation to increase carbon sequestration. Although it does contribute to the share of renewable energy sources in the energy mix, systematic combustion of production forest areas only causes a temporary offset in atmospheric carbon. It should cause continuous removal. Furthermore, rather than researching product applications for a forestry landscape, this research question targets beneficial conditions for forest growth. Moreover, in line with a carbon mitigation forest, a synergy between forest development and renewable energy production was found.

5.3.3.1. Forestvoltaics: how does it work?

This section establishes the theoretical baseline for the function combination of forest development and renewable energy production with photovoltaic panels.

The concept

Any ecological development demands certain (micro)climatic circumstances. Except for pioneer species, forest development demands relatively cool temperatures and shade. The microclimate under the canopy is relatively cooler and has a higher humidity than the air above the canopy. In addition, wind speeds are generally much lower beneath the canopy than above it (Samson, Groudriaan & Mohren, 2011). Providing such circumstances beforehand could lead to faster forest development of non-pioneer species (Nabuurs, personal communication 14 December, 2020). Faster development of non-pioneer species could lead to an increased carbon sequestration rate, depending on which tree species are used.

FV is the synergetic combination of forest development using tree saplings, rather than succession, and a PV-system. This synergy is created through the microclimatic conditions that the PV-system can provide to the forests and the microclimatic conditions that the forest can provide in return to the PV-system. The PV-system provides shade and lower temperatures beneath the system, as well as slightly increased humidity and less overall diurnal temperature and humidity variation (Armstrong, Ostle & Whitaker, 2016). If the panels are close enough to the vegetation layer, the vegetation may prevent or at least reduce overheating of PV-panels in the summer through plant respiration. The two systems (PV and forest) thereby create a synergy between forest development and renewable energy production.

In contrast to AgriPV, realistically, FV is in nature a temporary measure, as trees will grow up to 35m or higher and PV-systems at that height are assumed economically not interesting. Lower systems are more feasible in this regard. Forest growth defines the temporality of an FV system.

A forestvoltaic system for developing new forests consists of 4 steps (see figure 7). Step 1: set up 10m-high PV system and plant tree saplings underneath. Step 2: Let forest develop under improved circumstances for forest development, storing CO_2 from the air, while producing renewable energy. Step 3: af-

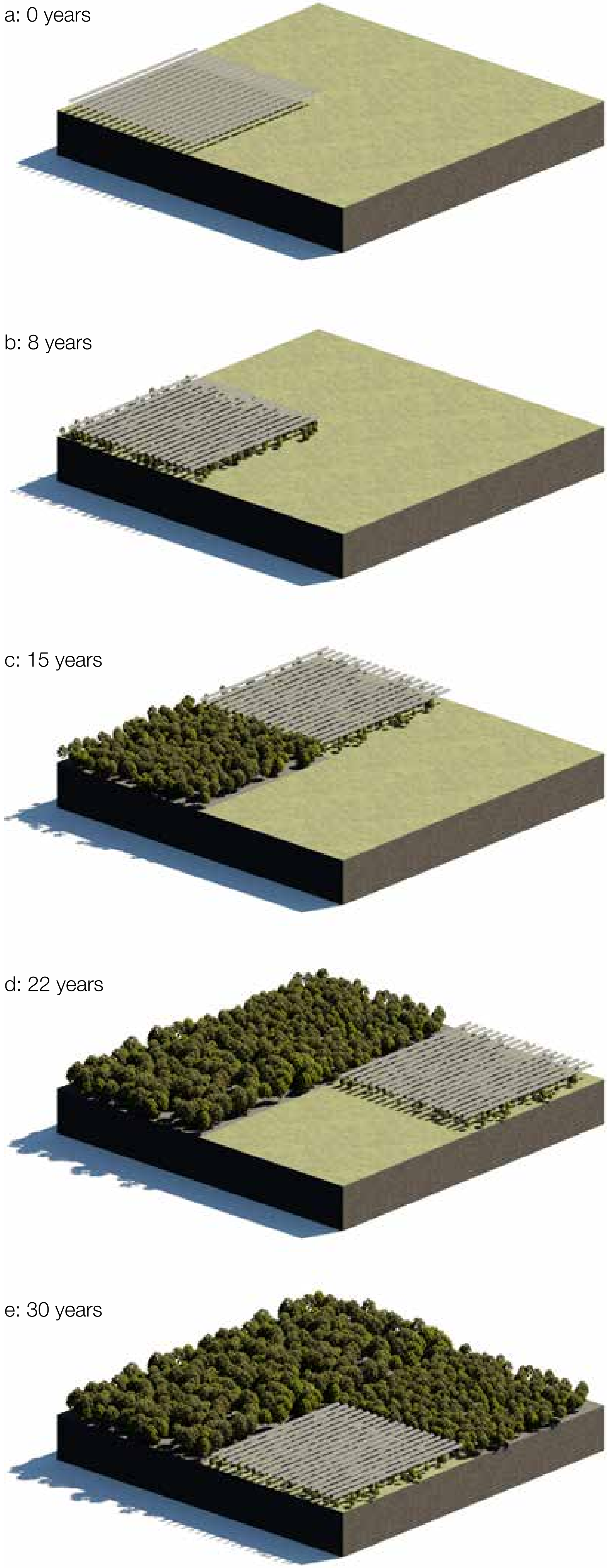


Figure 26. FV principle. Plant trees under PV-system (a), let young forest develop (b), move the PV-system as forest grows high (c), repeat until PV-panel lifetime is reached (d).

ter 5 years, the tree sapling have grown and will soon overgrow the 5 metres of the PV-system. The system is therefore moved to a new patch of land where new forest is to be developed as well. This step is repeated until the PV-system reaches the end of its lifetime (25-30 years).

Considerations and limitations

Some crucial considerations must be taken into account with regard to this concept, which create design variables to explore various possibilities in creating a working concept. The most prominent considerations are related to light and water interception, tree species shade tolerance and intended use of wood products. These variables are highly related to one another. Light interception is caused by the PV-system and prevents the light from reaching trees below the system. Shade tolerance is therefore crucial in tree species selection in a forestvoltaic system. Light interception is a design variable. For example, the choice between opaque c-Si cells or transparent perovskite cells influences the amount of light that reaches the forest floor. Light interception is also variable with regard to PV-density in the system. The lower the density, the less light is intercepted by the PV-system.

Photovoltaic cells also intercept rainwater. Runoff from panels affect areas where infiltration is concentrated, predominantly under the edge of the panel, and areas where water infiltration is greatly reduced, under the surface of the panel. Soil moisture differences due to PV-systems prevail in the top 20 centimeters of the soil (Elamri et al., 2018). The variable component in designing with this challenge is the system density. In addition, avoidance strategies can be applied to the PV-system. With such strategy, the system tilt changes based on the wind direction in a rainfall event, in order to mitigate the infiltration concentration effects that are caused with a static system. This is shown to be an effective measure (Elamri et al., 2018). Furthermore, tilting PV-systems can also track the sun throughout the day, yielding more electricity (see section 2.1.7.2).

The intended use of wood products is another consideration for a forestvoltaic system. Wood quality is determinant for the use of wood in a variety of products (see Table 10). Wood that is intended for building construction must be straight and strong. Tree growth is guided by competition for light (Muys, Den Ouden & Verheyen, 2011). Therefore, a tree that is growing under a PV-system may grow deformed, as it tends to grow towards a spot with more light. Such growth is unsuitable for high quality wood uses, but more suitable for lower quality wood products.

Applications

This type of PV-system can be used for two different types of land-use: forest or production energy forest. Depending on the assigned land use, one of two things can happen after the lifetime of the PV-system. For a forest land-use, the systems and supporting structures are all removed. The FV serves as a tool to develop the forest faster, while generating renewable energy. For a production energy forest, new PV-panels are placed, and the process can be made cyclic. Clearcut harvest in an RF is required to achieve this circulation of forest development and renewable energy production synergy on a large scale. A trend in production forests harvesting is moving away from clearcut, as discussed earlier. The main drawbacks from clearcut harvesting and the potentials of a PV-system with regard to these drawbacks are shown in Table 11, demonstrating that a PV-system has a high potential in removing some drawbacks, or reducing their impacts significantly. Additionally, the practice of clearcutting is misconceptualised as causing too much negative impacts. Forest openings can provide beneficial environments for wildlife, as long as the harvest is done well (McEvoy, 2004). Furthermore, new forest environments can be created in a forestvoltaic system, creating new biomes for more species. Alternatively, group harvest in a CCF makes possible smaller scale forestvoltaic systems. However, it is questioned how efficient the system is in a group harvest, as there will be a lot of drop shadow from surrounding trees. This minimizes the PV-coverage on a designated a plot.

5.3.4. Lifecycle of production forest products

Sustainable development also involves taking into account the lifecycle of produced wood from production forests. Lerink et al. (2020) point out some considerations with regard to such products. [1] use harvested wood in applications with a long lifespan (such as buildings). One wooden house requires approximately 50m^3 wood (van Capelleveen, 2019). Depending on soil fertiliy and tree species, one hectare of production forest yields between 3 and 12m^3 ha^{-1} year^{-1} (Felton et al., 2017; Lorenz, Englert & Dieter, 2018; Bréda & Brunette, 2019). Assuming a high yield stand, just over 4 hectares of forest is required to build on average one house per year from its products. [2] Use sawing residues in plating products or biomass energy production. As not all parts of a tree can be used for high-quality products (see also Sass-Klaassen, Sterck & Den Ouden, 2011), other parts should be used for other, lower quality uses such as plating material, tinder matches. Biomass should be the last resort.

5.4. Conclusions

5.4.1. Design considerations

The results from the knowledge questions can be summarized and translated into design and management considerations with spatial dimensions. The considerations are grouped into considerations for carbon sequestration, forest health, recreation and FV. The considerations are not exclusively linked to just one of these concepts, but can be related to others as well. The considerations are rather grouped into the concepts in which they are most prevailing. Figure 27 provides more in-

Table 8. Wood quality classification and main use per classification (Muys, Den Ouden & Van Acker, 2011).

Class	Use
F	Rotary cut veneer, stitch veneer
A	Furniture wood, cutlery wood
B	Poles, planks, beams, battens, sleepers.
C	Palettes, packaging, paper
D	Paper, fire wood, fibre wood
TF	Veneer, decorative, art, ship-building restaurations

Table 9. Main drawbacks of clearcutting and potential solutions through a forestvoltaic system

Drawback	Forestvoltaic potential
Increased soil respiration due to soil exposure	Soil exposure reduced significantly
Temporary destruction of microclimate	Microclimate partly recovered under PV-system
Temporary destruction of flora and fauna communities	Microclimate alias potentially decreases recovery time and could create conditions for new communities
Competition of grass and herbs with new seedlings	-

sight into the various concepts the considerations are related to. For carbon sequestration, the following design considerations are formulated:

» Usage of tree species with the highest carbon sequestration rates: Pseudotsuga menziesii, Fagus sylvatica, Fraxinus excelsior.
» Store sequestered carbon for as long as possible (i.e. use long rotation periods) and use harvested biomass for high-end products.
» Limit soil tillage.
» Use multifunctional synergies, such as APV and FV.

For forest health, the following design considerations are formulated:

» Create large forest areals.
» Create wide forest edges.
» Avoid monocultures.

For recreation, the following design considerations are formulated:

» Create variety in landscape experiences.
» Make the landscape easily accessible and penetrable.
» Embrace current landscape qualities.
» Educate visitors on new landscape elements and the landscape transition.

5.4.2. Trade offs

There are several trade-offs inherent to creating a carbon mitigation landscape. The primary trade-off is between landscape quality and renewable energy production. Landscape experience quality includes variety and contrast (see section 2.2 on page 20). Renewable energy landscapes often manifest as extremely repetitive orthagonal pieces of land. The trade-off is therefore between carbon source removal through renewable energy generation and creating higher quality landscapes. A variation on this trade-off occurs as well with the choice between maximising biological carbon sequestration and landscape quality, but the negative impact on landscape quality from complete afforestation is much less severe than with solar landscapes, as forests can have much more inherent variation. These trade-offs are also related to the economic value of the landscape. A more profitable landscape is valued higher economically and some land uses are more profitable than others. Therefore, a balance between such trade-offs must be found when incorporating these considerations into the landscape design.

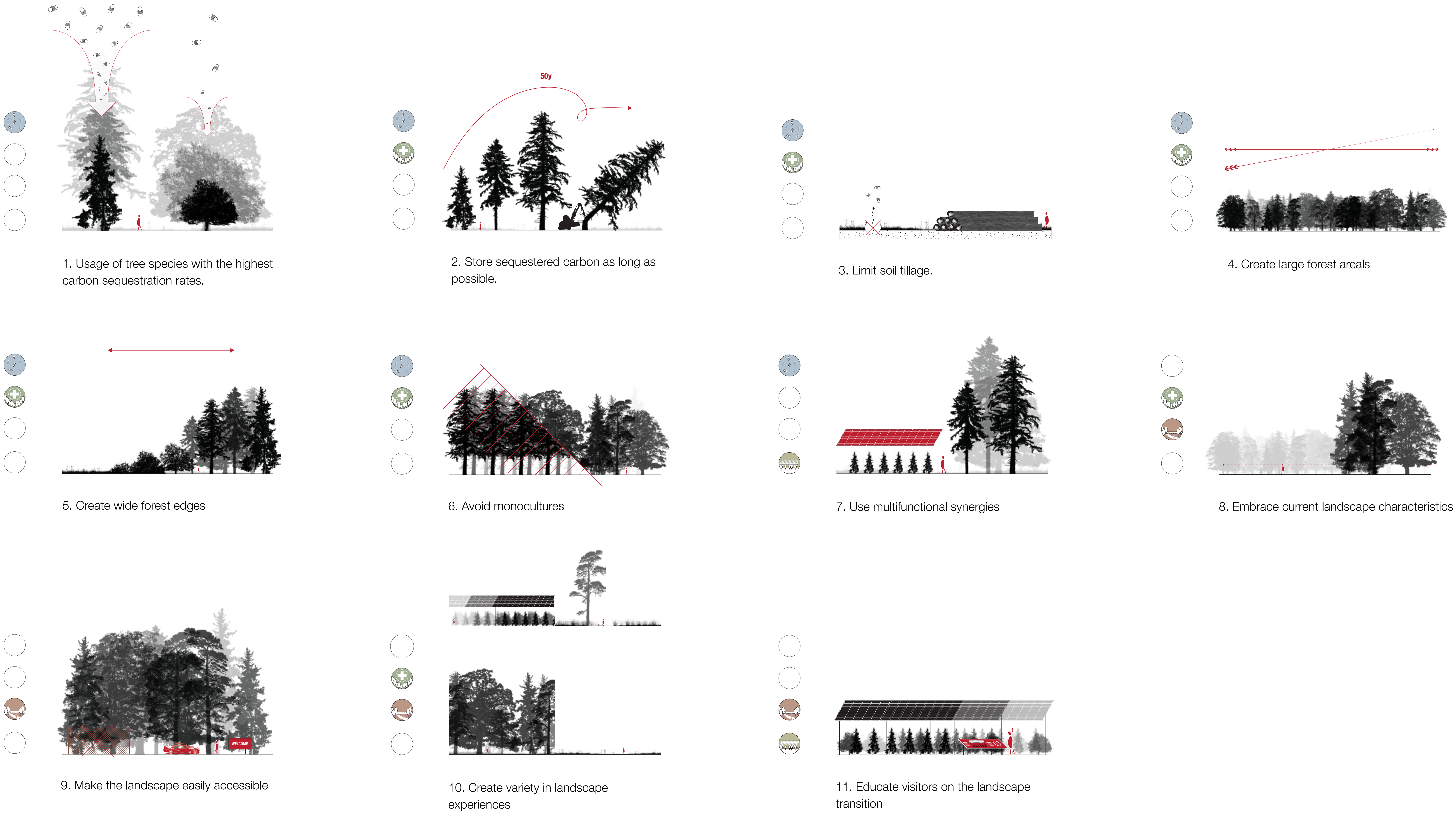


Figure 27. Design considerations. These considerations serve as starting points for the RTD phase of this thesis (see Chapter 6). A consideration can encompass more than one theme, as indicated to the left of each consideration.

6. Research through designing

6.1. Forestvoltaics: spatial manifestation

6.1.1. Forestvoltaic configuration

This section builds upon the previously established design considerations regarding FV-systems. As the theoretical potentials are drawn, the next step is to look at the spatial manifestation of such a system in the landscape. Seven models are tested with regard to spatial configuration of the PV-system. A system with transparent perovskite solar panels is used. This simulates a forest crown, and thereby reduces the light interception for the vegetation and forest floor beneath the panels, minimizing growth reduction for light sensitive tree species. The most shadow rich areas under the system are dedicated to the more shadow tolerant tree species (see Figure 28). Other parts are dedicated to species for fast wood production, which generally need more light. These options are tested along several criteria: carbon sequestration, energy production, timber production, forest health and experience. Carbon sequestration is tested according to tree growth potential. Energy production is tested along PV-density, i.e. how many panels per hectare are placed. Timber production is tested along wood quality criteria, e.g. the ability for trees to grow straight and the use of species that are suitable for wood production (see section 5.3.3.1). Forest health is tested along potential biodiversity, based on microclimate variations. Experience is tested along variety in the landscape and the natural perception of the forest that is developing. The configuration of the seven models is shown in Table 10 and the results of the evaluation in Table 11.

The different models demonstrate relevance for different landscape developments. Some patterns emerge. There is a negative correlation between energy production and landscape experience. This can be related to the way experience is valued here, in addition to the geometry of a PV-system, with its hard edges, right corners and reflective surface, which strongly contrasts the natural surroundings. Additionally, in the Max PV model, the trees in between the PV arrays are placed in rows, in order to prevent crooked growth, as crooked growth renders such trees useless for some high quality wood products. This in turn results in a very artificial forest structure. This is not necessarily problematic during the forestvoltaic phase, as the cause for this structure is being made clear by the presence of the PV-system. Nevertheless, what remains after the PV-system is relocated is a very artificially planted production forest, which scores very low on experience of naturalness.

The models are here presented as scalable tiles of land use. This is done to create a set of baseline models which can be quantified in terms of PV-density and therefore electricity production, as well as carbon sequestration rates. Nevertheless, the models have an inherent flexilibity in their application, depending on the context in which they are applied in. For example, the lane in the FV strips model (4), can be applied as an actual lane in the landscape, with a route going through. The lane will be somewhat wider, but the principle of the application will comply to the model. This way, the models are tensible in their physical implementation compared to the rigidness in which they are presented here.

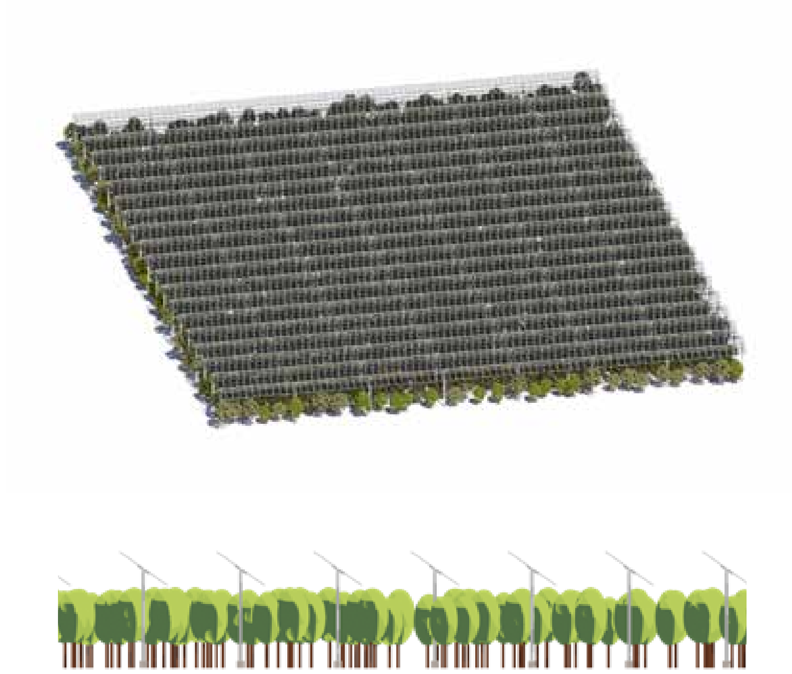
6.1.2. PV-systems and landscape quality

A forestvoltaic system is demonstrated to be a temporal measure in nature. Apart from the rotational character of the system between different stands, there is also a temporal element within the duration of operation on one stand. This element also has spatial implications for which design choices can be made. The most relevant question is wether the PV-system is height adjustable. This choice impacts both the synergetic potential of the system, as well as the landscape quality of a forestvoltaic system.

Height-adjustability of the systems is a major factor in perception of the forestvoltaic system. It differentiates between a static PV-array under which some trees are growing (see Figure 29), and a dynamic forestvoltaic synergy, where the entire landscape unit is a growing element in the landscape (see Figure 30). A system that grows along also demonstrates the synergetic potential from the cooling effect of the vegetation towards the PV-panels to prevent or reduce overheating of the panels (Shafique, Luo & Zuo, 2020).

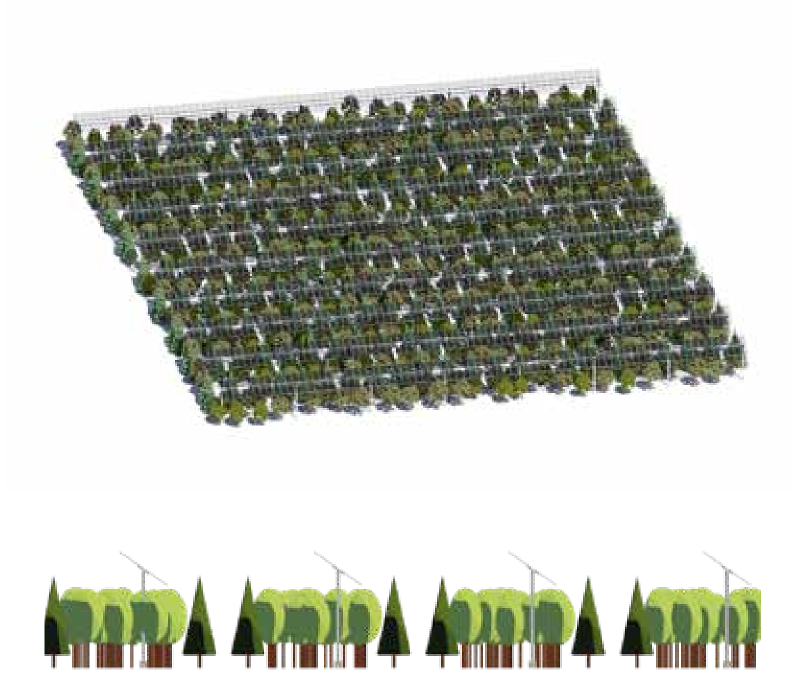
Table 10. Forestvoltaic spatial configurations, indicating the PV-coverage and tree configuration per model. PV-coverage describes the PV-panel covered surface on an area.

Model		PV-coverage	Tree configuration
0	*Reference*	0%	Randomly
1	*Max PV*	50%	Randomly
2	*Dual production*	25%	Shade intolerant species in rows, shade tolerant species randomly
3	*Energy forestry*	12.5%	Randomly
4	*FV strips*	15%	Shade intolerant species in rows in between PV-strips, randomly elsewhere
5	*FV offset*	10%	Randomly
6	*FV low density offset*	6%	Randomly
7	*PV offset strips*	6%	Randomly



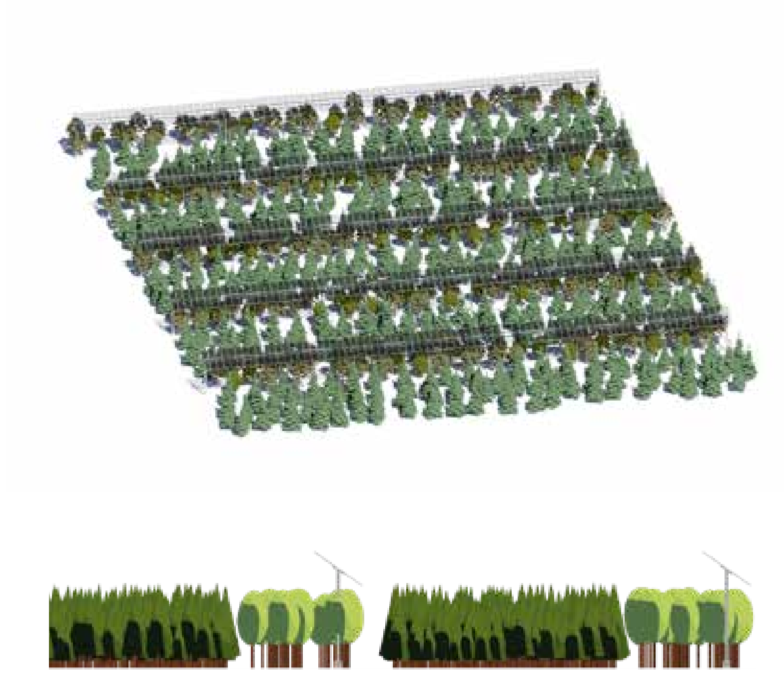
1. Max PV

50% PV-density above a mixed deciduous, shade tolerant forest. This models focuses on electricity production.



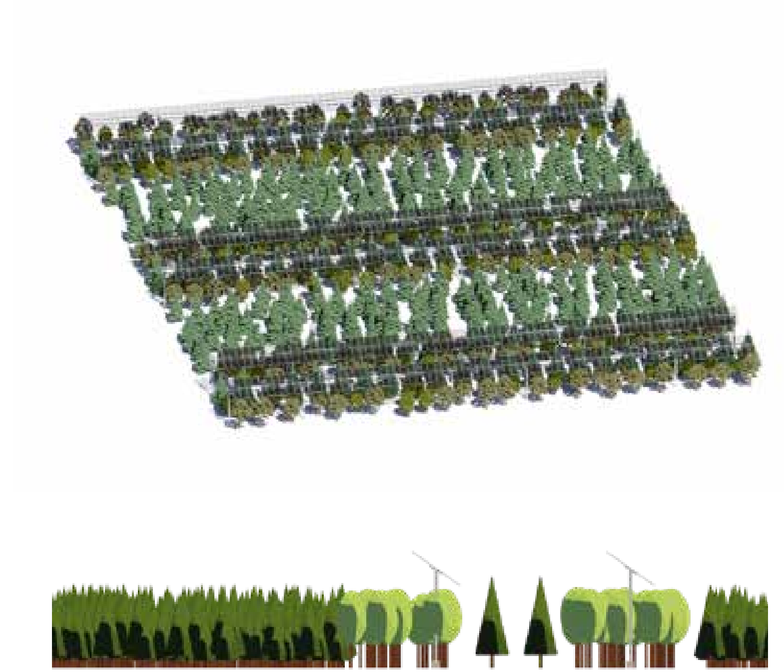
2. Dual production

A lower PV-density (25%) creates space for fast growing, shade-intolerant, tree species with a high carbon sequestration rate. Wood production focused in the rows between the panels, to prevent trees from growing crooked



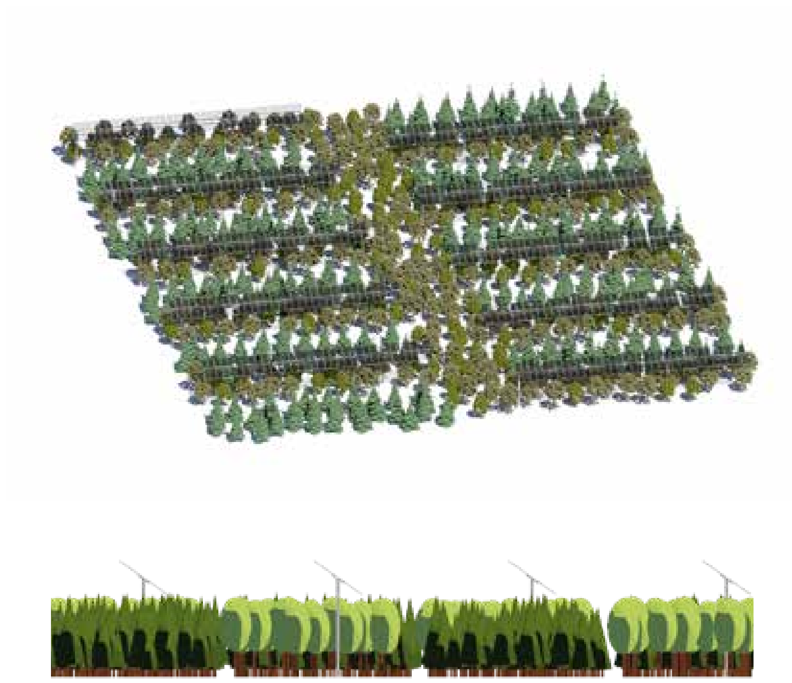
3. Energy forestry

Further lowering the PV-density (12,5%) allows for the production forest patches to be placed more naturally, instead of the antropogenic configuration of model 2. It thereby contributes to the landscape quality through the natural perception of the landscape



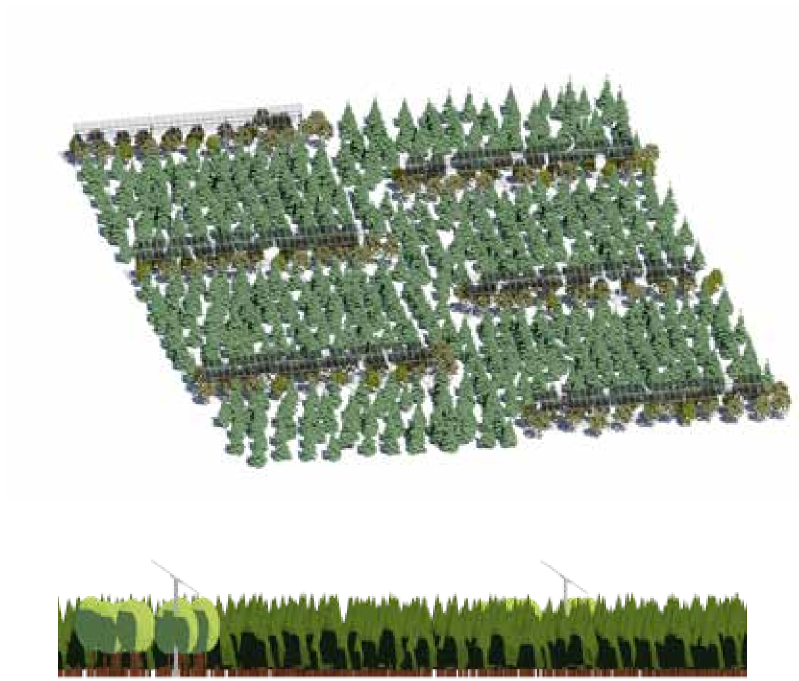
4. FV strips

Offsetting the PV-arrays allows for a higher electricity output compared to model 3 (15% PV-density). Alternating trees in rows with trees randomly placed in patches creates different growth circumstances which leads to more variety in the landscape.



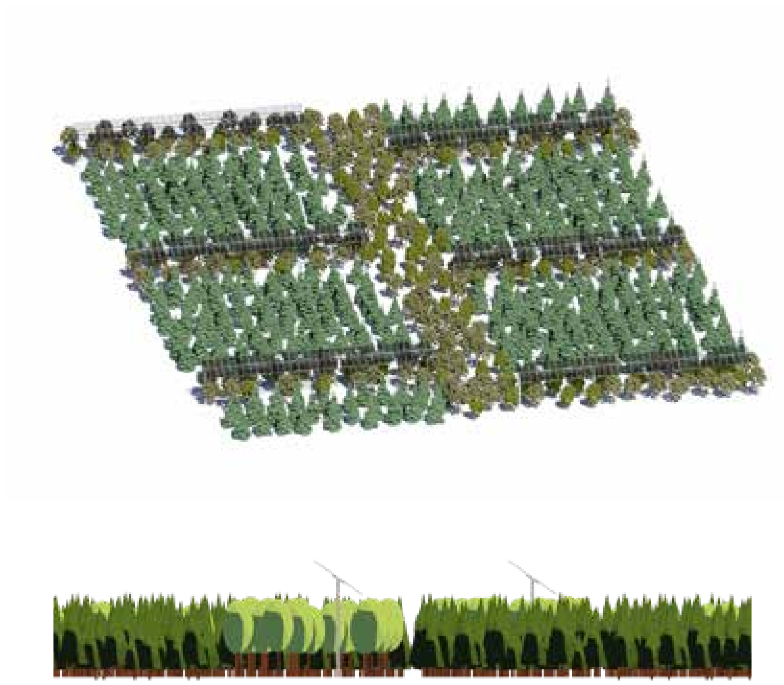
5. FV offset

This model focuses on nature development, rather than wood production, by creating a strong framework of deciduous forest patches with high sequestrating, fast-growing patches within its chambers, while still maintaining 10% PV-density.



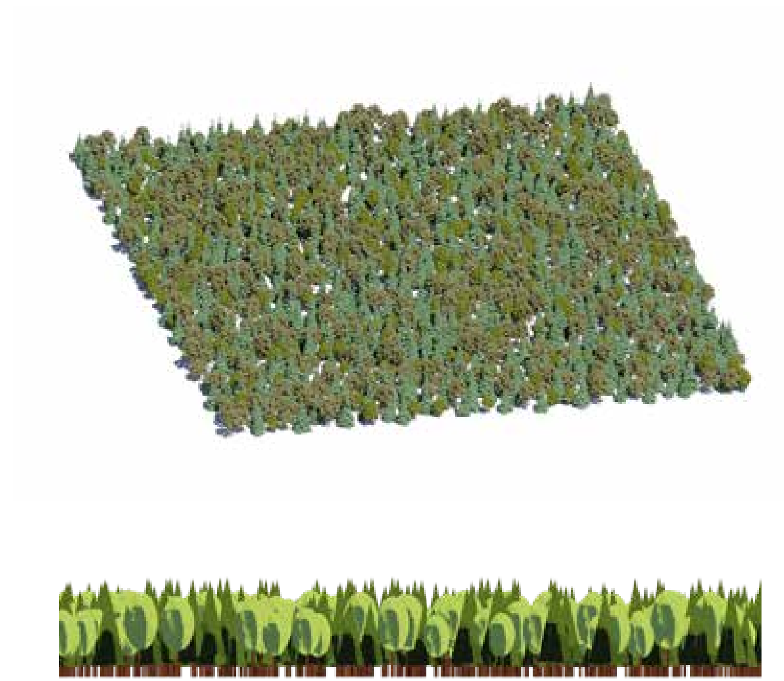
6. FV low density offset

This model, although similar to model 5, has a higher focus on wood production and fast carbon sequestration. The framework here consist of the production forest. It has a low PV-density of 6%.



7. FV strips offset

This model combines the natural framework of model 5 with the larger wood production patches of model 6. It thereby reduces its PV-density to 6%, while maintaining a stronger natural framework that is less prone to disturbance, as the species here tend to grow slower.



0. Reference

The reference model exists of a common mixed forest that is located near the testbed area.

Figure 28. FV: spatial manifestation models. All models show a forestvoltaic system near the end of the forestvoltaic phase, i.e. after approximately 10 years. The reference model is deplayed at the same age. For clarity, the sections below the models show the model principle from another angle. The models are visually simplified: the deciduous trees represent a mix of tree species; this is also true for the evergreen trees.

6.2. Business model

The research focused predominantly on the concept of biological carbon sequestration through afforestation, and its spatial concepts for landscape design.Revenue is mentioned before, but is put better into perspective when set out against construction and maintenance costs of new forests and PV-systems. Then, the economic viability of this landscape can be determined.

6.2.1. Planting new forests

Teeuwen, Reichgelt & Oldenburger (2020) estimate costs of new forests between €7.600 and €22.100 per hectare, with an average of €13.750 per hectare. Included in these costs are preparation (approximately 19% of the total costs), purchase of plant materials (25%), planting itself (19%), sapling maintenance (8%) and losses (replanting required, 4%), as well as organisational costs. In a clearcut production forest, ca 70% of replanting costs are expected, as it is assumed the costs are predominantly for purchase of plant material, planting and sapling maintenance. In a 50 year rotation system, the annual forest planting costs are estimated on €275. Additionally, on average €270 per year is spent on management, adding up to a total of €545 y^{-1} in forest upkeep costs.

6.2.2. Forestry revenue

Forest revenues are very much dependent on the type of forestry and the products that are made from the harvested trees. For this business model, the latest available average revenues for forests on dry sandy soils are used. This is €137 $ha^{-1}y^{-1}$ (Silvis & Voskuilen, 2020).

6.2.3. Carbon allowances

Being a solar power plant allows for taking part in the EU emission trading system. As a net mitigator of carbon, the allocated carbon allowances, or carbon credits, can be sold. This would generate extra revenue. As carbon credits are expected to increase in price over the coming decades (Reuters, 2021), the revenue will also increase over the years.

6.2.4. PV-system costs

The installation costs of the PV systems have dropped tremendously over the past decade (NREL, 2021). The trend is still moving towards lower prices. The moment of investment is therefore very relevant. Nevertheless, an indicative installation cost is presented, based on costs in 2021. The average costs for solar panels is €0,35 Wp^{-1} (Schachinger, 2021). Approximately 500 kWp ha^{-1} can be installed (Spruit, 2015). This results in panel costs of €670.000 ha^{-1}. A panel lifetime of 30 years brings this to €22.333 $ha^{-1}y^{-1}$.

6.2.5. PV system revenue

The estimated electricity yield for a south-oriented PV-system with 50% panel coverage is around 775 MWh ha^{-1} $year^{-1}$. With an electricity price of €0.22/kWh (as per 2020 in the Netherlands (Hage, 2020)), its revenue is around €162.750 $ha^{-1}y^{-1}$.

Summing up the revenues and substracting the costs, it can be concluded that a forestvoltaic system results in a profitable business model. The installation costs of height-adjustable PV-systems was not taken into account, nor was the implementation of lower-density systems (see Figure 28). Neverthe-

Table 11. FV spatial manifestation evaluation. Valuation is done in a Likert scale with seven steps ranging from --- to +++ and given values are are relative to each other. The reference model is a mixed forest with thinning management without PV installations. Carbon sequestration is based on the share of highest sequestration tree species in between the solar arrays. These species are also indicative for timber production. Energy production is based on the PV-density. Timber production is based on the ability of the trees to grow straight between the panels. Forest health is based on variation within a stand with regard to species mix and various edges and transitions between microclimates. Experience is based on natural perception of the forest and variety in configuration. The more randomly the vegetation is distributed and the more variation, the higher the score.

Model		Carbon sequestration	Energy production	Timber production	Forest health	Experience
0	*Reference*	+++	---	++	+++	+++
1	*Max PV*	--	+++	---	--	---
2	*Dual production*	-	++	-	-	--
3	*Semi density*	+	+	+	+-	+-
4	*Strips*	+-	+-	+-	+	-
5	*Offset*	++	+-	++	++	+
6	*Offset semi*	++	-	++	++	++
7	*Offset strips*	++	-	++	++	++

Figure 29. PV-systems that are not height adjustable will not benefit as much from the synergetic relation with regard to overheating prevention. In addition, they score lower on landscape quality.

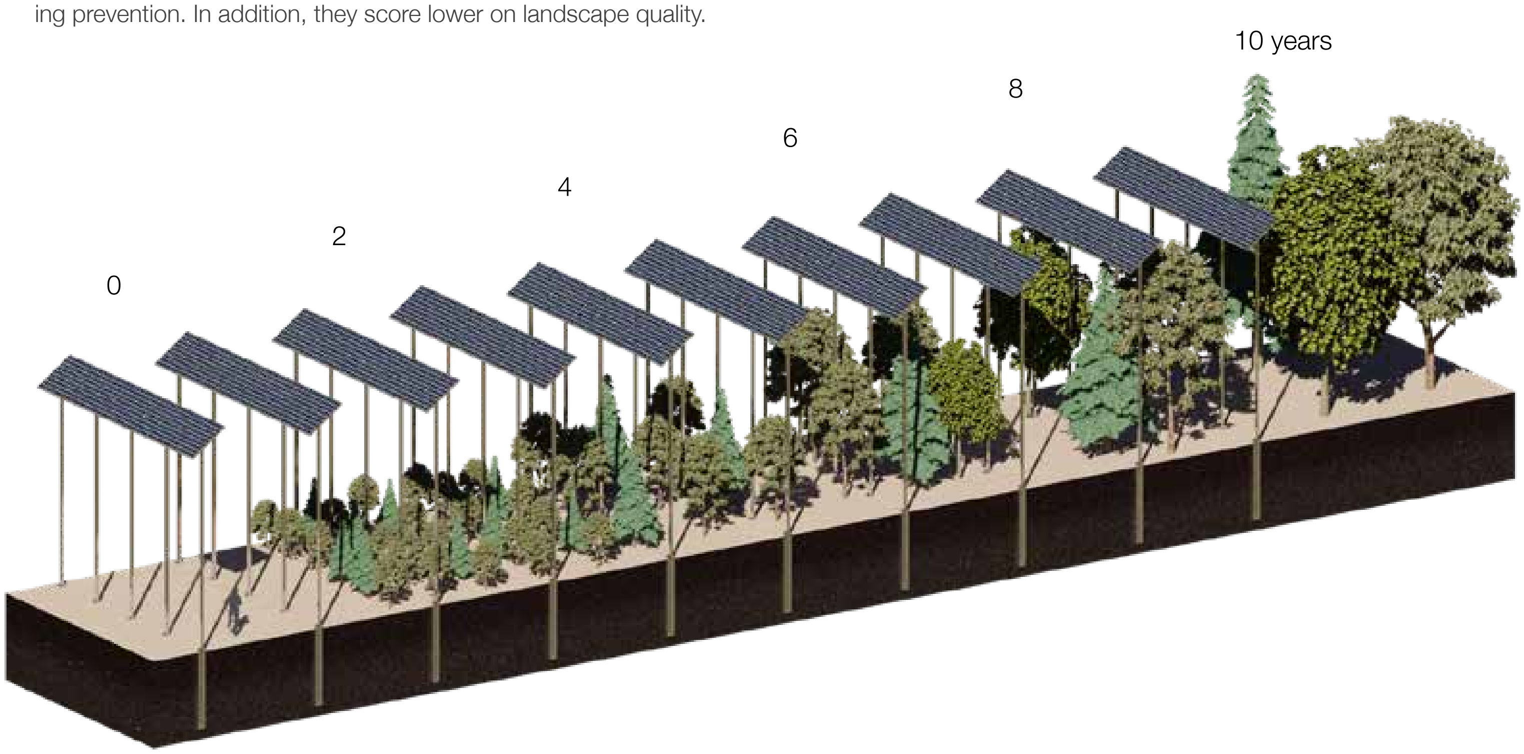
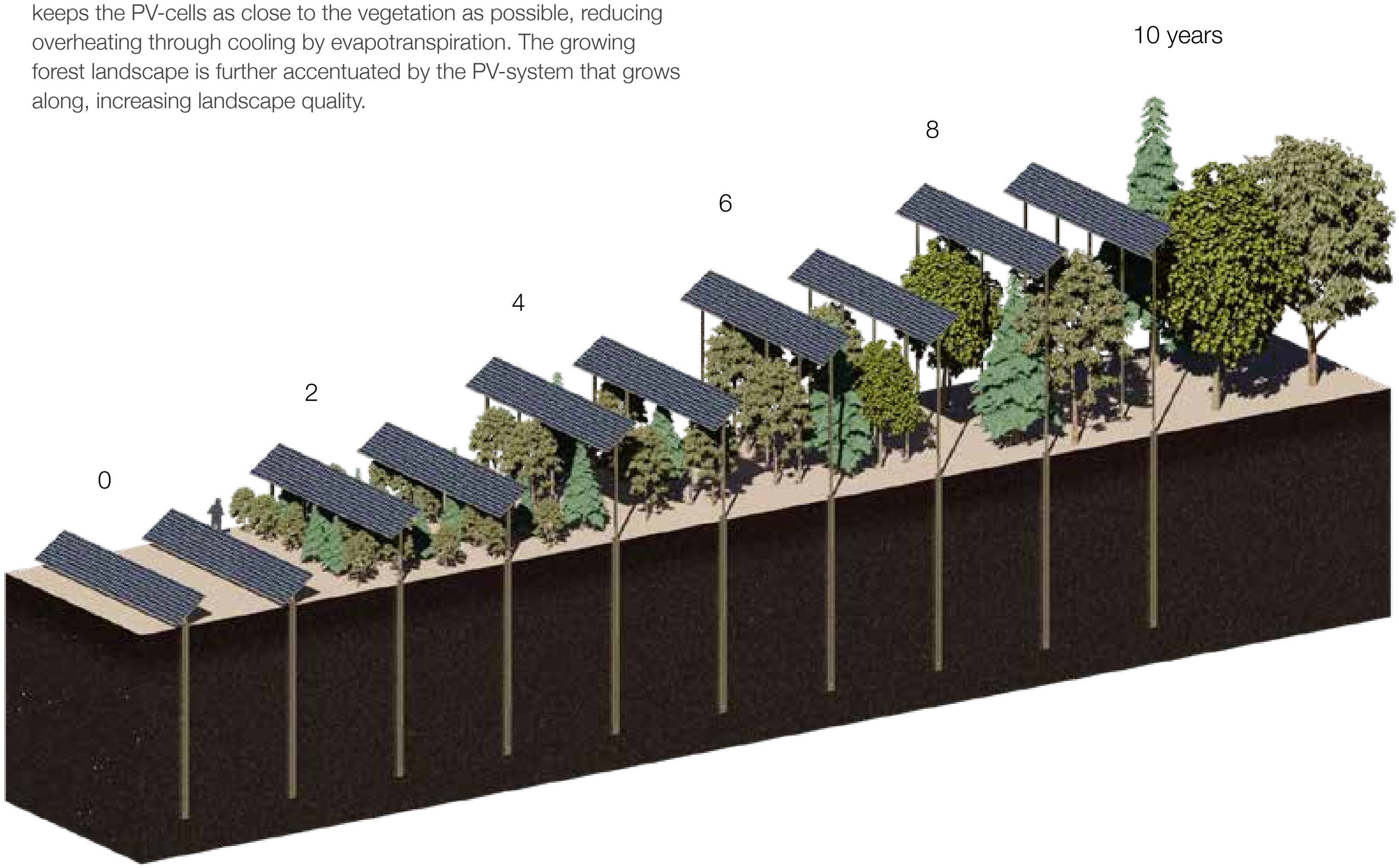


Figure 30. A PV-system on a structure with variable height, keeps the PV-cells as close to the vegetation as possible, reducing overheating through cooling by evapotranspiration. The growing forest landscape is further accentuated by the PV-system that grows along, increasing landscape quality.



less, neither considerarions are expected to be a dealbreaker for the business model.

6.3. Landscape vision

Making accessible the site of airbase Deelen will make possible to extend the Gelders Arcadië landscape to the north. In addition, it greatly increases landscape permeability to the north of Arnhem. This landscape can add a modern interpretation of an estate to the Arcadië landscape, in which the self-sufficiency of the estate focuses on contemporary issues that cause landscape transformations, such as the energy transition and carbon reduction movements. This landscape will set its focus to the future, and will not be stuck in the past. Nevertheless, the decades old military history is respected, as some prominent features of the airbase are preserved, and the themes of aviation and modern airborne activities are still present in this landscape transition.

6.4. Landscape design: The estate

The landscape design is predominantly shaped by prominent circular shapes, inspired by the class C airspace surrounding the airports (see Figure 31). Various sections of the estate are neamed after landscape features, historic references or new landscape design elements (see Figure 33). The Plateau focuses on high productivity, for both wood products as well as renewable energy production. FV is used as a long-term rotational land-use here. The other parts focus more on other landscape experiences. The Slope focuses on human experiences, and housing development with wood produced on the estate. The Schaarsbergen area focuses on forest biodiverity and experiences with high naturalness. The Park is the core of the estate, showcasing the estate as a landscape entity. Here, a visitor centre is present, serving as a place to stop for coffee and information on the estate. It also serves as a starting point for several recreational routes around the estate, each with different themes. To the west of the estate, the existing runway forms the border between the Plateau, a strongly defined estate area and the Start, a transition landscape towards national park De Hoge Veluwe. Such transition zones are also present along the other borders of the estate, which makes the landscape design go beyond the current fences of the airbase. These transition zones are used to create more natural transitions between the various landscapes, rather than having the current fencing determine these transitions, as it represents a very different intent of landscape claim and transitions. Throughout the estate, many vistas cut through the forests, pointing towards points of interest in the landscape. This is done in order to adhere to some current landscape qualities, such as the far views over the landscape.

Figure 31. Aeronautical map of the Netherlands (lvnl, 2021). Class C airspace areas in semi-transparent blue (predominantly circular) used as inspiration for the landscape composition.

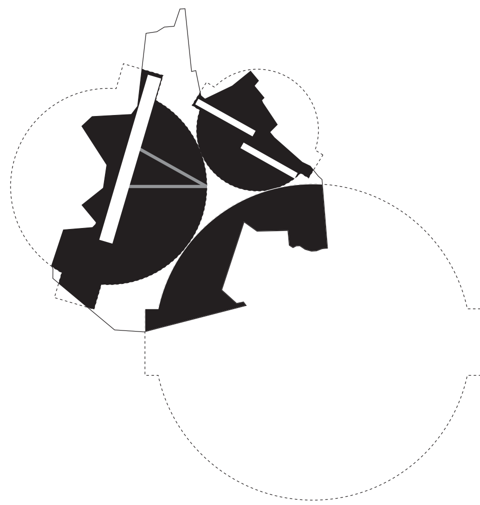
The presented landscape design (see Figure 33) is a captured moment of a possible situation in 2070 and represents the landscape design as it would be fully developed. A transition in the forestvoltaic system is visible in the areas that shift from the first to the second phase (northern most slices). The other afforested areas have also reached maturity. The landscape design is further discussed through the main features and functionalities of the main sections of the estate.

6.4.1. The Plateau

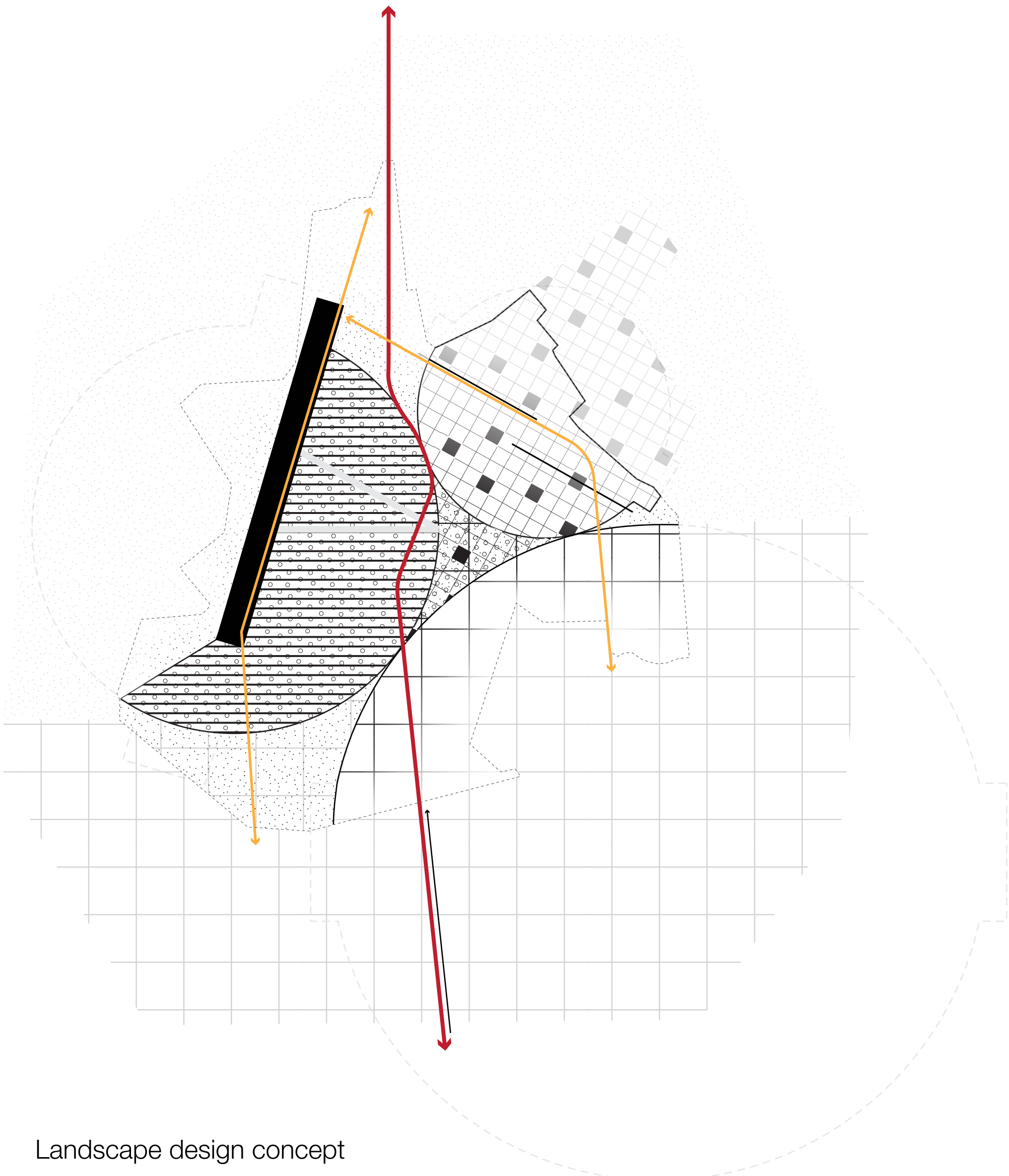
The Plateau is defined by a radial design that houses a forestvoltaic rotation system. This means that the forestvoltaic land use is an indefinite continuous land use in this area. The PV-panels are replaced with new ones once they reach their maximum lifetimes (see Figure 36). The area therefore becomes a dynamic forestvoltaic production landscape that produces both high quality wood, as well as renewable energy. In order to avoid much repetitiveness, variety is introduced by creating stands with different PV-densities within one stage of the radial. Being the centre part of the landscape, and visually the most prominent area of the landscape, this variety is required in light of multifuntionality and creating variety for recreational users, to increase landscape experience.

6.4.2. The Slope

This part of the landscape is more elevated than the rest of the estate. It therefore has as a natural overview over the airfield landscape. The Slope therefore somewhat maintains its openness and current agricultural land use. Nevertheless, the

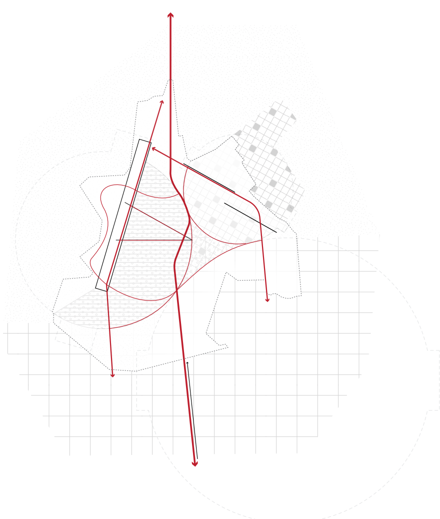


Landscape composition

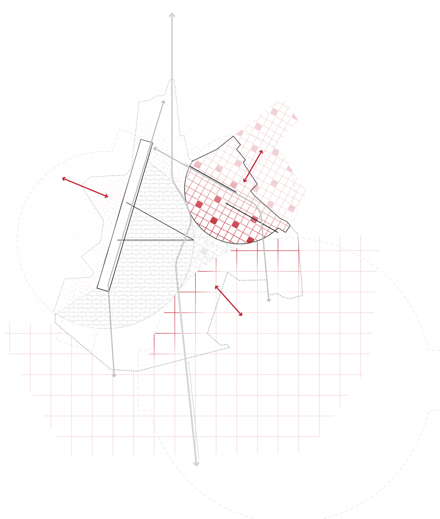


Landscape design concept

Production



Accessibility



Transitions

Figure 32. Landscape design concept guided by three priniples: production, accessibility and transitions

existing forest adjacent to the estate is extended into this circle. Two lines in the landscape define the transition between the two worlds. These lines are oriented in the same direction as the former Northwest-Southeast runway on the airfield, and are more or less parallel to the height contours of the landscape. Lanes of trees mark longer vistas further into the airbase landscape. A wood-based housing development is also located in this circle. These houses are built from the wood that is produced locally on the estate. As wood production takes places on a decadal time scale, this is envisioned as a long term development.

6.4.3. Schaarsbergen

The Schaarsbergen area is dedicated to development of forests with high naturalness. The objective in this area is biodiversity. Nevertheless, the forest development is done with an FV-system in which the PV-system is removed after the lifetime of the PV-panels. The system thereby only helps to develop a mixed forest by creating circumstances that are preferabe for non-pioneer species, mostly deciduous species. It neither focuses on timber production. Rather, selective cutting forest management yields timber as a side product of these forests. It is expected that this will still yield some high quality timber wood, but the intensity of the management is not pointed towards this quality. Rather, it is pointed towards maximising biodiversity, which sometimes contradicts high wood quality forest management. The recreational value of this forest is aimed towards multisensory appreciation of the natural landscape, rather than facilitated types of recreation.

6.4.4. The landing

The North-South runway and its taxiway to the west make up the Landing area. This is the most open element in the landscape and houses the longest vista of the estate with a view of over 2 km. The asphalt of the runway is kept as a relic of the former landscape. It can be used recreationally by cyclists, inline skaters, drone pilots and many more. The open space in between the runway and taxiway reminds to the openness and vastness of an airport landscape. It is covered in a heathland to facilitate open ecological connections between the east and west of the estate. The adjacency of the FV in the Plateau area creates a dynamic variety of forest edges along the Landing area. Sand paths and boardwalk routes run through the heatherland, to be able to experience the area from different perspectives.

6.4.5. The air-space

The air-space of the estate is the space that is not part of the main circles and lines that form the landscape composition (also refered to as negative space). These shapes are, though, very much defined by the main composition elements. It in-

LANDSCAPE DESIGN

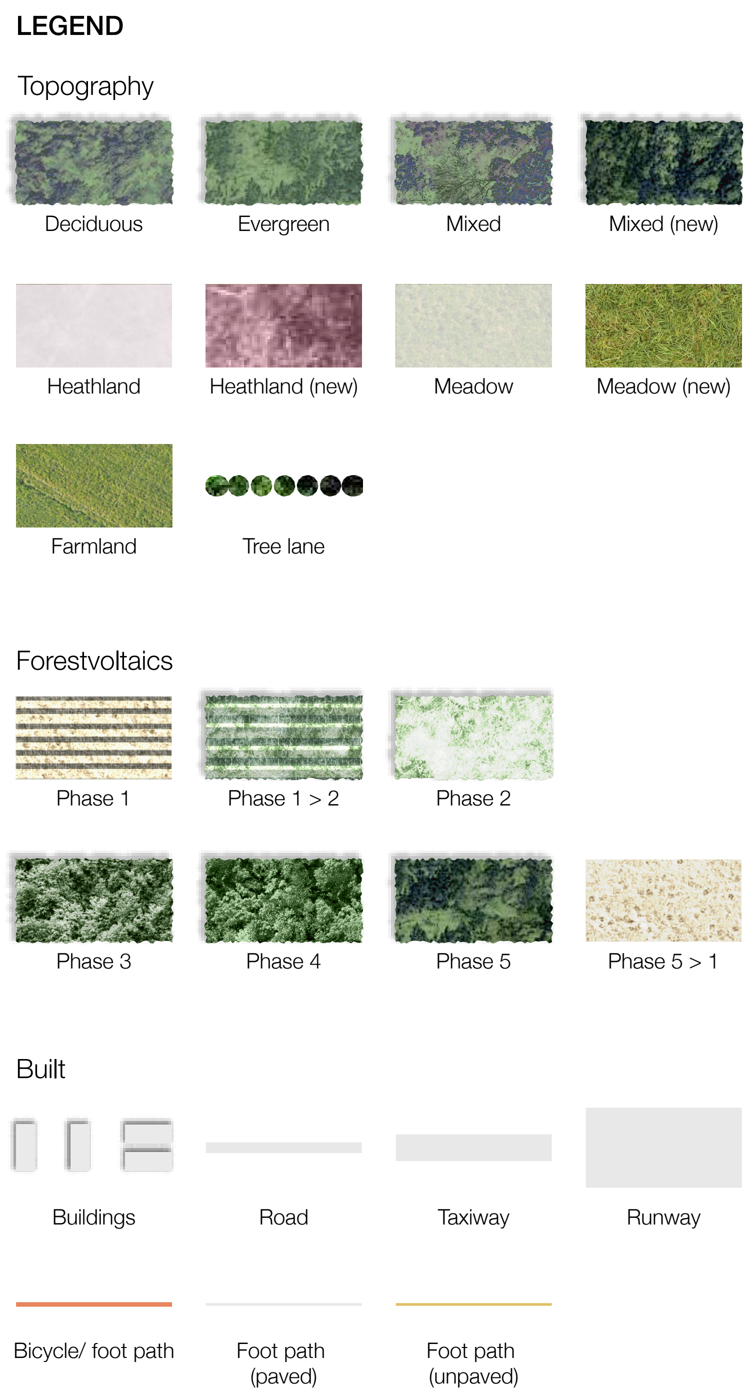
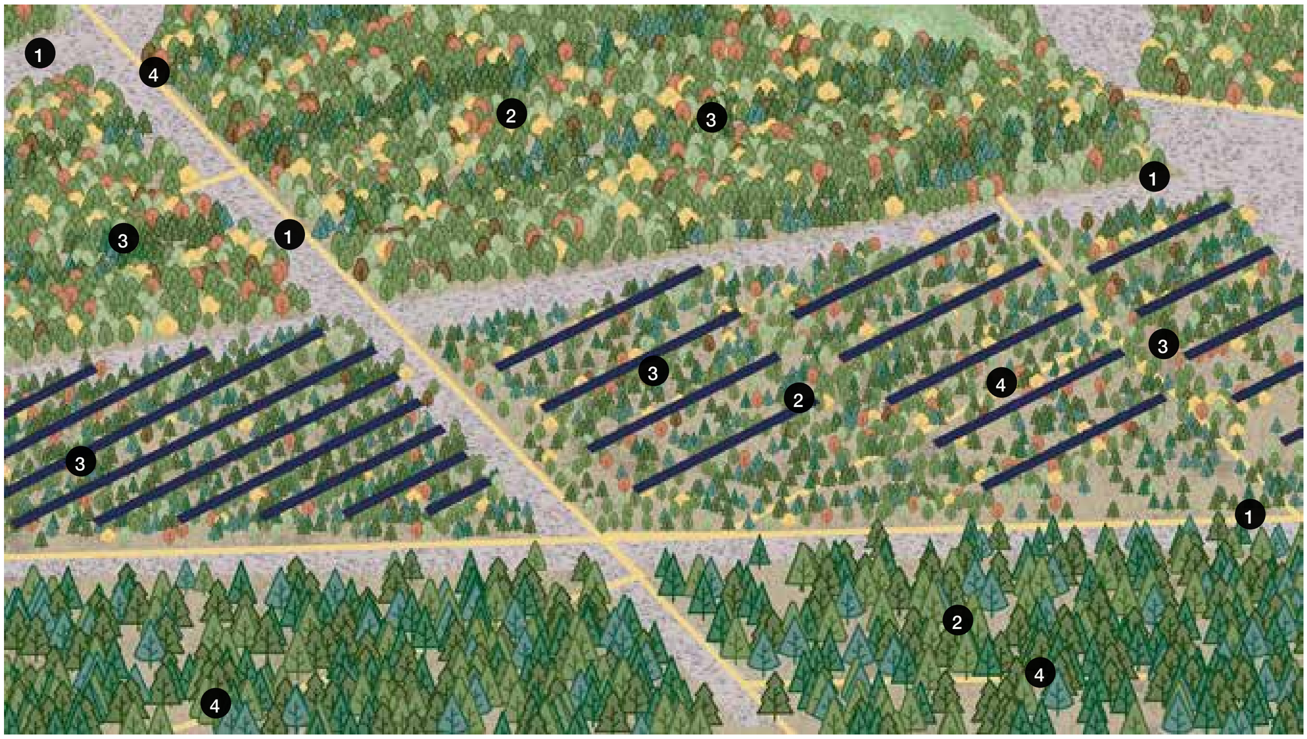


Figure 33. Landscape design of the Deelen carbon mitigation estate. Translated section names (black box with white text) from North to South: The Sand (1), The Start (2), The Slope (3), The Landing (4), The Park (5), The Plateau (6), The Schaarsbergen (7) and The Kempen Heatland (8). The various regions of the design are named after landscape features (3, 6), historic names of certain places (1, 2, 4, 7, 8) (see Kadaster, n.d.) or new names that correspond with the landscape design (5).

Deelerwoud
1. HET ZAND
Nationaal Park de Hoge Veluwe
2. DE START
3. DE HELLING
Deelen Museum
Lookout tower
4. DE LANDING
Treetop cycle route
Forestvoltaic rotation system
5. HET PARK
6. HET PLATEAU
Visitor centre
7. DE SCHAARSBERGEN
Veteran estate Vrijland
8. DE KEMPERHEIDE
0 100 200 300 400 500 600 700 800 900 1.000m
N


Currently

The plateau



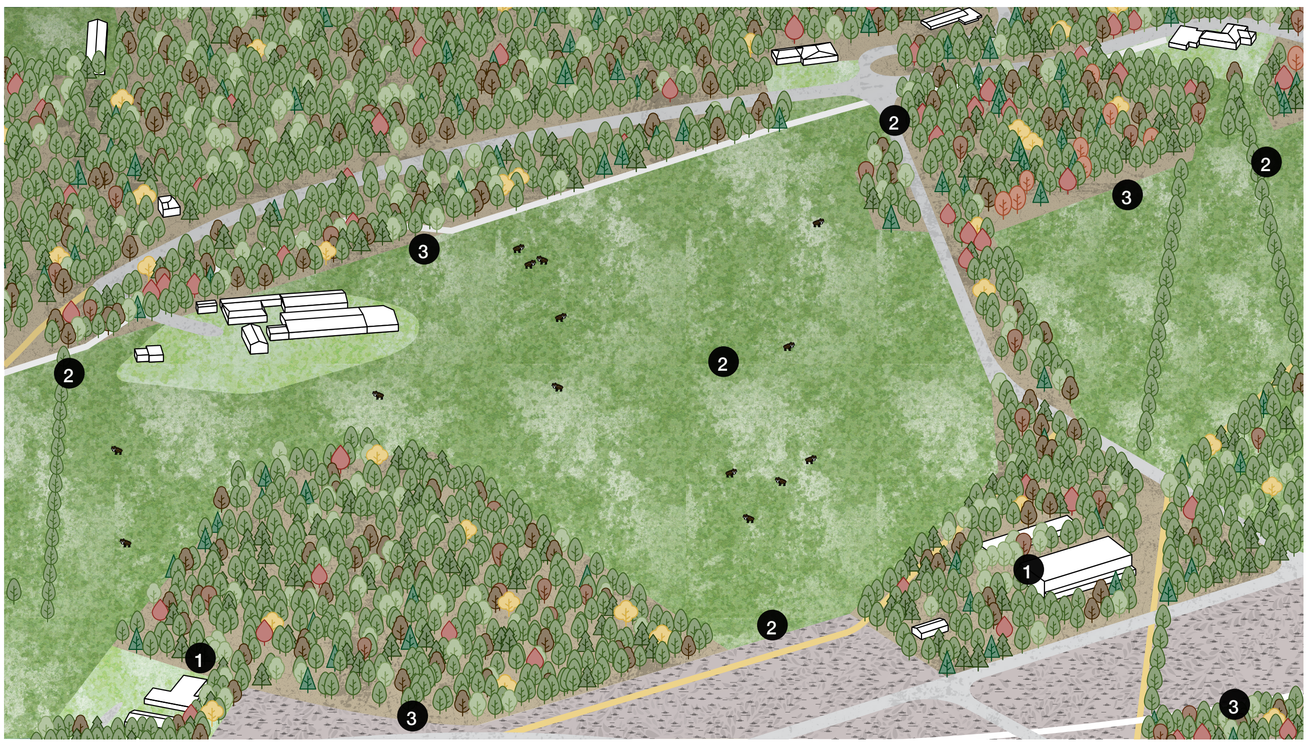
1. Long vistas in the landscape are maintained

2. Different stages of the permanent rotation FV-system clearly distinguishable

3. Variety in composition visible within one stage

4. Area accessible for visitors

The Slope



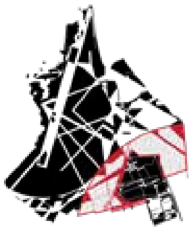
1. Retrofit on-site buildings to dwellings where possible

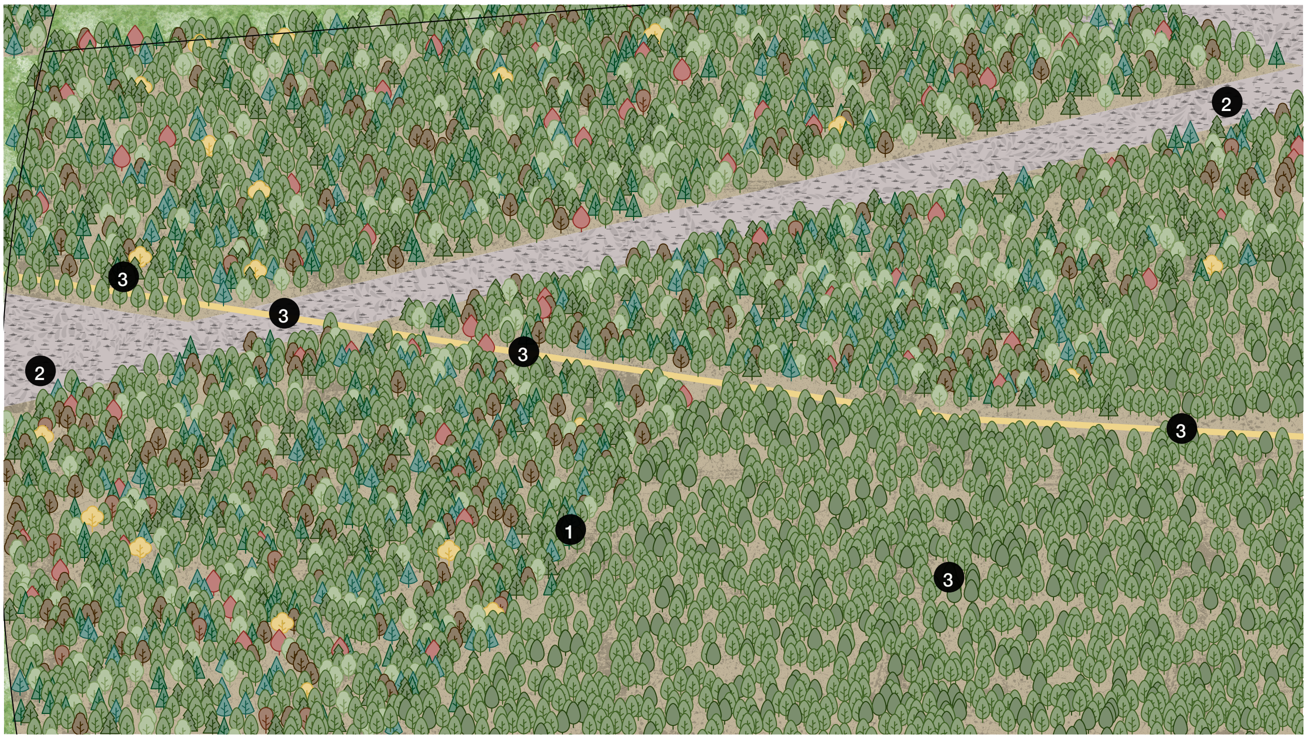
2. Keep some of the current land use to maintain wide open views downhill into and onto the landscape

3. Composition strongly defines the landscape

Figure 34. Landscape entities. Showing main principles in each landscape entity.

Schaarsbergen



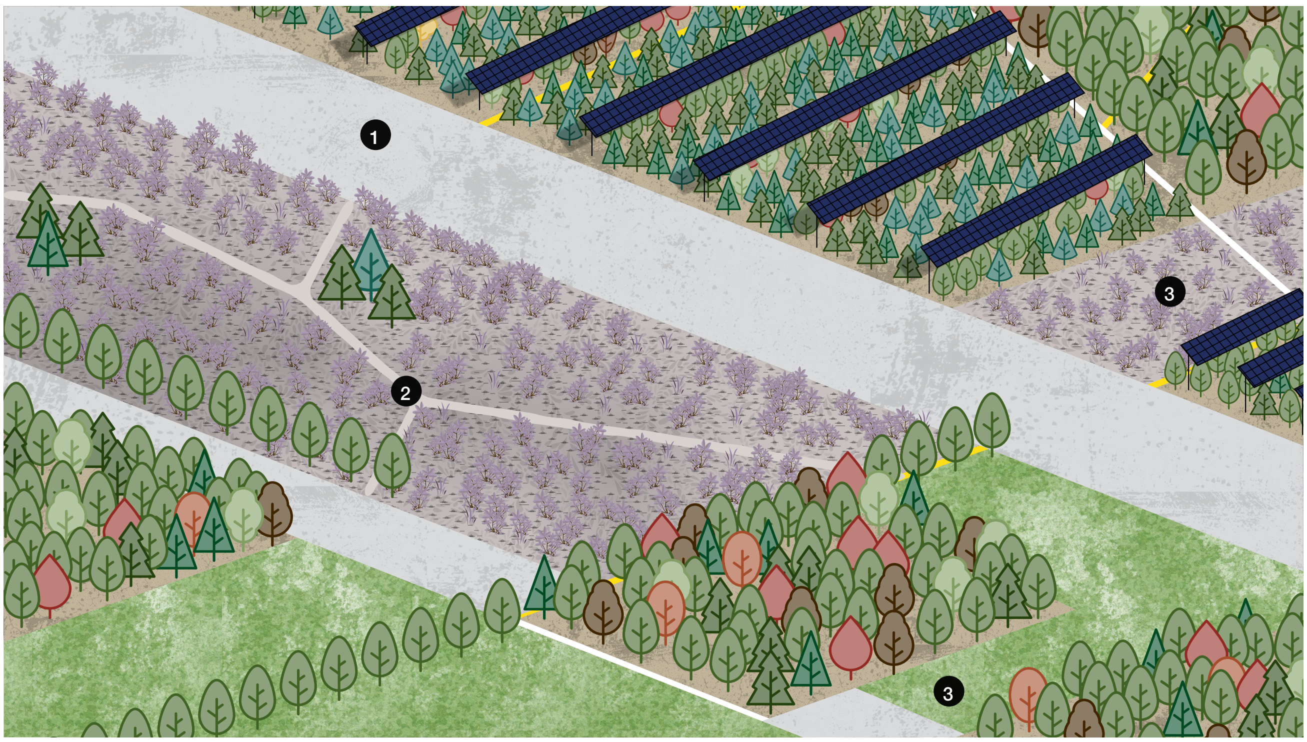


1. New mixed, biodiversity focused forest distinguishable from old patches

2. Long vistas maintained

3. Recreational routes provide a range of landscape experiences

The Landing

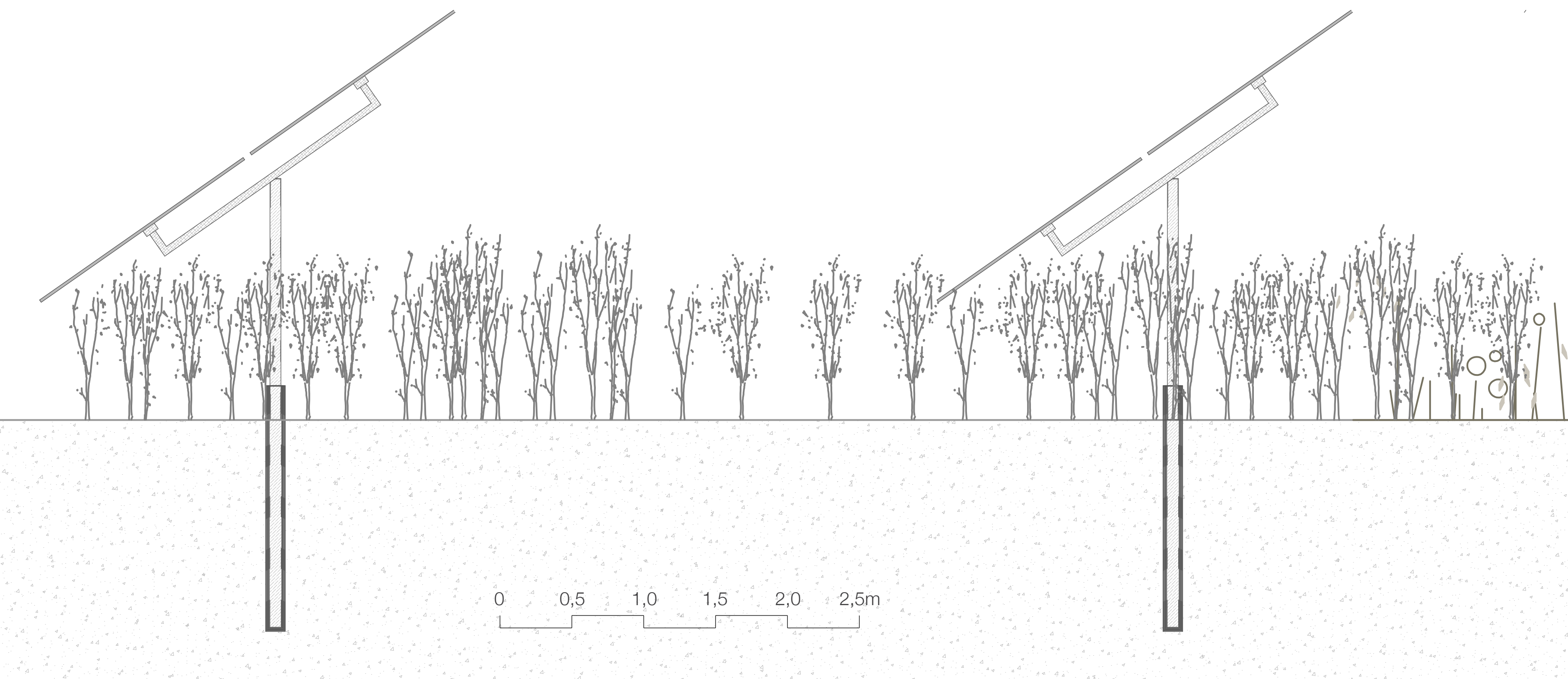


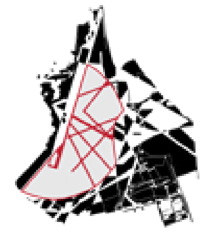
1. Runway kept as a relic in the landscape, serving as a giant axis for recereational uses such as skeelering

2. Heatherlands pulled further into the estate, sometimes accessible. serving as ecological connection and contribute to the openness of this landscape.

3.Various vistas throughout the landscape visible from here

Figure 35. Detail section of FV-system in the landscape in early stage (left page, right after planting) and by the end of phase 1 (right page, when trees reach approximately 8m height).





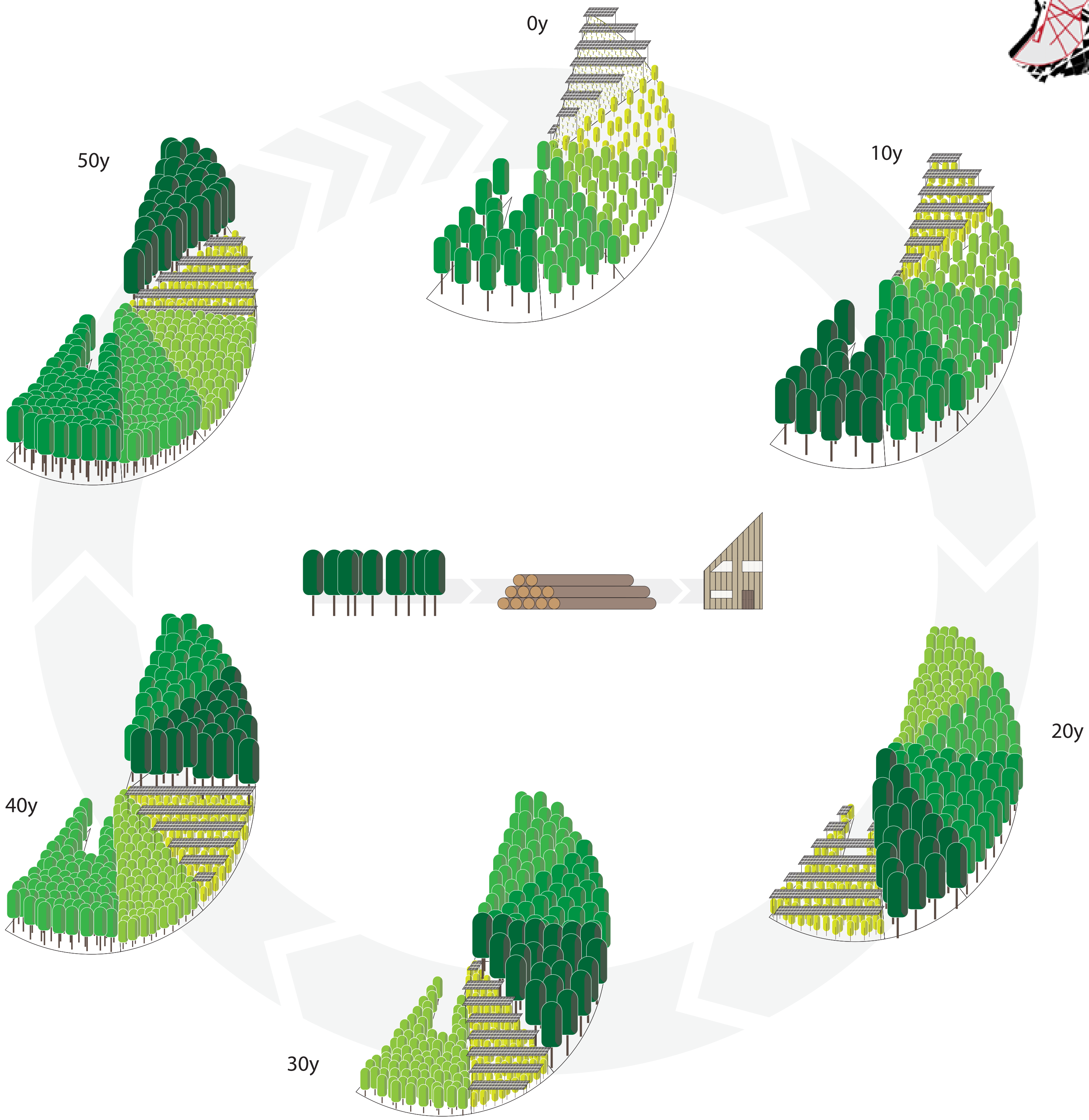


Figure 36. Forestvoltaic rotation system in an already forested area, or after a full startup development cycle, guided by FV. Different colours and tree size represent the age of a plot, small and light green is young, large and dark green is old, y = years in the cycle. A long term forestvoltaic system for repeated use, producing both for renewable energy and timber. The forest age advanced clockwise as the PV-systems move counter-clockwise. PV-panels are replaced after they reach their lifetime (ca 30 years). In a rotational system, the replanting time may be extended to fit 50 year lifetime of the trees, contrasting the single use forest development use of the forestvoltaic system which is catered to the lifetime of the PV-panels. Using the wood for biomass energy production nullifies the sequestered carbon in the biomass. Therefore, it is important that the timber is used for high quality products, such as building construction materials and furniture.

cludes the Sand, the Start and the Kempen Heathland. These areas serve predominantly as ecological connection zones between the national park and the heathery landscape to the east. They are characterized as visually more open, and host some forest patches within them. These forest patches can serve as smaller experimental research entities for forest development, forestvoltaic development or other forest-related research. Thereby, in addition to wood and renewable energy, the landscape can also be a source of new knowledge. The Park is an air-space in the estate as well. It is the most defined one, as it lays in between the main composition features, and is discussed next.

6.5. Site Design: The Park

The core of the estate is representative of the various landscape elements that are present throughout the estate. The estate core is characterized by smaller scale entities. This allows for a showcase of the estate within walking distances. The visitor centre is an educational hub for the various landscape transitions that are going on in the estate, providing explanations and back-stories. More so, the park adds to the educational function by letting people experience first hand what is happening in this landscape transition. Visitors can take a route through the park that highlights the features and functionalities of the estate. The small scale is therefore a very important characteristic of this area. From the visitors centre, there are several starting points for routes throughout the estate. The shorter walking routes are thematic, and often cover just some sections of the estate. This variety in walking routes serves different kinds of people, from technology-avoiding nature enthousiasts to people that appreciate modern renwable energy landscape multifunctionalities. The various pathways through the plateau area rotate along in these different kinds of experiences as the forestvoltaic cycle develops. The longer routes and bicycle routes cover more of the estate, among which the treetop bicycle route (see Figure 38).

Figure 37. Site design of the Park area: the core area of the estate, showcasing the features and functionalities of the estate

Table 12. Model evaluation for 2030 and 2050. The landscape design model is evaluated against the maximisation models that were introduced in chapter 4. The higher the number, the better the model performs. For carbon sequestration and energy production, both 2030 and 2050 are evaluated, in order to capture the effect of the temporary non-rotational forestvoltaic systems. The same sequestration and power generation values are used as in Table 4 and Table 5. A complete overview and explanation of the valuation can be found in Annex E.

	2030			2050		
Criterium \ Model	Carbon sequestration maximisation	Electricity maximisation	Multifunctional carbon mitigation forest landscape design	Carbon sequestration maximisation	Electricity maximisation	Multifunctional carbon mitigation forest landscape design
Carbon sequestration rate (Mg $CO_2 y^{-1}$)	2424	138,8	2311,4	4796	138,8	4037,0
Energy production (TWh y^{-1}, see Annex G)	0	0.35	0.083	0	0.55	0.021
Landscape quality (see Annex E)				150	107	211

6.6. Design evaluation

The landscape design model is evaluated against the mono-functional models presented in Chapter 4. The models are evaluated on carbon sequestration rate, energy production and landscape quality. The maximisation models show expected results: high values on their target use. The electricity maximisation models scores very low on landscape quality. The carbon sequestration model scores much higher on landscape quality than the energy maximisation model, but strongly lacks variety and a sense of placemaking.

The landscape design model scores lower on carbon sequestration rate and energy production than its maximisation counterparts. Still, the function combination of the forestvoltaic system does create a land use in which both carbon sequestration and energy production are present simultaneously, rather than either the one or the other. Theoretically, covering the entire estate with a forestvoltaic system could be most optimal in terms of combining carbon sequestration and energy production. However, in a very densely built country, landscape quality out-

Figure 38. Treetop bicycle route

weighes such considerations. The landscape design model is valued the highest for landscape quality. It was expected that a considerate designing process for a multifunctional landscape would result in higher landscape quality than the monofunctional alternatives. Nevertheless, the difference with the other models is very significant.

6.7. Design principles

Reflection on the RTD process has yielded four design principles for designing multifunctional carbon mitigation forest landscapes. These principles are guides in spatial configurations of forestvoltaic landscapes. They relate to the design considerations. The design considerations were literature based tools to set starting points for the designing process and focus on certain landscape functionalities. The design principles are guides in the spatial manifestations of these considerations. Although the principles are a result of a site-specific designing process, the formulation is generalized in order to fit other high sandy soil landscapes as well.

6.7.1. Design principle 1: Use the proper PV-configurations for the intended main land use.

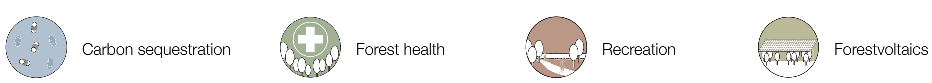
The spatial configuration of an FV-system is determinant for the main land use. When designing the landscape with FV, the main land use should be considered and the FV-system should be configurated accordingly. The land use after the PV-phase is the main director in choosing which FV-configuration is used. The targeted land-use and the permanence of FV or lack thereof are the main drivers behind these decisions.

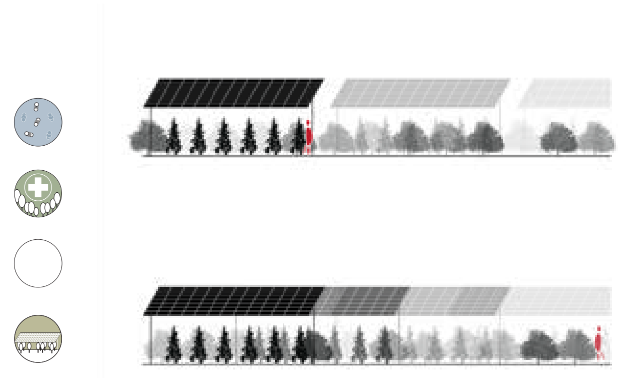
6.7.2. Design principle 2: Use a variety of forestvoltaic configurations on large plots.

A variety of configurations creates several other varieties in the landscape. (1) Variety in forest compositions, edges and transitions to other stand. Thereby a variety in ecological conditions. This has potentials for increased biodiversity. (2) Variety in landscape experiences. This improves landscape quality in both user value and experience value.

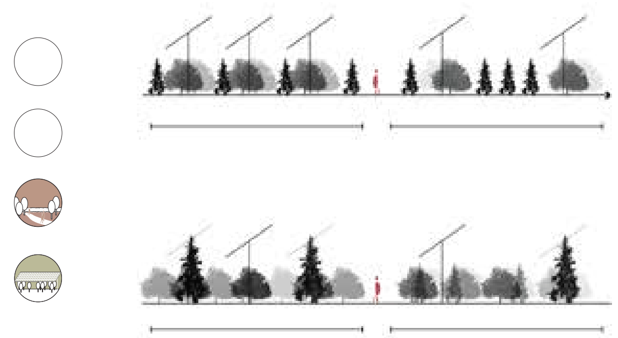
6.7.3. Design principle 3: Use height-adjustable PV-systems

Height adjustability of the FV-system is crucial in aiming for the synergetic cooling benefit that the forest can provide towards the PV-system. In addition, a height-adjustable system has landscape quality benefits over a static system, as it adheres to the dynamic of a growing forest.

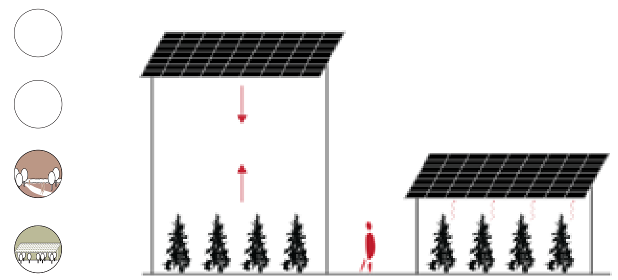




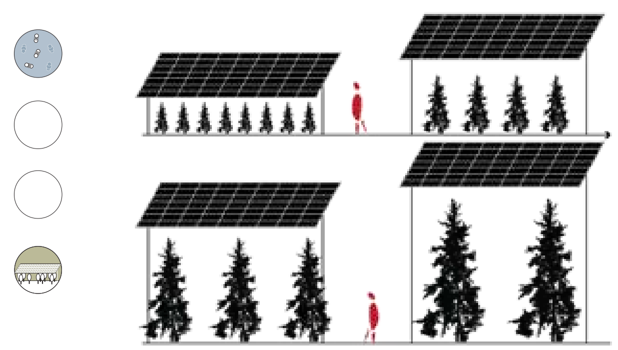
1. Use the proper PV-configurations for the intended main land use



2. Use a variety of forestvoltaic configurations on large plots



3. Use height-adjustable PV-systems



4. Use the temporal characteristic of the landscape entities to create a dynamic landscape

6.7.4. Design principle 4: Use the temporal characteristic of the landscape entities to create a dynamic landscape.

Creating dynamic multifunctional landscapes over static energy landscapes greatly improves landscape quality for user value, experience value and future value. The temporal characteristic of different stages of forest development, as well as the temporal characteristic of an energy system, due to its limited lifetime, create opportunities to create a lot of variety in the landscape through time. These dynamics will not be very obvious for daily visitors, but occasional visitors will experience an ever changing landscape.

7. Discussion

This chapter discusses the process and results of this thesis. First, the methods are adressed. Then, the results are discussed. This part covers the forestvoltaic principle, the design considerations, the landscape design, the absense of a participatory process, and the FV design principles.

7.1. Validity and reliability

Several techniques are used to increase validity and reliability of this research (see section 3.4). Most techniques rely on other work or reviews of experts, students or projects. The time available for this research strongly limits the amount and variety of experts and peers that can be consulted or to have discussions with.

7.2. Forestvoltaics

7.2.1. New forest synergy

The forestvoltaic system is a new proposed synergy between forest development and renewable energy production. To our knowledge, there are no practical examples of (tests with) such a system. The theoretical baseline of the principle is therefore somewhat speculative. It is recommended that further studies are carried out with regard to forestvoltaic systems. A range of studies is required to get a good understanding of the system itself. These studies can focus on topics such as tree growth (for various species), biological carbon sequestration, biodiversity, effects on the hydrological situation, the effect of various types of PV-cells (opaque c-Si, transparent perovskite, tandem cells) on these topics. Despite this concept being novel and yet to become experimental, the need for climate action is high enough to have this area serve as a pilot project for the forestvoltaic principle. The energy production is relatively predictable, so the potential for renewable energy production is certainly present in this landscape. The highest uncertainty is the quality of trees that have grown underneath or in between PV-arrays in the first stages of their lives, the growth speed of these trees and the true effects on carbon sequestration.

7.2.2. Spatial configurations

Seven spatial models for a forestvolatic system were analyzed and tested. These models are a result of an iterative designing process. Although various models were carefully considered, it is not an exhaustive list of all imaginable possibilities. These models give a bandwidth of configurations that have shown to be of interest for various forest developments. Moreover, the model analysis was done on one scale and shows scalability. Nevertheless, designing on other scales may have resulted in other models in addition to the seven that are discussed in this research.

7.3. Design considerations

The design considerations are generated within the limitations of the available time and used literature. The researcher is aware that the formulation of the design considerations is possible in many ways, depending on the previously mentioned limitations, as well as the analytical and design capabilities of the researcher. The presented design considerations are therefore *a* set of considerations, rather than *the* set of considerations on designing a carbon mitigation forest landscape.

7.4. Participation & landscape design

PV-park projects are prone to a lot of resistance from local residents (see section 2.1.7.2). This thesis however, seems to propose a landscape design without the notion of a participatory process. The reason for this approach is (1) because it is research oriented, rather than site oriented, but more importantly (2) because the chosen site is owned by the national army, and no concrete plans of relocation of this army base are yet announced. There have been some off the record voices saying this landscape will change its function in a few years. However, the only public information available for this site is that it is allocated as an energy landscape in the draft version of the environmental vision document of the municipality of Arnhem for 2040 (gemeente Arnhem, 2020). Therefore, this design research has been done without notifying the authorities of that landscape and without including local citizens.

7.5. Actors and sources of inspiration

The fact that no other parties are involved in this landcape design means that a lot of information from various parties with a potential interest in the area may be missing. Such information could have led to new insights into the area. These information bases and insights would probably have impacted the way the landscape design unfolded. The landscape design was thus based on the landscape vision as defined by the researcher of this thesis, some available documents on the area, which often were quite objective descriptions of the area. The input that was closest to stakeholder input came from (Dekker & Jungerius, 2017), in which several experts in landscape design, cultural geography or land art shared stories, visions and addressed issues on the landscape. Nevertheless, this source views the landscape from expert views in related fields of study, and does not entail the view of potential everyday users of the landscape.

7.6. Design interpretation

This thesis should not be regarded as a finished landscape design to be implemented at the site, but as a possible future situation in a landscape that is now inaccessible in a larger landscape that suffers from impermeability. A participatory process for this energy landscape design is recommended once the land use change of this area becomes public. The results from this thesis should then be used in the designing process, and the landscape design proposed in chapter 6 can be used as a reference or starting point.

7.7. Design principles

The design principles that are extracted from the RTD process predominantly focus on the forestvoltaic system, and only to some extent on other carbon mitigation landscape design entities. This result can be explained from the novelty of the forestvoltaic system. The design considerations on this topic are not necessarily spatial in nature. The implementation of the other design considerations have shown to be very site dependent and difficult to distill into generalizable design principles.

8. Conclusions

Climate change mitigation efforts are steering governments into planting new forests on large scale. Simultaneously, fossil energy sources are to be replaced by renewable energy sources. Both trends have a large impact on land use and call for landscape transformations on a large scale.This design research responds to challenges that emerge from these trends. The research attempts to optimize land use efficiency by proposing new ways of combining these landscape transformations to create multifunctional landscapes. This is especially relevant for very densely built countries. The research is done at a testbed location, airbase Deelen inn the Netherlands. It is therefore conducted along the following research question:

> *Can the landscape of airbase Deelen provide design principles for designing multifunctional carbon mitigation forest landscapes on dry, sandy soils?*

The answer to the research question is yes, Airbase Deelen is suitable as a testbed area to create design principles for multifunctional carbon mitigation landscapes.

The research consisted of a RFD part, with knowledge questions and a RTD part, with design questions. The knowledge derived from the RFD part was concluded into design considerations that were used in the RTD part. The design considerations created an evidence-based foundation to design the landscape while focusing on the afforestation and renewable energy challenges. The most promising finding was the FV-system, a potential synergetic land use between forest development and solar power production. It establishes new function combinations in the landscape. The temporal factors of a growing forest and a limited lifetime of a PV-panel is embraced in order to create a dynamic landscape, rather than feared to keep maintenance of the FV-system as low as possible. Various configurations of an FV system are tested and have resulted in a toolset of various different kinds of FV developments with a focus on production, biodiversity and/or recreation. As a result, several principles with regard to carbon sequestration, biodiversity and recreational combinations were retrieved from the iterative RTD process.

The design considerations and the design principles form a set of guides for designing carbon mitigation landscapes. The design considerations provide guides for the workings and composition of the landscape. The design principles guide in the spatial configuration. It is concluded that both sets of guides combined contribute to designing multifunctional carbon mitigation landscapes. Either one set on it's own does not cover the full range of multifunctionality between carbon sequestration, energy production, biodiversity management and recreation.

The landscape designing process served as a way to create design principles, steered by the design considerations. The landscape design was evaluated against the criteria carbon sequestration, energy production and landscape quality. The proposed landscape design does not maximise the potential of carbon sequestration or energy production, as can be seen by the comparative evaluated landscape models. This research shows that, in countries or places where landscape quality is or should be regarded important, landscape transitions should not aim to maximise one productive potential in the landscape. Rather, a balance between productivity and landscape quality should be found. It was found that these parameters can be mutually exclusive, especially in a large scale landscape design. Nevertheless, smart function combinations can help in keeping productivity high, while still creating high quality landscapes.

This research contributes to the scientific knowledge base in energy landscape architecture by proposing design principles to deal with several landscape transitions. This research focused on dry sandy soils, but the principles may serve as a starting point for other landscape types as well, where the potential principles should be re-evaluated against the various conditions (geology, hydrology, ecology, et cetera). Additionally, these design principles and in particular the FV-system, may serve as an inspiration for finding new function combinations in other fields. It can direct a way of thinking about systems that on first hand do not really seem to have a high combination potential.

This research proposes a new, literature based land use function combination. It provides opportunities for empirical studies in the actual workings of the system for various fields: photovoltaics, forestry, ecology, as well as environmental psychology. This research thereby contributes to an expanding body of knowledge on multifunctional carbon mitigation landscapes.

The design considerations and principles can serve as a toolbox for landscape design projects that involve afforestation. Additionally, it can serve as a starting point for discussions with land owners concerning land use changes on their land, in light of both afforestation and the energy transition.

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Appendix

Annex A. European forest categories & types

Annex table 1. European forest classification. Categories that are present in the Netherlands in bold, potential natural occurence in the Netherlands in italics (Barbati et al., 2014; European Environment Agency, 2007; van der Sluis et al., 2019).

Category		Type	
1.	Boreal forests	1.1. 1.2.	Spruce and spruce-birch boreal forest Pine and pine-birch boreal forest
2.	**Hemiboreal forest and nemoral coniferous and mixed broadleaved-coniferous forest**	2.1. **2.2.** 2.3. 2.4. 2.5. 2.6.	Hemiboreal forest **Nemoral Scots pine forest** Nemoral spruce forest Nemoral Black pine forest Mixed Scots pine-birch forest Mixed Scots pine-pedunculate oak forest
3.	Alpine coniferous forests	3.1. 3.2. 3.3.	Subalpine larch-arolla pine and dwarf pine forest Subalpine and mountainous spruce and mountainous mixed spruce-silver fir forest Alpine Scots pine and Black pine forest
4.	**Acidophilous oak and oak-birch forest**	**4.1.** **4.2.**	**Acidophilous oakwood** **Oak-birch forest**
5.	**Mesophytic deciduous forest**	5.1. 5.2. *5.3.* **5.4.** 5.5. 5.6. 5.7. 5.8. 5.9.	Pedunculate oak–hornbeam forest Sessile oak–hornbeam forest *Ashwood and oak-ash forest* **Maple-oak forest** Lime-oak forest Maple-lime forest Lime forest Ravine and slope forest Other mesophytic deciduous forests
6.	**Beech forest**	6.1. **6.2.** 6.3. 6.4. 6.5. 6.6. 6.7.	Lowland beech forest of southern Scandinavia and north central Europe **Atlantic and subatlantic lowland beech forest** Subatlantic submountainous beech forest Central European submountainous beech forest Carpathian submountainous beech forest Illyrian submountainous beech forest Moesian submountainous beech forest
7.	Mountainous beech forest	7.1. 7.2. 7.3. 7.4. 7.5. 7.6. 7.7. 7.8.	South western European mountainous beech forest (Cantabrians, Pyrenees, central Massif, south western Alps) Central European mountainous beech forest Apennine-Corsican mountainous beech forest Illyrian mountainous beech forest Carpathian mountainous beech forest Moesian mountainous beech forest Crimean mountainous beech forest Oriental beech and hornbeam-oriental beech forest
8.	Thermophilous deciduous forest	8.1. 8.2. 8.3. 8.4. 8.5. 8.6. 8.7. 8.8.	Downy oak forest Turkey oak, Hungarian oak and Sessile oak forest Pyrenean oak forest Portuguese oak and Mirbeck's oak Iberian forest Macedonian oak forest Valonia oak forest Chestnut forest Other thermophilous deciduous forests
9.	Broadleaved evergreen forest	9.1. 9.2. 9.3. 9.4. 9.5.	Mediterranean evergreen oak forest Olive-carob forest Palm groves Macaronesian laurisilva Other sclerophlyllous forests

Category		Type
10.	Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.1. Mediterranean pine forest 10.2. Mediterranean and Anatolian Black pine forest 10.3. Canarian pine forest 10.4. Mediterranean and Anatolian Scots pine forest 10.5. Alti-Mediterranean pine forest 10.6. Mediterranean and Anatolian fir forest 10.7. Juniper forest 10.8. Cypress forest 10.9. Cedar forest 10.10. Tetraclinis articulata stands 10.11. Mediterranean yew stands
11.	Mire and swamp forest	11.1. Conifer dominated or mixed mire forest 11.2. Alder swamp forest 11.3. Birch swamp forest 11.4. Pedunculate oak swamp forest 11.5. Aspen swamp forest
12.	**Floodplain forest**	12.1. Riparian forest **12.2. Fluvial forest** 12.3. Mediterranean and Macaronesian riparian forest
13.	**Non riverine alder, birch, or aspen forest**	13.1. Alder forest 13.2. Italian alder forest 13.3. Mountain birch forest **13.4. Other birch forest** 13.5. Aspen forest
14.	**Plantations and self sown exotic forest**	**14.1. Plantations of site-native species** **14.2. Plantations of not-site-native species and self-sown exotic forest**

Annex B. Carbon sequestration rates

Annex table 2. Carbon sequestration rates for various tree species. Context 1 = plantation 5000 trees/hectare with thinning and an average bonity with a rotation length of 50 years.

Tree species	Context	Carbon sequestration rate (tCO_2/ha/y)	Source
Deciduous			
Acer pseudoplatanus	1	9.0	Lerink, et al., 2020
Alnus glutinosa	1	7.3	Lerink, et al., 2020
Betula pendula	1	3.2	Lerink, et al., 2020
Fagus sylvatica	1	11.8	Lerink, et al., 2020
Fraxinus excelsior	1	10.9	Lerink, et al., 2020
Populus nigra	1	5.4	Lerink, et al., 2020
Populus tremula	1	3.7	Lerink, et al., 2020
Quercus robur	1	7.5	Lerink, et al., 2020
Quercus rubra	1	8.0	Lerink, et al., 2020
Conifers			
Larix kaempferi	1	4.4	Lerink, et al., 2020
Picea abies	1	8.1	Lerink, et al., 2020
Pinus nigra	1	6.3	Lerink, et al., 2020
Pinus nigra spp nigra	1	5.5	Lerink, et al., 2020
Pinus sylvestris	1	4.3	Lerink, et al., 2020
Pseudotsuga menziesii	1	12.0	Lerink, et al., 2020

Annex C. Explanation of tree species characteristics

Based on Lerink et al., 2020

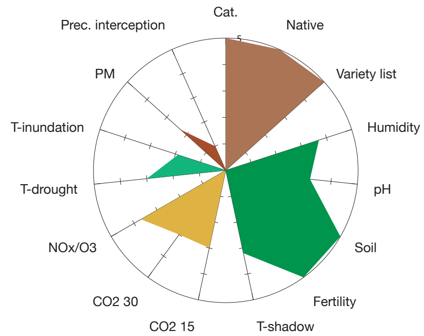
Annex table 3. Explanation of the labels and values of the tree species characteristics comparison in Annex D. Colours in the diagrams represent the characteristics group (first column).

Group	Label	Explanation	Values (data points with value 0 are unknown)
General	Cat.	Experiences with the species in forests or in the landscape	1 = lesser known species, 5 = known species.
	Native	Is the species native to the Netherlands?	1 = no, 5 = yes.
	Variety List	Presence on variety list (de Raad voor Plantenrassen, n.d.).	1 = no, 5 = yes.
Habitat properties	Humidity	Soil humidity requirements	1 = humid/wet, 2.3 = humid, 3.7 = humid/dry, 5 = dry.
	pH	Soil acidity	1 = 1, 2 = 4, 3 = 7 (neutral), 4 = 10, 5 = 13. (float number scale)
	Soil	Soil type that suits the tree	1 = clay, 2.3 = “bodemvaag”, 3.7 = sandy, 5 = sand.
	Fertility	Required soil fertility	1 = not too poor, 2 = low fertility, 3 = nutrient poor to rich, 4 = average to high fertility, 5= high fertility / no preference.
	T-shadow	Shadow tolerance	1 = very intolerant (>50% light required), 2 = intolerant (25-50%), 3 = moderately tolerant (10-25%), 4 = tolerant (5-10%), 5 = very tolerant (2-5%).
Climate properties mitigation	CO2 15	CO_2-sequestration capacity relative to other species over a time period of 15 years, based on growth rate.	1 = relatively low, 5 = relatively high (integer number scale)
	CO2 30	CO_2-sequestration capacity relative to other species over a time period of 15 years, based on growth rate.	1 = relatively low, 5 = relatively high (integer number scale)
	NOx/O3	Relative capture rate of O_3 and NOx-gases. Based on leaf size	1 = small capture capacity, 2.3 = moderate capture capacity, 3.7 = large capture capacity, 5 = very large capture capacity.
Climate properties adaptation	T-drought	Drought tolerance	1 = very intolerant, 5 = very tolerant (integer number scale)
	T-inundation	Inundation tolerance	1 = very intolerant (at most a few days of water saturaed soil during growth season), 2 = intolerant (1-2 weeks of water saturated soil in growth season), 3 = moderately tolerant (up to 30 days of water saturated soil in growth season), 4 = tolerant (the whole growth season water saturated soil), 5 = very tolerant (more than a conscutive year water saturated soil).
Ecosystem services	PM	Capture capacity of fine particle matter (PM)	1 = small capture capacity, 2.3 = moderate capture capacity, 3.7 = large capture capacity, 5 = very large capture capacity
	Prec. interception	Interception of the precipitation. Based on crown size and bark roughness.	1 = little interception, 5 = much interception

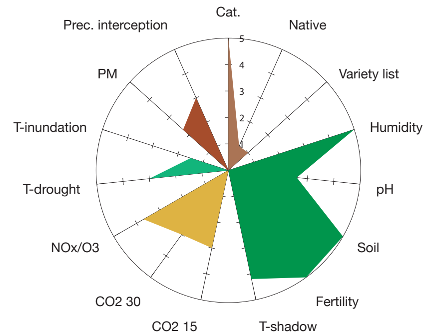
Annex D. Tree species characteristics

Based on Lerink et al., 2020

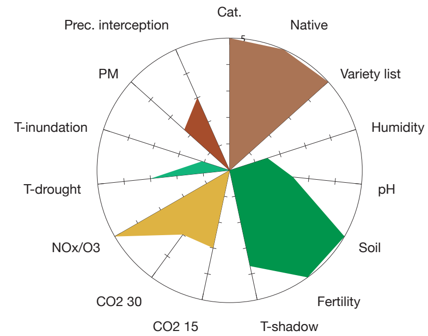
Broadleaf



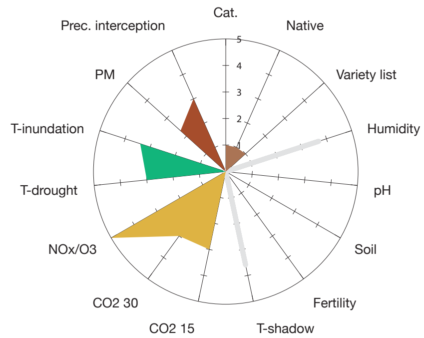
Acer campestre



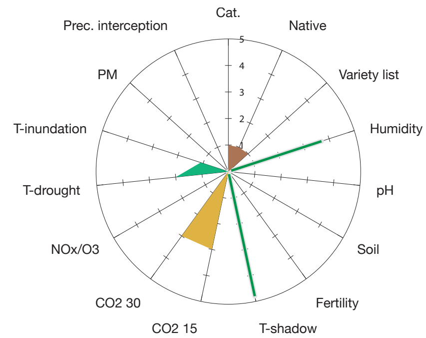
Acer platanoides



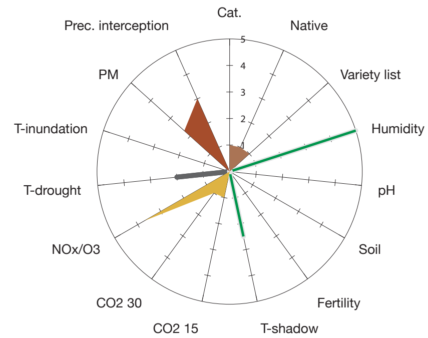
Acer pseudoplatanus



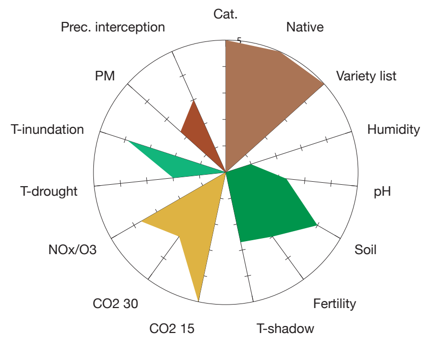
Acer saccharinum



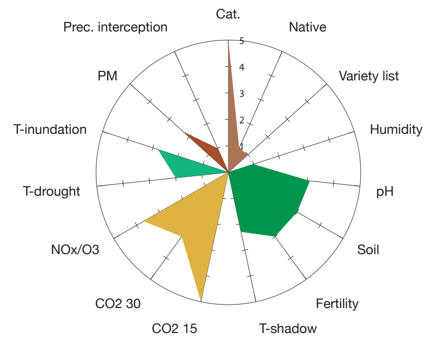
Acer saccharum



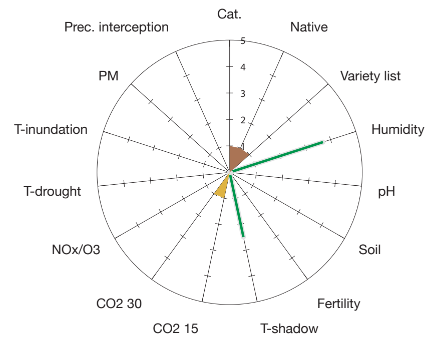
Alnus cordata



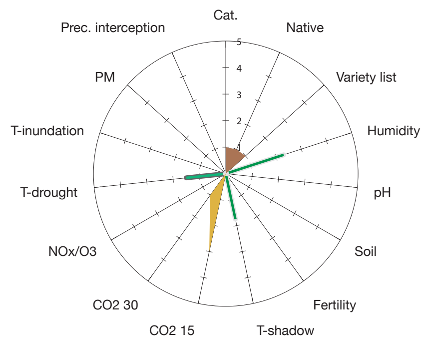
Alnus glutinosa



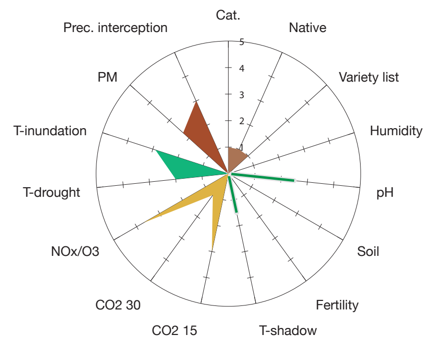
Alnus incana



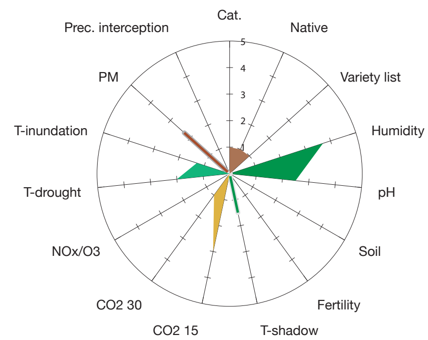
Alnus subcordata



Betula maximowicziana

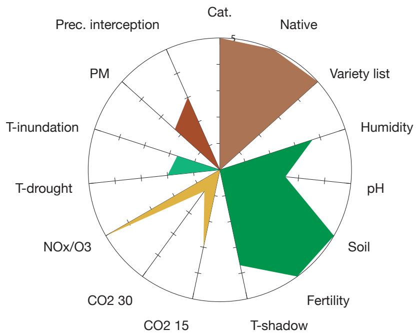


Betula nigra

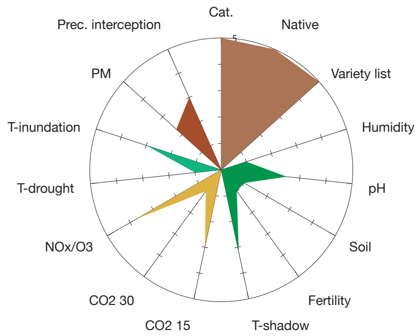


Betula papyrifera

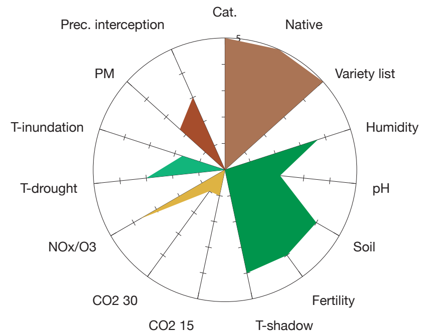
Broadleaf



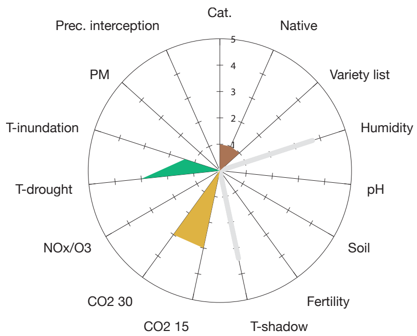
Betula pendula



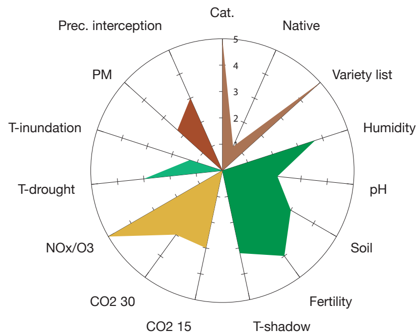
Betula pubescens



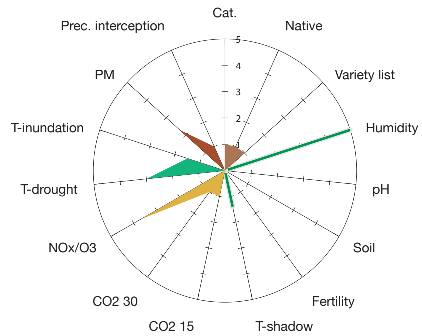
Carpinus betulus



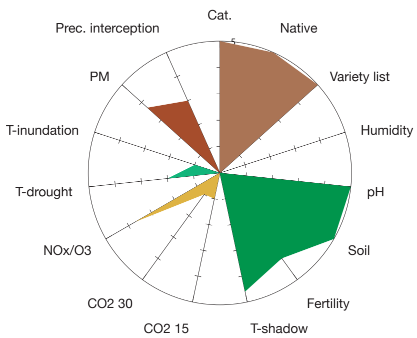
Carya ovata



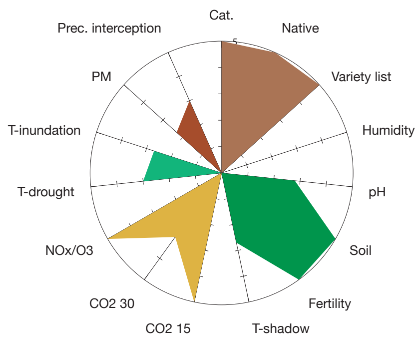
Castanea sativa



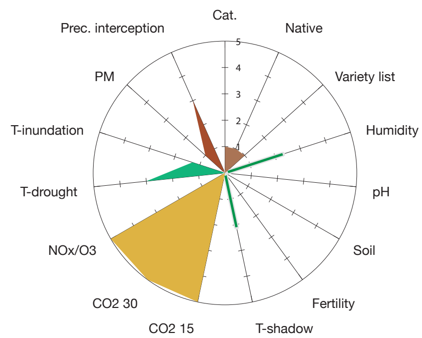
Corylus colurna



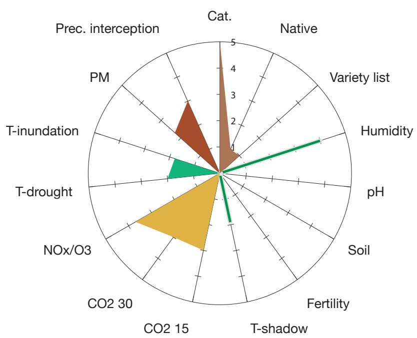
Fagus sylvatica



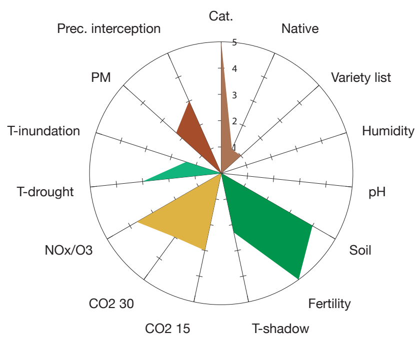
Fraxinus excelsior



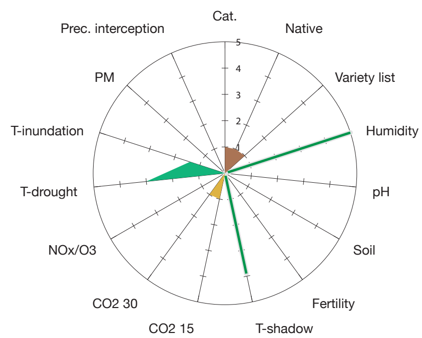
Liriondendron tulipifera



Juglans nigra

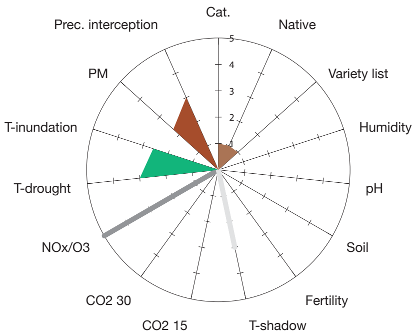


Juglans regia

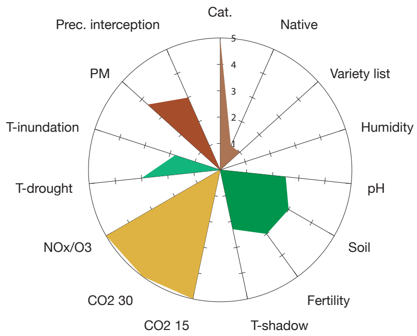


Ostrya carpinifolia

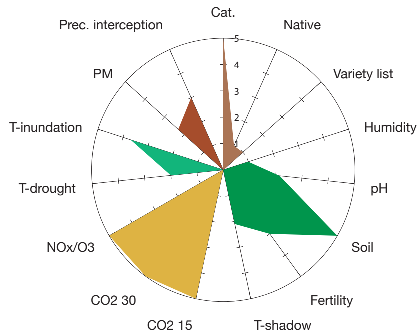
Broadleaf



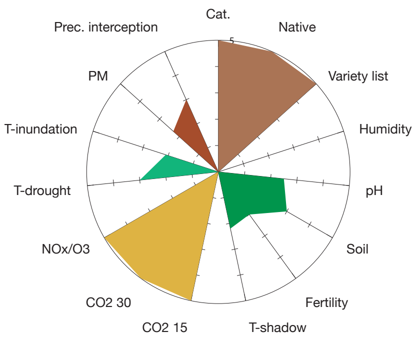
Platanus x acerifolia



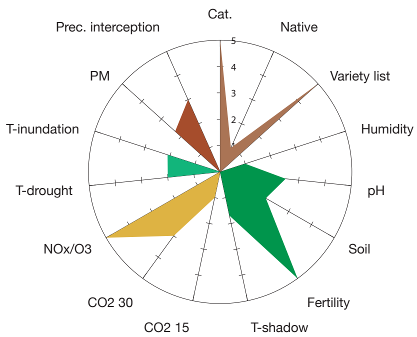
Populus alba



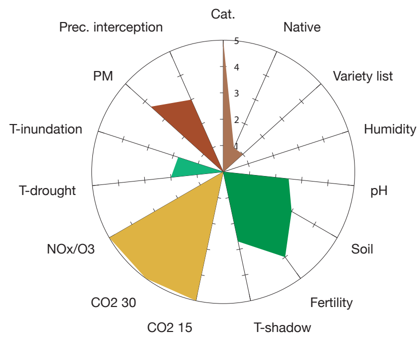
Populus nigra



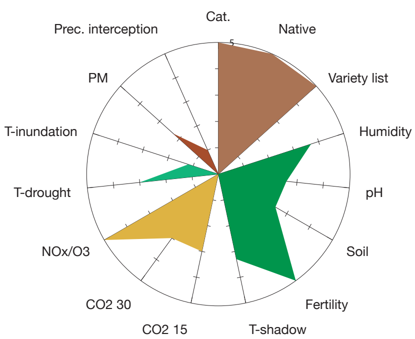
Populus tremula



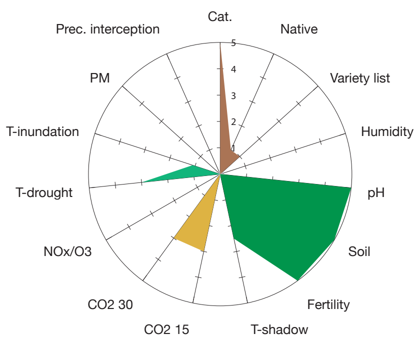
Populus x canadensis



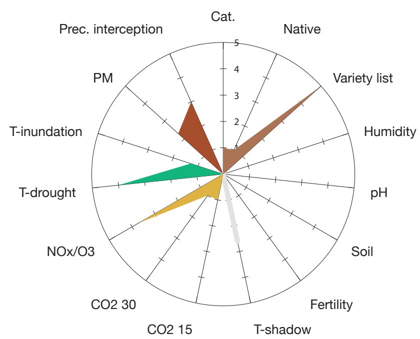
Populus x canescens



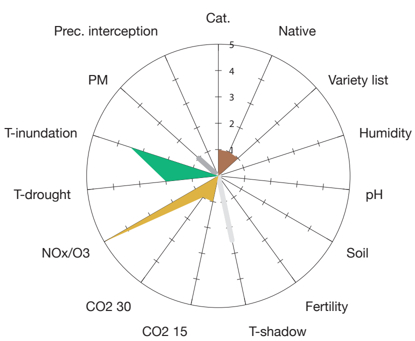
Prunus avium



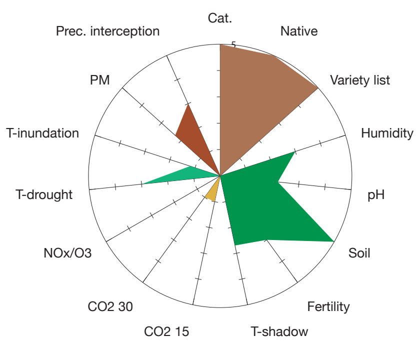
Prunus serotina



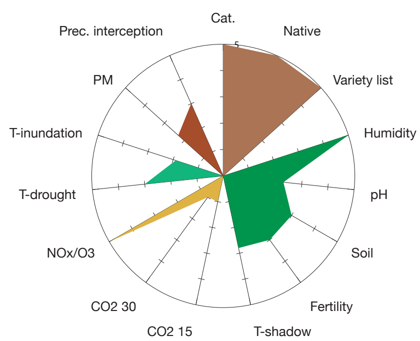
Quercus cerris



Quercus palustris

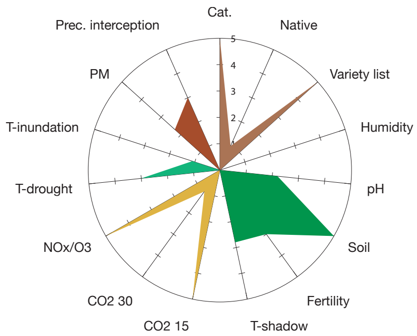


Quercus petraea

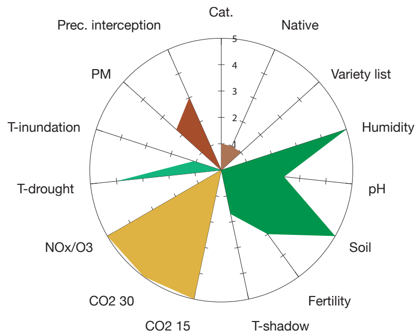


Quercus robur

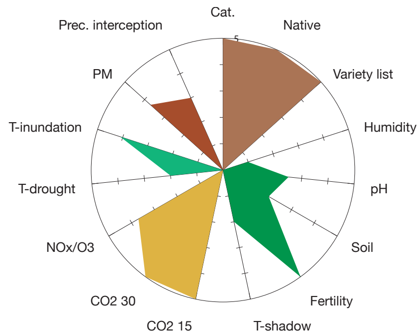
Broadleaf



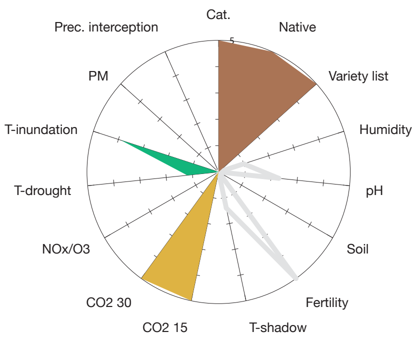
Quercus rubra



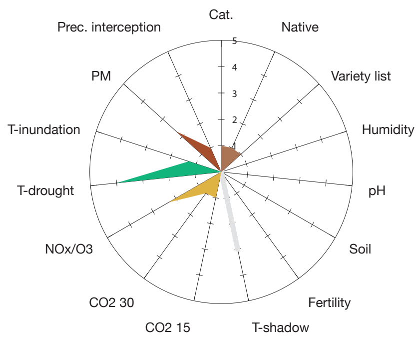
Robinia pseudoacacia



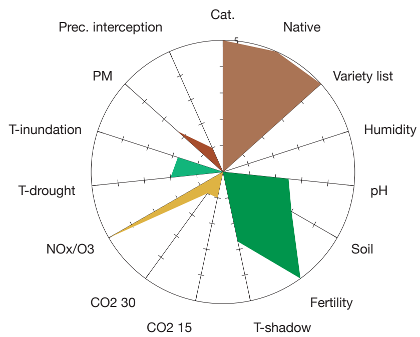
Salix alba



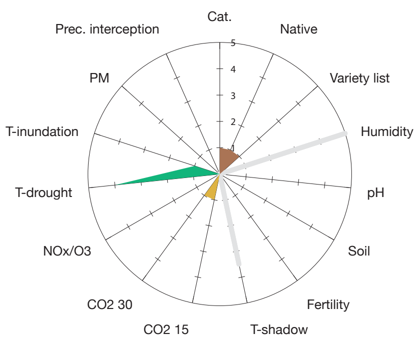
Salix fragilis



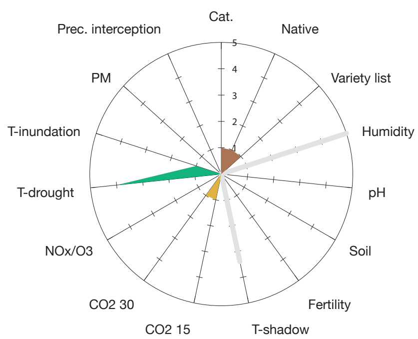
Sorbus aria



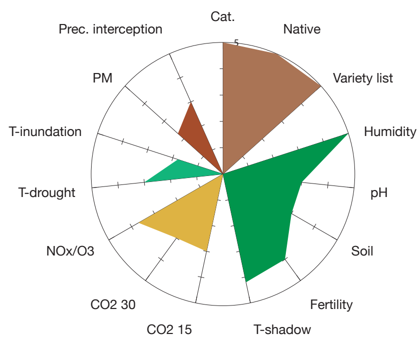
Sorbus aucuparia



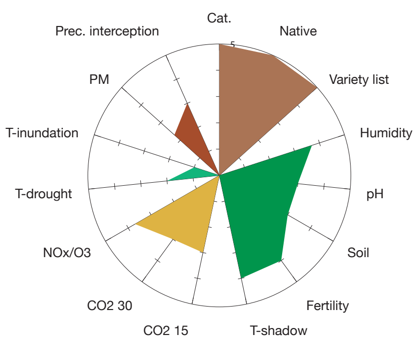
Sorbus domestica



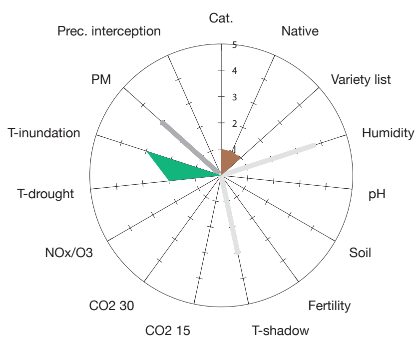
Sorbus torminalis



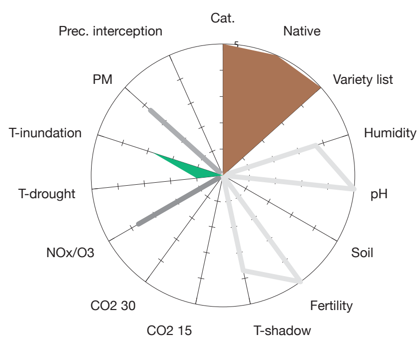
Tilia cordata



Tilia platyphyllos

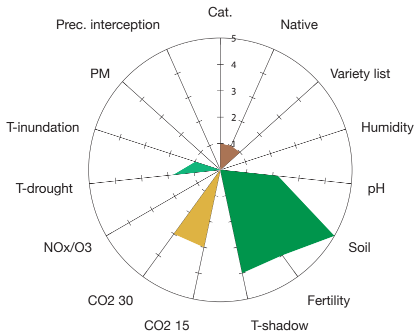


Ulmus davidiana

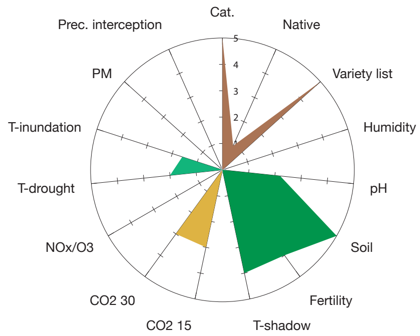


Ulmus laevis

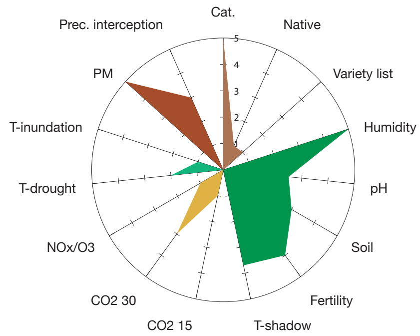
Conifer



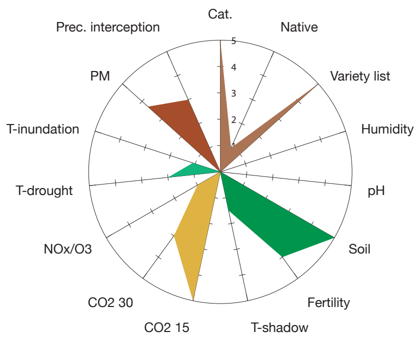
Abies alba



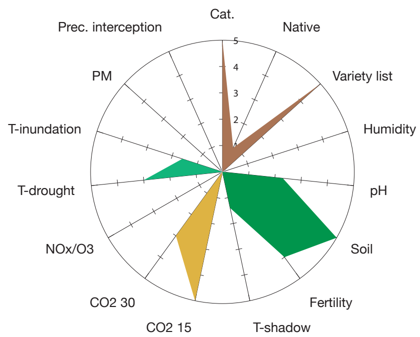
Abies grandis



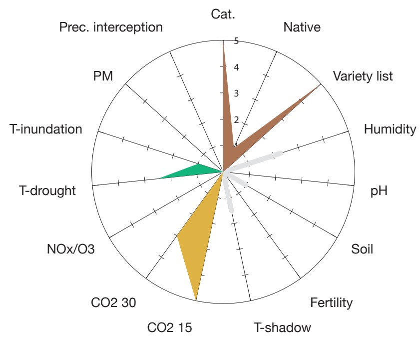
Chamaecyparis lawsoniana



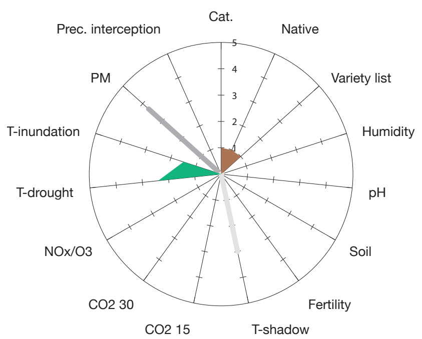
Larix decidua



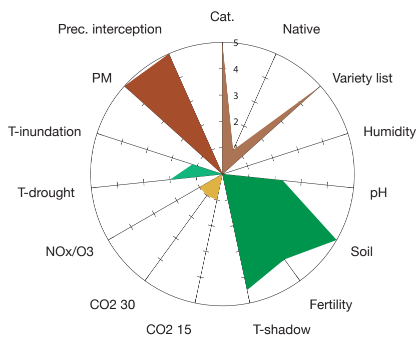
Larix kaempferi



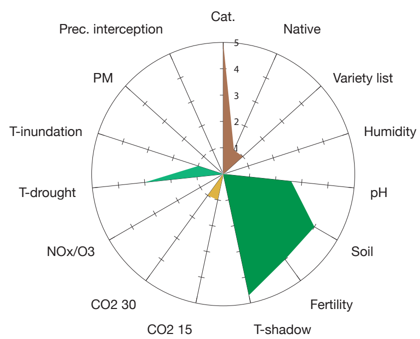
Larix x eurolepis



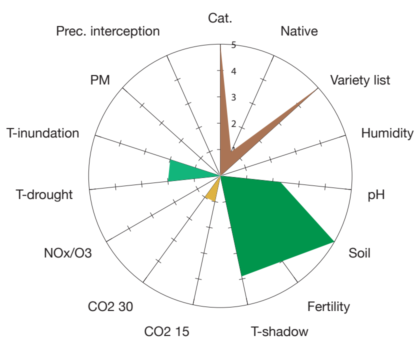
Metasequoia glyptostroboides



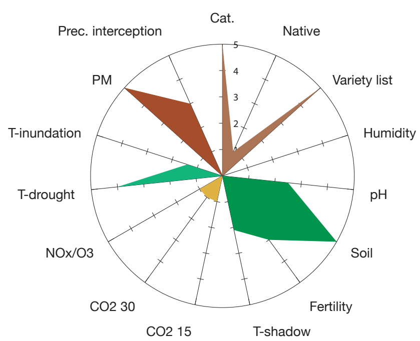
Picea abies



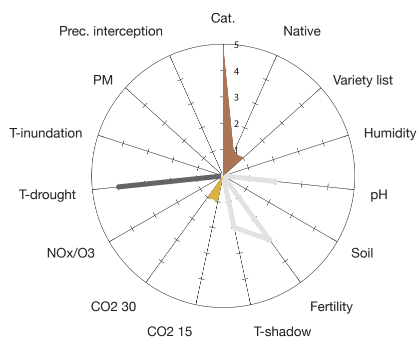
Picea omorika



Picea sitchensis

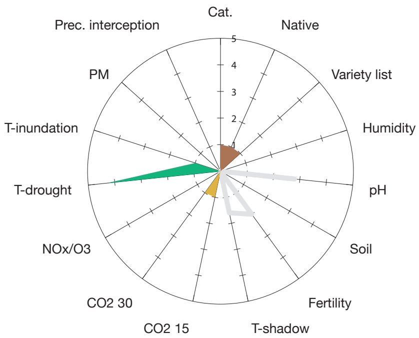


Pinus nigra

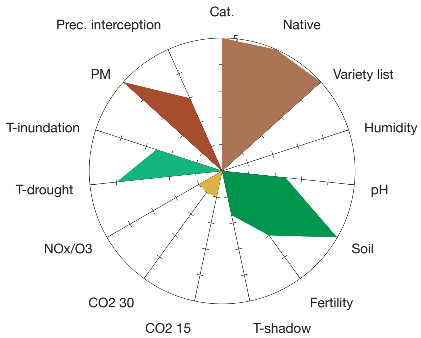


Pinus pinaster

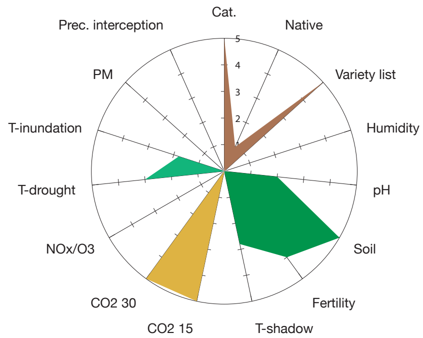
Conifer



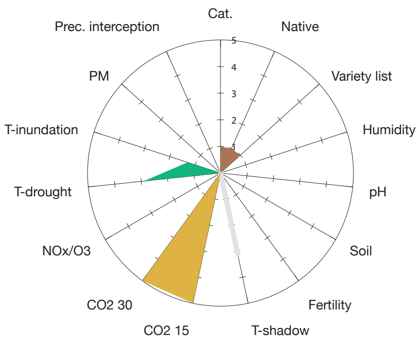
Pinus ponderosa



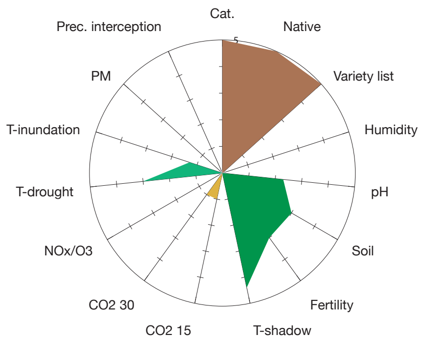
Pinus sylvestris



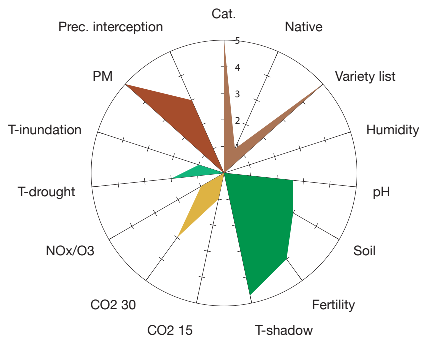
Pseudotsuga menziesii



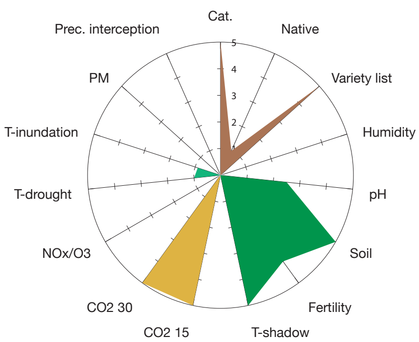
Sequoiadendron giganteum



Taxus baccata



Thuja plicata



Tsuga heterophylla

Annex E. Landscape quality evaluation

Annex table 4. Landscape quality evaluation of the landscape models (see Table 2). Values (1-7) are relative between models, higher values represent higher quality. Operalisation according to Hooijmeijer, Kroon & Luttink (2001).

SEQUESTRATION MAXIMISATION		Economic interest		Societal interest		Ecological interest		Cultural interest	
User value		Allocation efficiency	1	Access	7	Safety, disturbance	6	Liberty of choice	6
		Accessibility	3	Division	6	Pollution	4	Variety	3
		External effects	4	Participation	2	Desiccation	2	Encounter	2
		Multi-purpose	3	Choice	4	Fragmentation	7		
Experience value		Image	1	Disparity	6	Space, rest	4	Uniqueness	2
		Attractiveness	4	Connectedness	5	Beauty	5	Beauty	6
				Safety	6	Health	7	Contrast	3
Future value		Stability/flexibility	5	Inclusion	5	Stocks	6	Cultural heritage	2
		Agglomeration	3	Cultures of poverty	5	Ecosystems	5	Ingration	2
		Cumulative attraction	4					Renewal	4
Total	150		28		46		46		30

ENERGY MAXIMISATION		Economic interest		Societal interest		Ecological interest		Cultural interest	
User value		Allocation efficiency	6	Access	1	Safety, disturbance	2	Liberty of choice	1
		Accessibility	1	Division	6	Pollution	4	Variety	1
		External effects	4	Participation	1	Desiccation	4	Encounter	1
		Multi-purpose	1	Choice	4	Fragmentation	1		
Experience value		Image	2	Disparity	4	Space, rest	1	Uniqueness	6
		Attractiveness	2	Connectedness	2	Beauty	2	Beauty	4
				Safety	6	Health	3	Contrast	5
Future value		Stability/flexibility	4	Inclusion	5	Stocks	1	Cultural heritage	2
		Agglomeration	1	Cultures of poverty	5	Ecosystems	1	Ingration	2
		Cumulative attraction	3					Renewal	6
Total	105		24		34		19		28

LANDSCAPE DESIGN	Economic interest		Societal interest		Ecological interest		Cultural interest	
User value	Allocation efficiency	5	Access	7	Safety, disturbance	6	Liberty of choice	7
	Accessibility	7	Division	5	Pollution	4	Variety	7
	External effects	6	Participation	6	Desiccation	3	Encounter	5
	Multi-purpose	7	Choice	7	Fragmentation	6		
Experience value	Image	5	Disparity	6	Space, rest	5	Uniqueness	7
	Attractiveness	6	Connectedness	6	Beauty	6	Beauty	5
			Safety	6	Health	6	Contrast	7
Future value	Stability/flexibility	6	Inclusion	5	Stocks	6	Cultural heritage	6
	Agglomeration	5	Cultures of poverty	5	Ecosystems	7	Ingregation	6
	Cumulative attraction	6					Renewal	6
Total 211		53		53		49		56

Annex F. Landscape design carbon sequestration

Annex table 5. Carbon sequestration maximisation when transforming the entire airbase (excluding existing forests and buildings) into a mixed forest. 1: Boosten et al., 2020, 2: Farage, et al., 2010, 3: Lal, 2008, 4: Yang et al., 2019.

Land cover	Carbon sequestration rate (Mg C $ha^{-1}y^{-1}$)	Coverage (ha, 2021)	Sequestration (Mg C, 2021)	Coverage (ha, 2030)	Sequestration (Mg C, 2030)	Coverage (ha, 2050)	Sequestration (Mg C, 2050)
Mixed forest (young)	4,6 in the first decade[1]	0	0	435,92	2005,23	42,21	194,16
Mixed forest	9,1 after the first decade[1]	0	0	0	0	393,71	3582,76
Heathery grassland	1,1[2, 4]	186	204,6	186	204,6	8,91	9,80
Cropland	0,4[3]	137	54,8	137	54,8	63,97	25,59
Heather	1,46[2]	32	46,72	32	46,72	153,87	224,65
Total					2311,35		4036,96

Annex G. Landscape design energy production

Annex table 6. Landscape design energy production calculations. Assumed PV effeciency for 2023-2033 is 22%, after 2033 is 36% (see Table 4). A division is made between the permanent FV system in the plateau and the other temporary FV for forest development. Assumed completed installation by the end of 2022. Dutch standard solar radiation used: 0.88 Wp.

Used model	PV-density (%)	Coverage (ha, 2023-2033)	Energy production (GWh/year, 2023-2033)	Coverage (%, after 2033)	Energy production (GWh/year, after 2033)
Permanent forestvoltaic wood production system		**38**	**12.30**	**38**	**20.12**
1. Max PV	50%	2	1.94	2	3.17
2. Dual production	25%	5	2.42	5	3.96
3. Energy forestry	12.5%	10	2.42	10	3.96
4. Strips	15%	15	4.36	15	7.13
5. FV Offset	10%	3	0.58	3	0.95
6. FV low density offset	6%	3	0.35	3	0.57
7. Offset strips	6%	2	0.23	2	0.38
Temporary forest development PV		**217**	**70.20**	**0**	**0**
1. Max PV	50%	11.4	11.04	-	-
2. Dual production	25%	28.6	13.84	-	-
3. Energy forestry	12.5%	57.1	13.81	-	-
4. Strips	15%	85.7	24.89	-	-
5. FV Offset	10%	17.1	3.31	-	-
6. FV low density offset	6%	17.1	1.99	-	-
7. Offset strips	6%	11.4	1.32	-	-
Total			***82.50***		***20.12***