Climate change impacts on biomass production (national case studies)

Claire Jacobs, Jelle van Minnen, Virpi Junttila, Nina Pirttioja, Bruno Smets, Kasper Bonte

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1 Introduction

To tackle the climate crisis, the European Union has decided for a transition towards a climate neutral, circular bioeconomy (ref. European Green Deal, EC, 2020) in which biomass will play an important role. Biomass production provides food, feed, fibre and timber, as well as materials for renewable energy. Agriculture and forestry also play an important role in climate change mitigation by reducing greenhouse gas emissions (especially methane and nitrous oxide) and increasing the amount of carbon sequestration.

In this context, the EEA is preparing a biomass assessment report. Covering the major production and supply routes of biomass, it will analyse the environmental co-benefits and trade-offs of biomass production in the agriculture, forestry and land use (AFOLU) sector, as well as the role of the Green Deal. This document serves as input to the EEA report and provides insights in climate change impacts for two countries in Europe. An earlier EEA study showed that climate change is projected to reduce crop productivity in parts of southern Europe and can improve conditions for growing crops in northern Europe (EEA, 2019). This report illustrates two national case studies with focus on (above ground) biomass production from agriculture and forests, involving food, feed, energy and production materials. Fisheries and livestock are not included. The report explores:

- Recent trends in agriculture and forestry production from observations (last two decades).
- Impact of climate change in the near future (projections for 2030-2050);
- Relevant policies and implications;
- Country examples of adaptation to increase resilience.

National case studies

Finland and France have been selected as national case studies because of their relevance in forestry and respectively agriculture production volumes in Europe. Finland is the most forested country in Europe while France is the largest agricultural producer in Europe. Figure 1.1 shows the forestry and agriculture shares for both countries.

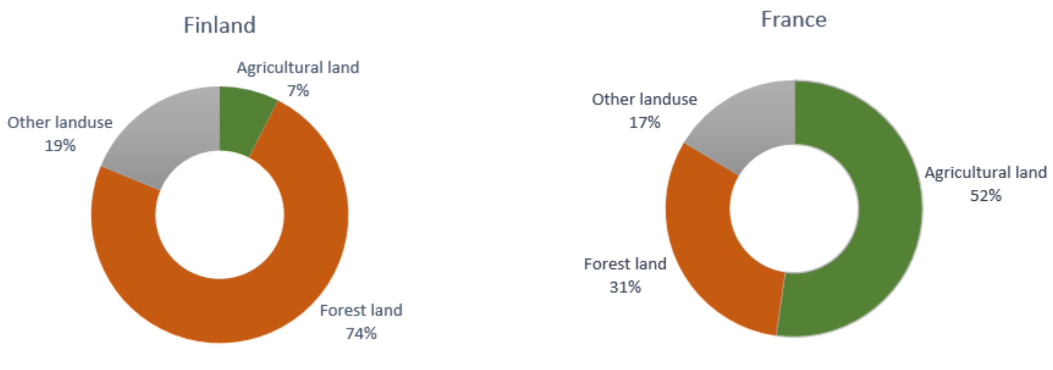

Figure 1.1 Forest and agriculture land use in Finland and in France (source data FAOSTAT 2019)

2 Case study Finland

2.1 Biomass from agriculture and forestry in Finland

Finland is a country with a mixture of landscapes and influenced both by maritime and continental climate patterns. Due to the high share of forests, wood is an important resource. Already today 40% of all construction materials are wood based (ETC CM, 2022). The total area of forest land, which is suitable for efficient wood production, is approximately 20 million hectares (Natural Resources Institute Finland, 2022a). It is mostly in commercial use, approximately 6.6% (3.3% in south and 11.8% in north) of the forest land is protected with no fellings allowed, and 9.9% (5.2% in south and 15.6% in north) protected with restricted forestry use (Natural Resources Institute Finland, 2022b).

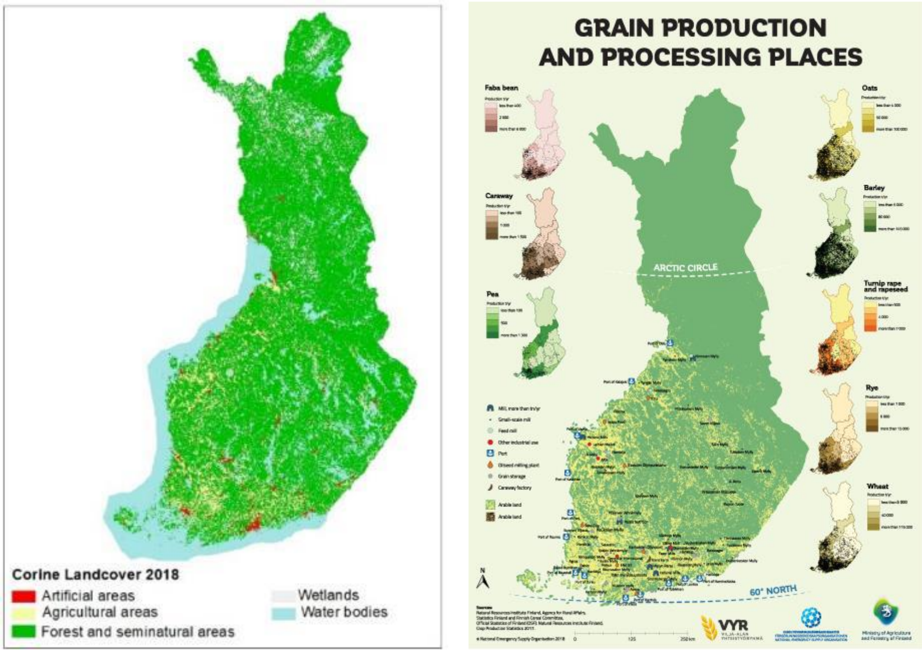

Figure 2.1 Left: Finland land cover map 2018 (Source: Finnish Environment Institute, EEA, EU Copernicus), Right: Grain production and processing places in Finland (National Emergency Supply Organisation, 2018)

The main tree species in the managed forests of Finland are Scots pine, Norway spruce and birch. According to the national forest inventory 12/13 (2016-2020), coniferous trees dominate most of the forest land area - in the south 52% of the land area is pine dominated and 33% spruce dominated, in the north 76% is pine dominated and 16% spruce dominated (Natural Resources Institute Finland, 2022c). Proportion of peatlands in southern Finland forest land area is approximately 28%, in northern Finland 41% (Natural Resources Institute Finland, 2022d).

The total utilized agricultural area was in 2021 approximately 2.27 million hectares (approximately 7% of the total land area) on a total of 44343 holdings. The main production areas are in the southwest and along the western coast (Figure 2.1 Right). Cereals are cultivated on roughly half of the agricultural area (Table 2.1.) with yields ranging from 2.5 t/ha to 3.7 t/ha in 2021.

Table 2.1 Utilized agricultural area and total yields of main crops in Finland in 2021

Main crops	Area (100 ha)	Yield (1000 mton)	Yield per hectare (t/ha)

Barley	448	1032	2,7
Oats	332	790	2,5
Wheat	217	678	3,2
Rye	18	67	3,7
Grain total	1062		
Turnip and oilseed rape	38	41	1,2
Grasslands	798		
Other crops	171		
Fallow area	213		
Utilized agricultural area	2268		

Four cereals are produced on a wider scale: barley, oats, wheat and rye. Under current conditions, only spring varieties, bred and tested for the Finnish conditions, are cultivated on a larger scale (Figure 2.2) Production is primarily rainfed. Spring barley is the most cultivated crop in Finland, used as animal feed, in the malting, starch and alcohol industry and exported to global markets (Vilja-alan yhteistyöryhmä, 2014). While, Finland's grain yield is small compared to the global scale, it is one of the largest producers and exporters of oats in the world. Of the annual grain production, roughly half is used as animal feed and the rest for human consumption and other purposes. While the short growing season limits production, cold winters currently reduce the number of plant pests and diseases (Vilja-alan yhteistyöryhmä, 2014).

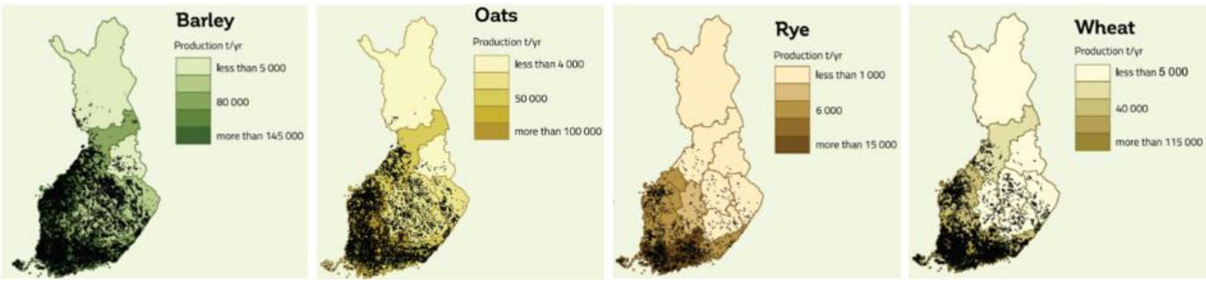

Figure 2.2 Production places of main cereals cultivated in Finland in 2018 (National Emergency Supply Organisation, 2018)

2.2 Observed trend of biomass production major crops and tree species

Trends in biomass production were looked at by VITO from observations for the past 20 years, based on Copernicus productivity data (see Annex 1 for methodology).

Forests

Satellite-based estimates of changes in forest gross primary productivity (GPP) per year in forests suggest a significant or insignificant increase across all but one of the regions (NUTS level 3) in Finland, see Figure 2.3. The most significant increase is located to south and south-west Finland, where, however, the forests do not play as important a role in the land area as in the other locations in Finland, where the observed trend has been insignificant increase (Figure 2.3).

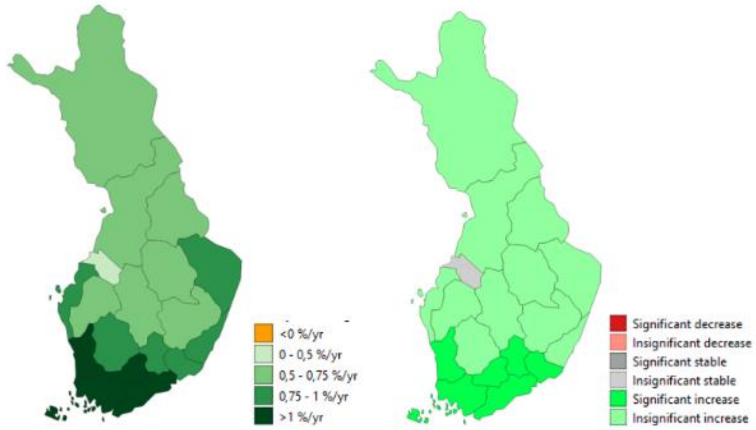

Figure 2.3 Left: The percentage of GPP change per year for forest at NUTS level-3 in Finland. Right: the corresponding subdivision in trend categories (maps by VITO, 2022)

The absolute values from the yearly GPP were compared with the National Forest Inventory (NFI) statistics (Figure 2.4). Note the NFI statistics include both branches (also stock) and foliage whereas GPP is limited to productivity and includes no stock, hence relation is set 2:1 in the graph below. Despite this ratio, a clear relation can be seen, except for one outlier (FI200, Åland). A trend from NFI could not be derived as there were only 3 measurement points available over the 2010-2020 period.

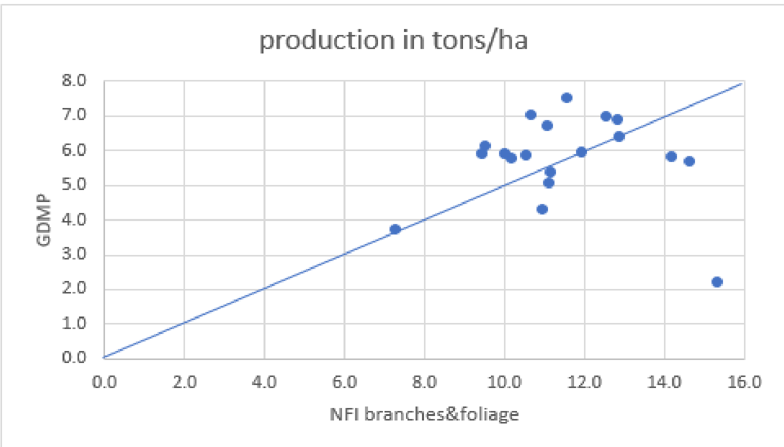

Figure 2.4 Satellite data estimated GPP compared to NFI statistics for forests in Finland

Cropland

Satellite-based estimates of changes in GPP per year in cropland suggest either an increase or yields remaining stable across regions in Finland, with a more pronounced change in the southernmost regions (Figure 2.5). While a range of crops is cultivated across the country, most of the production of the main crops is concentrated in the highlighted regions of the maps (National Emergency Supply Organisation, 2018). The maps in Figure 2.5 present an overall impression of the observed changes in GPP for crops in general.

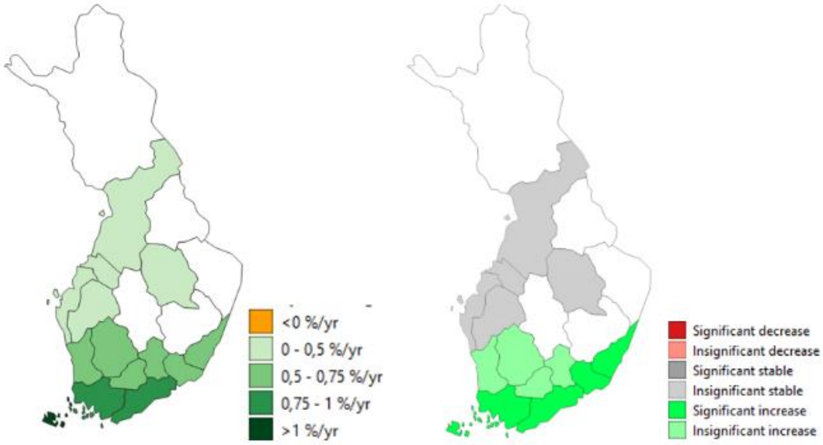

Figure 2.5 Left: The percentage of GPP change per year for cropland at NUTS level-3 in Finland. Right: the corresponding subdivision in trend categories. For the blank regions no trend could be calculated, because less than 1% of the 1 km pixels in that region are occupied by cropland (maps by VITO, 2022)

For comparison, the trends in GPP were compared against the trends found in the grain yields of main crops (wheat, rye, barley, oats, hay and silage) during 2000-2020 at two regions in Finland, Uusimaa and North Ostrobothnia (Natural Resources Institute Finland, 2022e). Analysis suggests the yields to have increased more with rye, barley and hay in North Ostrobothnia than in Uusimaa, while with oats it is the opposite (Figure 2.6) The increase has been most pronounced at both regions with rye (Uusimaa: 2.9%/year; North Ostrobothnia: 3.5%/year), while yields of wheat have declined in both regions by -0.09%/year and those of silage by -1.5%/year in Uusimaa and by -0.9%/year in North Ostrobothnia. It should be noted that due to data availability the comparison of GPP is made against grain yields of individual crops. Further, the trends in the satellite-based data are estimated by the Theil-Sen estimator, while a linear regression was used to estimate the trend in the observed crop yields.

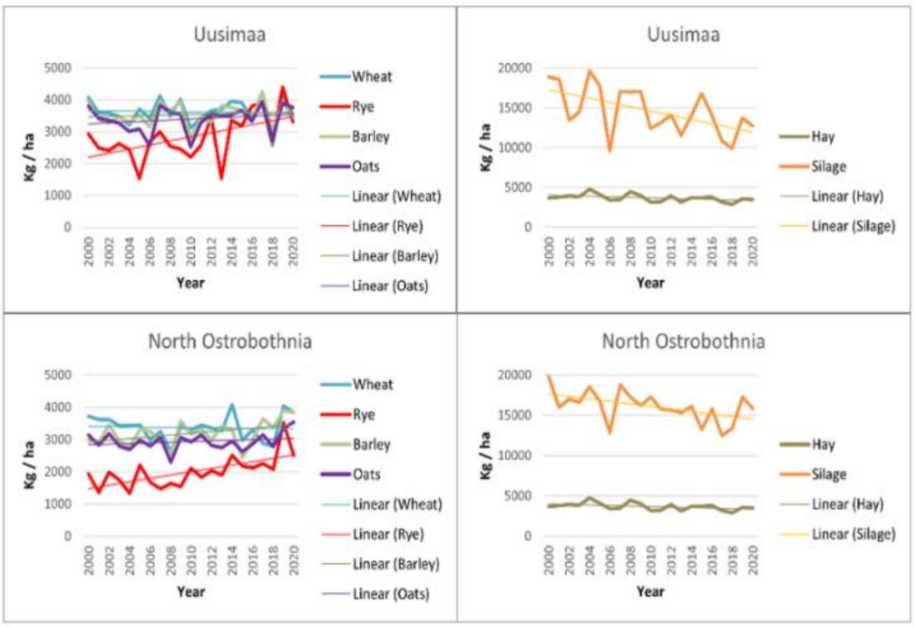

Figure 2.6 Observed yields of selected crops at Uusimaa (top row) and North Ostrobothnia (bottom row), with linear trends over 2000-2020 (Natural Resources Institute Finland, 2022e)

2.3 Future Agriculture and forestry under a changing climate

2.3.1 Climate change Finland up to 2030/2050

Mean temperature is projected to increase more and faster in Finland than globally (Ruosteenoja and Jylhä, 2021). Along with increasing temperature, thermal summer is projected to be prolonged, and winters shortened (Table 2.2). Table 2.2 summarizes projected changes in key climate variables for a southern Finnish region Kanta-Häme, where both forestry and agriculture are important sectors.

Table 2.2 Projected changes in key climate variables in Kanta-Häme region in Southern Finland by 2050. (Adpated from Table 18 in Gregow et al., 2021)

++	Increases/lengthens considerably	+	Increases/lengthens	/	Not much change	()	Uncertain change
--	Decreases considerably	-	Decreases	*	Unclear or negligible		

Variable	Winter	Spring	Summer	Autumn	Year
Mean temperature	++	++	+	++	++
Precipitation	+	+	/	+	+
Length of thermal season	--	+	+	+	*
Daily maximum temperature	++	++	+	++	++
Daily minimum temperature	++	++	+	++	++
Number of frost days	-	--	-	--	--
Snow	--	--	*	--	--
Number of rainy days	+	()	-	()	+
Intensity of heavy rains	+	+	+	+	+
Relative humidity	+	/	/	/	+
Wind speed	+	+	/	/	/
Amount of ground frost	--	--	*	*	--

Warming is projected to continue during the next few decades after which the responses between different forcing scenarios start to diverge, increasingly after the 2040s, depending on the level of mitigation (Figure 2.7). By 2040 warming is projected to reach 2°C relative to the baseline period of 1981–2010 even under the lowest examined emission scenario (SSP1-2.6). This implies an additional warming of about one degree compared to the current Finnish conditions (early 2020s; Ruosteenoja and Jylhä, 2021).

While temperatures are projected to increase in Finland in all seasons, the increase is likely to be stronger in winter than in summer. The GCMs are consistent with the sign of the change but diverge substantially in the magnitude. By the period 2040-2069, assuming the medium level SSP2-4.5, the projected increase is 3.3 (1.2–5.4) ◦C in winter and 2.4 (1.0–3.8) °C in summer. The values are the multi-model mean change relative to 1981– 2010 with the 90% uncertainty interval reflecting inter-model differences in parentheses (Ruosteenoja and Jylhä, 2021).

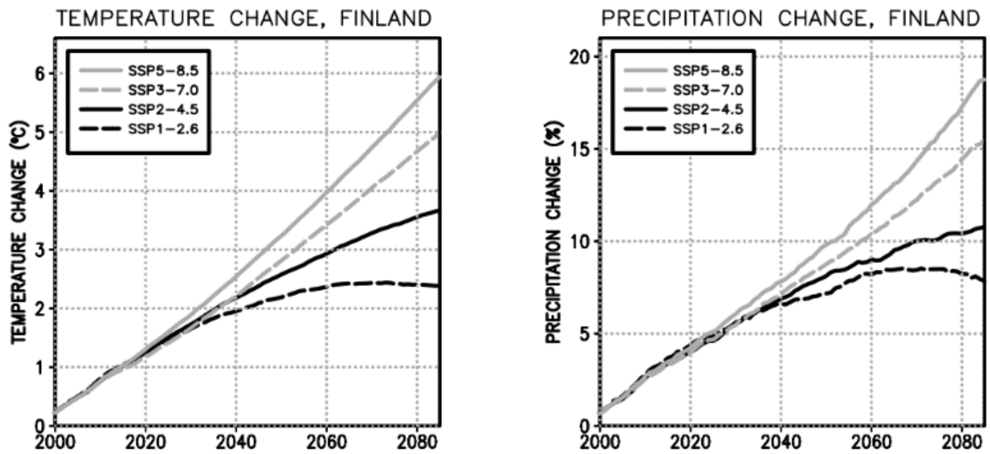

Figure 2.7 Multi-model mean changes in annual mean surface air temperature (in °C; left panel) and precipitation (in %; right panel) during 2000–2085, relative to mean of baseline period 1981–2010. The curves show 30-year running means of the spatial averages of Finland. Projections are given for four greenhouse gas scenarios: SSP5-8.5 (very high), SSP3-7.0 (rather high), SSP2-4.5 (medium) and SSP1-2.6 (lowest) (Source: (Ruosteenoja and Jylhä, 2021)

By 2040–2069, as simulated by the CMIP5 global climate models and assuming medium level RCP4.5, the average length of thermal summer is projected to increase by nearly 30 days relative to 1971–2000, and thermal winter to shorten by 30 to 60 days. This is seen as thermal spring starting earlier and autumn starting later, translating into a longer growing season offering opportunities for Finnish field crop production (Peltonen-Sainio et al., 2009b; Ruosteenoja et al., 2020).

For precipitation, solar radiation and wind speed, there is much more uncertainty around the sign of change across the climate models. Precipitation is more likely to increase than decrease in all seasons, in particular during the winter. In summer, the direction of the change is fairly uncertain, particularly in southern Finland. Solar radiation may increase to an extent in summer and early autumn and decrease in late autumn and winter, resulting to a further deepening of the contrast between the abundantly light-rich summers and dark winters. With wind-speed no clear messages emerge from the future projections. Consequently, despite the significant projected changes in temperatures, certain features of the Finnish climate may remain rather unaltered (Ruosteenoja and Jylhä, 2021).

With respect to differences between northern and southern Finland, projections for temperature are nearly identical for both regions, except in November-December, when warming is projected to be slightly stronger in the north than in the south. Contrastingly, the largest differences in precipitation projections occur in the warm season. From July to September, while precipitation is projected to remain nearly unchanged in the south, increase by 4–8 % is projected for the north (Ruosteenoja and Jylhä, 2021).

The projected changes to extreme weather events are less clear due to their sporadic nature (Gregow et al., 2020; Groenemeijer et al., 2016). The highest summertime temperatures are expected to increase at a similar rate as the mean temperature. Similarly, extremely cold temperature events expected to become rarer and snow frost to decrease considerably. Occurrences of short-duration rainfall extremes are likely to increase (Toivonen et al., 2021). While no major changes are projected in mean wind speed and in the occurrence and intensity of storms, their impacts are likely to be more severe especially in the forest sector due to the decrease in soil frost which makes the trees more prone to wind damage in the winter (Gregow et al., 2021). In certain flood prone areas, especially along the west coast of Finland, increases in floods are expected due to increased precipitation (Gregow et al., 2021).

2.3.2 Projected crop yields and forest growth up to 2030/2050

Forests

In the boreal forests of Finland, the climate change induces longer growing seasons, but also decrease in snow cover depth and duration, earlier soil thaw and later soil freeze (Barichivich et al., 2012, Holmberg et al. 2019, Mäkelä et al., 2020, Venäläinen et al., 2020). Increased CO_2 concentration, longer growing seasons and warmer temperatures generally enhance the gross primary production and growth, but can also lead to higher ecosystem respiration, which can cause a net flux of CO_2 from vegetation to atmosphere (Holmberg et al., 2019, Mäkelä et al., 2020). Most of the GPP increase is attributed to the summer periods, thus the summer season radiation conditions can be assumed to dominate as drivers of annual GPP increase (Kalliokoski et al., 2018). The resulting forest GPP depends also on different abiotic and biotic damage risks, as the damage affects the forest structure and its capacity to cope in the changing climatic conditions.

In northern Europe, the increasing atmospheric CO_2 content and warmer temperatures are expected to result in positive effects on forest growth, significantly more in the northern than southern boreal zone under all the RCP scenarios, at least in the short/medium term. The effect of the elevated CO_2 concentration alone is assumed to increase GPP in all main tree species, see Figure 2.8 (Lindner et al. 2010, Kellomäki et al. 2018, Kalliokoski et al., 2018).

Growth enhanced by the increased CO2 content can, however, become restricted due to limited access to nutrients, mainly nitrogen or phosphorus, especially in nutrient deficient sites (Wieder et al., 2015). In managed forests, the amount of nutrients depends also on the intensity of harvests. Very intensive harvesting, where also stumps and roots are removed, may deplete the soil base cation pools in the long term and additional inputs of nitrogen and potassium will be needed to ensure sustained forest growth in very intensive harvesting (Aherne et al., 2012).

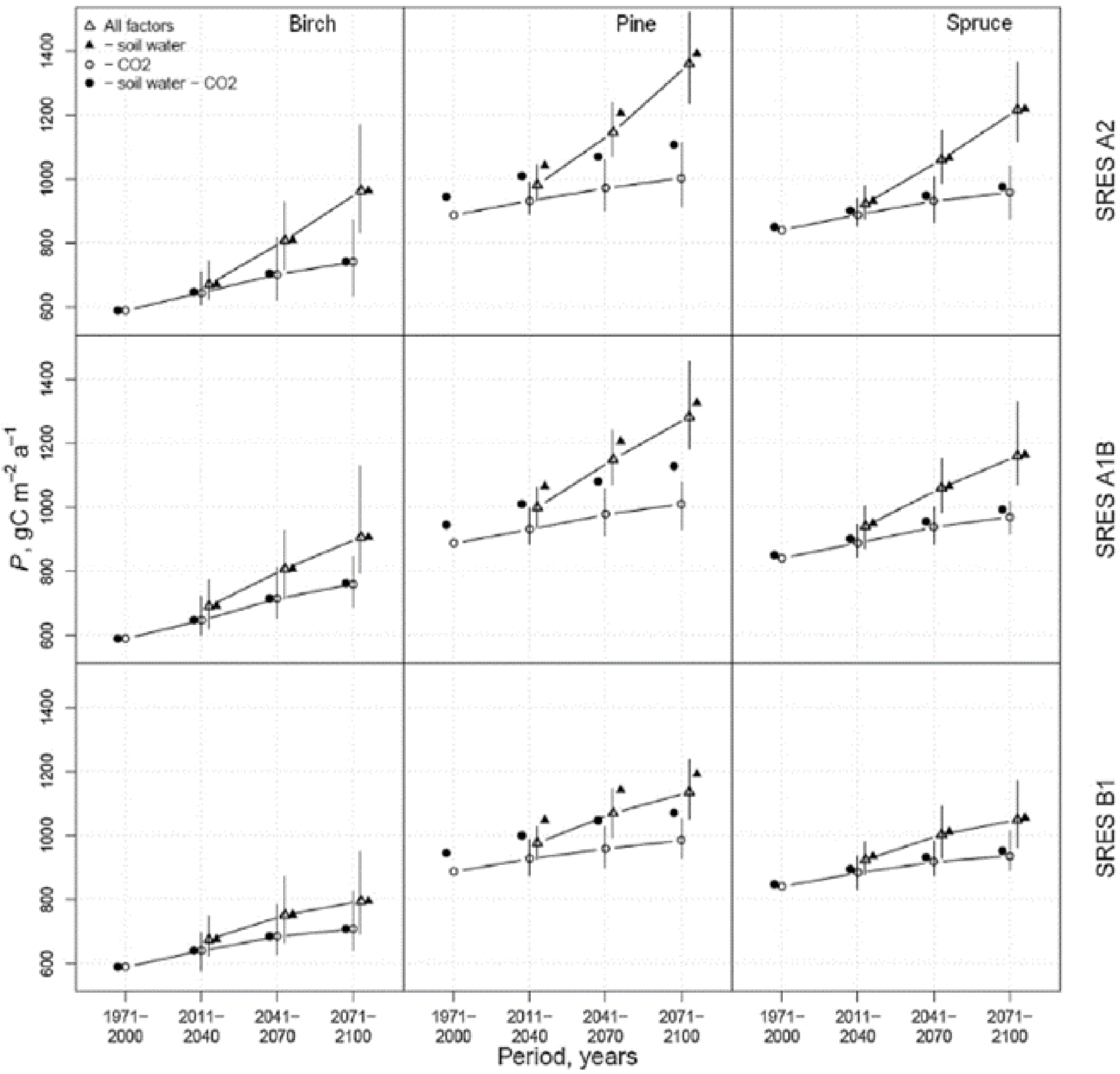

Figure 2.8 Effect of climate change on gross primary production (P) of forests in Finland with the fraction of absorbed photosynthetic photon flux density. Symbols show the mean prediction obtained using the downscaled projections of eight CMIP3 global circulation models in different SRES emission scenarios. Horizontal lines connect the symbols of "All factors" and "−CO2" simulation cases (see Section 2.4). Vertical lines show the range of predictions obtained with these projections (min – max), for clarity only for the same two simulation cases as in case of horizontal lines (Source: Kalliokoski et al., 2018).

Change in growth and GPP in Scots pine

Growth in Scots pine is projected to benefit from climate change under all scenarios. By modelling the effects of temperature sum, prevailing light conditions, soil moisture, nitrogen supply and atmospheric CO_2 on the growth, the projections show moderate increase in south Finland for fertile and medium fertile sites, in poor sites the growth is close to zero by the year 2050 (Figures 2.9-2.11). In the north, the relative increase in growth in Scots pine is higher than in the south, independent on the site fertility, and increases until the end of the century. The change in growth for the quite poor (VT) upland sites, where the effect of drought is more significant, is projected to be even negative in the south under scenario RCP8.5. Also, Kalliokoski et al. (2018) detected that GPP of pine under projections was more constrained by soil water deficit compared to reference climate than the other species, due to low soil water holding capacity. In the case of poor peatland sites, where the effect of drought is not included, the increase in diameter growth is estimated positive under all scenarios. (Kellokoski et al., 2018, Torssonen et al., 2014)

Change in growth and GPP in Norway spruce

Changes of growth in Norway spruce differ in the south compared to the change in the north (Figures 2.9-2.11). Norway spruce growth is reduced by severe droughts, and in the southern upland and peatland sites the spruce growth is estimated to decrease in all site fertility types, while in the central Finland and north the change in growth is projected to be positive. (Jyske et al., 2010, Kellomäki et al. 2018, Torssonen et al., 2014) According to Kalliokoski et al. (2018), the country level GPP in spruce is estimated to increase 22–29% (14–41%) by the mid-century compared to the reference period.

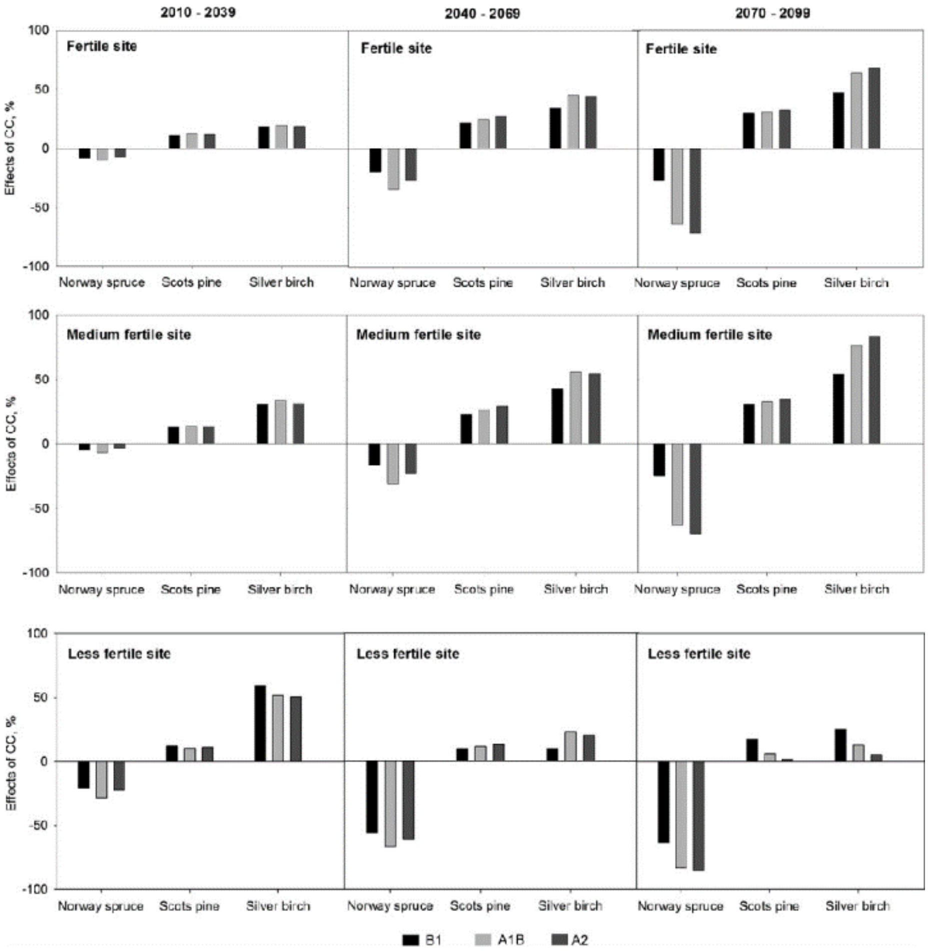

Figure 2.9 Percentage change of the volume growth for Norway spruce, Scots pine and silver birch under different climate change scenarios compared with the current climate in southern Finland on the fertile, medium fertile and less fertile sites for different time periods. (Source: Torssonen et al., 2014)

Change in growth and GPP in Birch

Growth in birch is projected to increase in Finland by the year 2050 independent of the location and site fertility under all RCPs, the biggest increase under RCP8.5 (Figures 2.9-2.11). In the less fertile sites, the drought is likely to affect the change in growth. (Kellomäki et al., 2018, Torssonen et al., 2014) Similar results hold for the country level projections of GPP in birch, which is estimated to increase on the average 16–62% by the mid-century. The higher increases of GPP in birch than in the other species is mainly caused by stronger effects of the increasing temperature on birch (Kalliokoski et al., 2018).

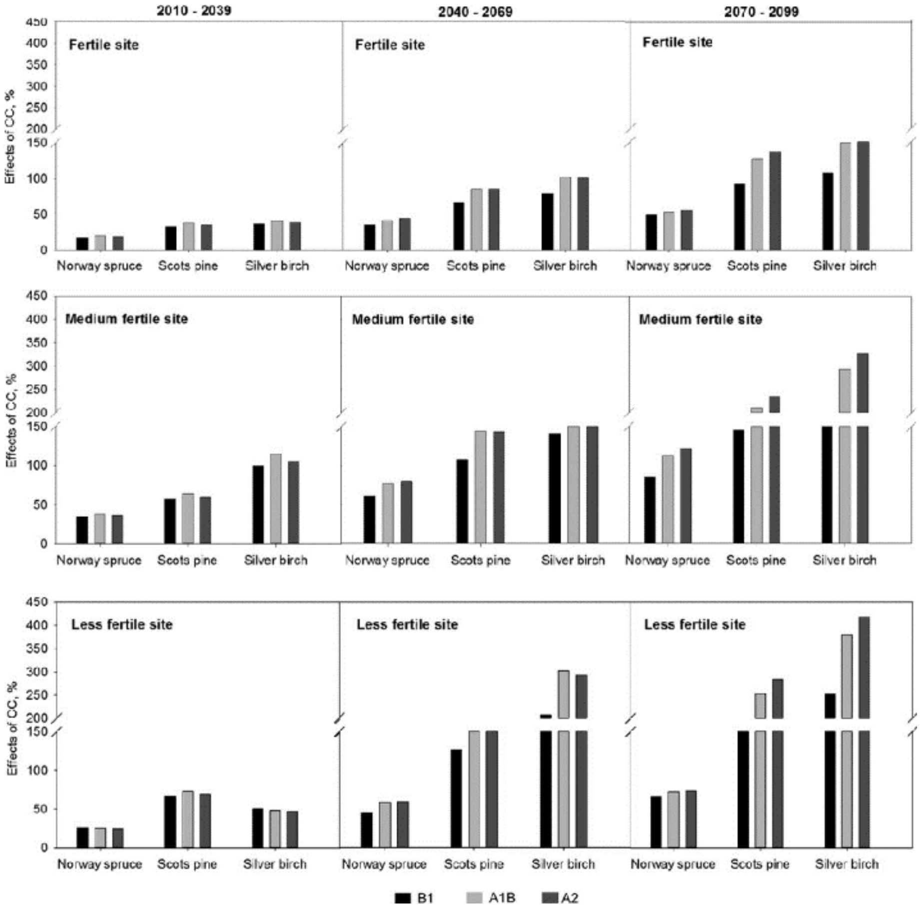

Figure 2.10 Percentage change (per cent) of the volume growth for Norway spruce, Scots pine and silver birch under different climate change scenarios compared with the current climate in northern Finland on the fertile, medium fertile and less fertile sites for different time periods. (Source: Torssonen et al., 2014)

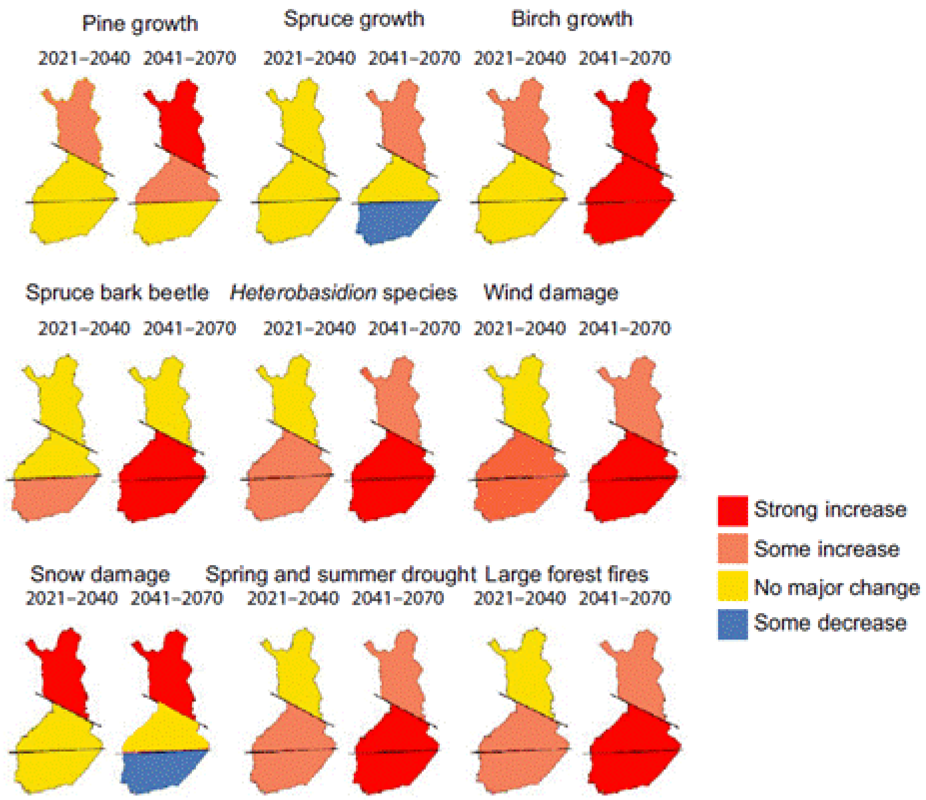

Figure 2.11 Estimated impacts of climate change (corresponding to RCP4.5) on forest growth (top row panels) and the incidence/severity of major climate-induced risks (middle and bottom row panels). The baseline period is 1981–2010.Source: Venäläinen et al. (2020) edited from Äijälä, Koistinen, Sved, Vanhatalo, & Väisänen, 2019.

Forest Fires

In Finland, the number of forest fires is currently approximately 1000 annually, but the average size of fire is less than one hectare. The conflagrations (10 hectares or more) have become very few due to active and efficient fire suppression. Majority of large fires in Finland occur in May and June due to human activities, lightning becomes a more important cause of fires later in summer. The number, severity rating, and area of large forest fires are projected to increase in the whole country by year 2050. However, there is large uncertainty in the projected forest fire areas, as there is a large uncertainty related to the climate change signal in fire activity (Lehtonen et al. 2016a).

Forest droughts

The risk for drought in Finland is estimated to be increasing depending on the location. This is caused by warmer temperatures, changed precipitation patterns, and increased forest growth, which all alter the water availability. By the year 2050, a substantial increase in the number of drought days is estimated in the whole country, from 4 days of the reference period 1981-2010 to 23 days in the south and 9 days in the north (Holmberg et al., 2019).

Wind, snow and soil frost

The annual areas and severity of wind damages vary a lot. For instance, the most severe individual windstorms can damage 2-4 million m3 timber alone (Venäläinen et al. 2020). In Finland, there has been no clear trend of increasing strong winds until now, and no significant change is also projected under climate change (Laapas and Venäläinen, 2017 and Ruosteenoja et al. 2019). In forested areas, the soil frost is important in keeping the trees anchored during the wind from late autumn to early spring. This anchorage is estimated to nearly disappear in the southern and central parts of the country (Gregow et al., 2011). The soil frost days are estimated to reduce by half to only 47-68 days in the south and by 40-60 days in the north by year 2050 (Holmberg et al., 2019). Thus, because of the warmer and shorter soil frost periods, the probability of wind damage can be assumed to increase. Also, combined with a heavy snowfall, which may become more common with climate change, windstorms can cause severe damages even with relatively slow wind speeds (Venäläinen et al. 2020).

The snow-induced damages themselves are caused by heavy snow load on three crowns, which cause breaking of the stem and branches. In eastern and northern Finland, where the coldest winters are located, heavy rime loads, wet snow loads and frozen snow loads are estimated to increase by up to 50% by year 2050. In southern and western parts of the country, this trend is estimated to decrease (Figure 2.11; Lehtonen et al. 2016b).

The combined changes in the occurrence of wind, snow loading and soil frost can also create an increasing risk for uprooting of conifers in southern, central and eastern Finland (Gregow et al., 2011). On the other hand, mixed stands and spruce dominated stands are also affected by snow and wind damage (Díaz-Yáñez et al., 2017). Ikonen et al. (2017) projected increasing summertime wind damages for all species in the south, but the probabilities and amounts of damage were substantially smaller for Scots pine than for the other species. Norway spruce has shallow rooting and is thus more prone to wind damage, especially in the southern boreal zone under severe climate warming. Birch is most vulnerable to wind damage during the leaf-on period in summer, but the risk is smaller in the autumn, when birch becomes leafless.

Biotic risks: Insect pests, mammalian herbivores and pathogens: The risk for biotic forest disturbances depends not only on the climatic conditions, but also on forest structure and condition. Some biotic disturbances occur as outbreaks, where the forest GPP collapses and the whole forest may require a clear-cut to prevent further and spreading damage, or they cause multiple years chronic stress where the forest GPP is declined.

For example, the youngest seedling stands may suffer from stress caused by large pine weevil (*Hylobius abietis*) and from outbreaks of cricetid rodents, independent of the tree species. Moose (*Alces alces*) browsing causes stress on the more mature pine and birch seedling stands, and it benefits from the expected reduction in snow depth and duration. As the stand age increases, the risk of stress caused by different species of wood decay fungi (*Heterobasidion spp*) and outbreaks of different insect pests increase among the coniferous stands, such as the European (spruce) bark beetle (*I. typographus*), the most devastating endemic insect pest in Finnish forests, outbreaks. Asikainen et al. (2019). With the increasing growing degree days more species that have so far caused only occasional outbreaks, may become more abundant (Venäläinen et al., 2020). Higher temperatures are also likely to promote distributional shifts in many native insect pest species and invasive alien species toward north (Battisti and Larsson, 2015 and Asikainen et al., 2019).

The lowest winter temperatures are projected to nearly disappear in south and western Finland and become rarer in eastern and northern Finland by the end of the century, which is beneficial to some pest species. Increased summer period precipitation, longer growing seasons and increasing drought periods may create beneficial conditions to different pathogens, e.g., root-decay fungi (Asikainen et al. 2019).

Projections of current forest structure and species decomposition

Considering the current forest growing stock covering whole Finland, and current forest practices to continue in the future, the annual forest growth is indicated to increase about 60% and annual carbon sink to increase roughly 40% from the period 1981–2010 to the end of the century (Holmberg et al. 2019). Under RCP8.5, the forests with larger increase in growth are more likely located in the north and the share of plots with small increase in growth in the south (Figure 2.12). In total, the forest gross primary production is assumed to increase by 34% for the mid-century under all RCP scenarios. The differences between the two high emission scenarios, RCP4.5 and RCP8.5, are evident only from the mid-century onward. However, risks for abiotic and biotic damage, which may have a significant impact on the growing stock and growth, were not considered in these projections.

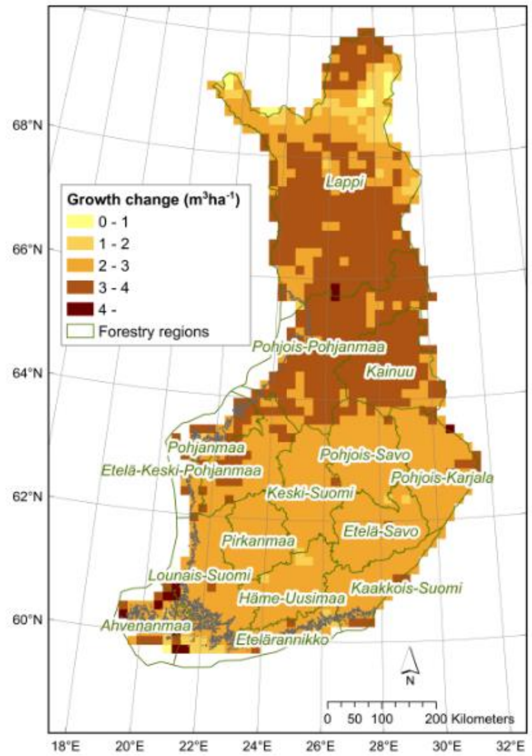

Figure 2.12 Mean modelled change in annual growth (m3 ha-1 yr-1) from 1981–2010 to 2041–2070, calculated over all climate change scenarios. Forestry regions and their borders indicated on the map. (Source: Holmberg et al., 2019)

There exist only a few studies, where climate change induced increase in growth, forest management scenarios, and different abiotic and/or biotic disturbances have been combined. Reyer et al. (2017) studied multiple sites in Europe with growth model projection combined with a disturbance (either wind, bark beetle or fire). The case study in Finland included a site in eastern Finland affected by wind disturbance, and it didn't show any substantial difference between forest productivity change induced by climate change and disturbances and climate change only induced productivity changes.

However, in other European study sites negative effects for different sources of disturbances were discovered.

Opportunities climate change for forests

There has been a lot of pressure to intensify the use of unprotected forests in Finland. The demand of timber wood needed in forest-based bioeconomy is growing, and these days, the current political situation may increase the demand of energy wood in Finland, as the use of Russian wood has become unfavorable.

The level of harvest intensity has substantial effects on the development of forest resources, timber supply, carbon balance and biodiversity. In the managed forests, under growth calibrated to current measurements, the highest annual harvest level which did not decrease the growing stock volume over a 90-year simulation period was estimated to be 73 million m3 (Heinonen et al., 2017). Over the whole period of 90 years, the annual harvest of 60 million m3 maximized the total timber production. The increment in volume continued to increase for several decades if the harvested volume was less than the current increment. Low harvest levels resulted in the highest carbon balance and values of biodiversity indicators. Heinonen et al. (2018) modelled climate change induced, species dependent increments in growth together with intense forest management (improved seed and seedling stock in artificial regeneration, fertilization and ditch maintenance in 40% of drained peatlands) for 90 years with several climate models and RCP scenarios. According to these simulations, the increase in wood demand of up to 80 million m3 year-1 is sustainable with respect to timber supply under RCP2.5 and RCP4.5. However, this is not possible under RCP8.5, due to rapid decline in forest growth in south Finland. Vauhkonen and Packalen (2018) remarked that the future harvests should not be defined with a fixed reference period but based on projections that account for uncertainties. Assuming continuation of business-as-usual forest management, when the development of forest differs from that based on current climate, is likely to result in selection of incorrect harvesting strategy and forecast of carbon sinks. With an uncertainty interval of possible future outcomes, the decision making is on solid ground and potential needs to adapt management practices can be accounted for.

Agriculture

Climate change could potentially cause both negative and positive impacts to crop production in Finland, which differs from the primarily negative impacts expected across most of Europe. Global warming is likely to extend the growing season at high latitudes where crop growth and yields are currently limited by the short growing season. A longer growing season together with milder winters and elevated CO_2, could offer potential for cultivation of longer duration and higher yielding crops and cultivars. However, effective adaptation is needed to address various challenges associated with the changing climate and realise the potential benefits (Peltonen-Sainio et al., 2009a; Peltonen-Sainio et al., 2009b; Peltonen-Sainio et al., 2016; Wiréhn, 2018). Increases in climate change-induced risks, together with insufficient adaptation or even maladaptation, may widen the gap between potential and attainable yields in the future. Plant breeding is estimated to play a substantial role compared to that of a prolonging growing season (Peltonen-Sainio et al., 2016).

Main drivers affecting agriculture and crop production under changing climate

A report reviewing the state of climate change adaptation in Finland across various sectors associated with natural resources identified five major drivers impacting Finnish agriculture under future climate change:

1. Increased variability in climate and frequency and magnitude of extreme events, impacts of which are difficult to assess due to the sporadic nature of the events,
2. Warmer and more humid conditions are likely to increase the occurrence of pests and diseases, including introduction of new types,
3. Increased need of irrigation due to projected changes in precipitation patterns. These suggest precipitation to be spread more unevenly during the growing season, more frequent heavy rains and insufficient increases of precipitation compared to the level of warming required to compensate for the needs of greater crop biomass and increased evapotranspiration. Drought is already the most recurring cause of yield reductions. The coastal region (incl. horticulture), where irrigation is already being used, is estimated to be most vulnerable to drought.
4. Climate change is estimated to aggravate the already problematic issues associated with soil quality that in turn affect yield e.g. soil compaction and depletion of soil organic carbon,
5. Increase of erosion and runoff of nutrients and pesticides due to increase in precipitation (Peltonen-Sainio et al., 2017).

Climate change impacts on main crops

The variety of crops to cultivate in Finland is limited due to the short growing season and only possible in regions where risks to production and associated uncertainties are manageable (Peltonen-Sainio and Jauhiainen, 2020). Projections about future changes in crop yields vary across studies, depending on choices made in each study. Below, is presented an overview across the studies focusing on the main crops cultivated in Finland and changes projected up to 2050’s.

Cereal crops

Based on an analysis of observed shifts in cultivation areas it was found that farmers’ crop choices have changed since the mid 1990’s. The most widely cultivated cereals, barley and oats have decreased in cultivation area (Figure 2.13), while spring wheat has become more popular, in particular in the inland regions and in the western coastal regions (Figure 2.14, top row). Spring rye, a novel crop in Finland, saw first an increase in popularity by 2006 but the growing intensity has since declined (Figure 2.14, bottom row; Peltonen-Sainio and Jauhiainen, 2020).

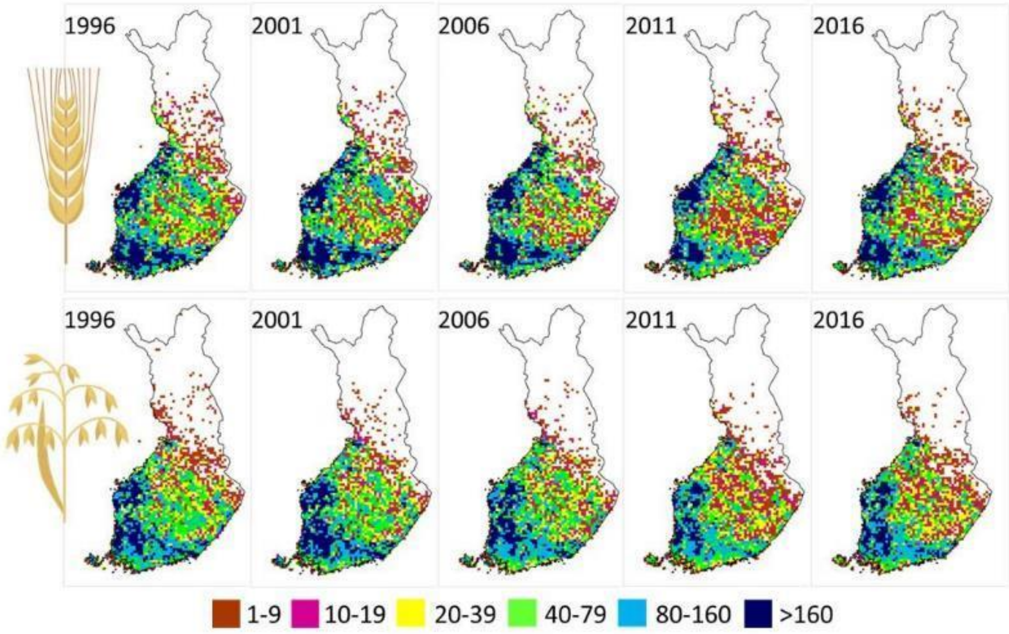

Figure 2.13 Maps indicating shifts in a 10 × 10 km grid in the number of field parcels with spring barley (top row) and oats (bottom row) under cultivation in 1996, 2001, 2006, 2011 and 2016. The number of parcels is shown with different colours. White means that there are no parcels in the grid with the crop in question (Source: Peltonen-Sainio and Jauhiainen, 2020).

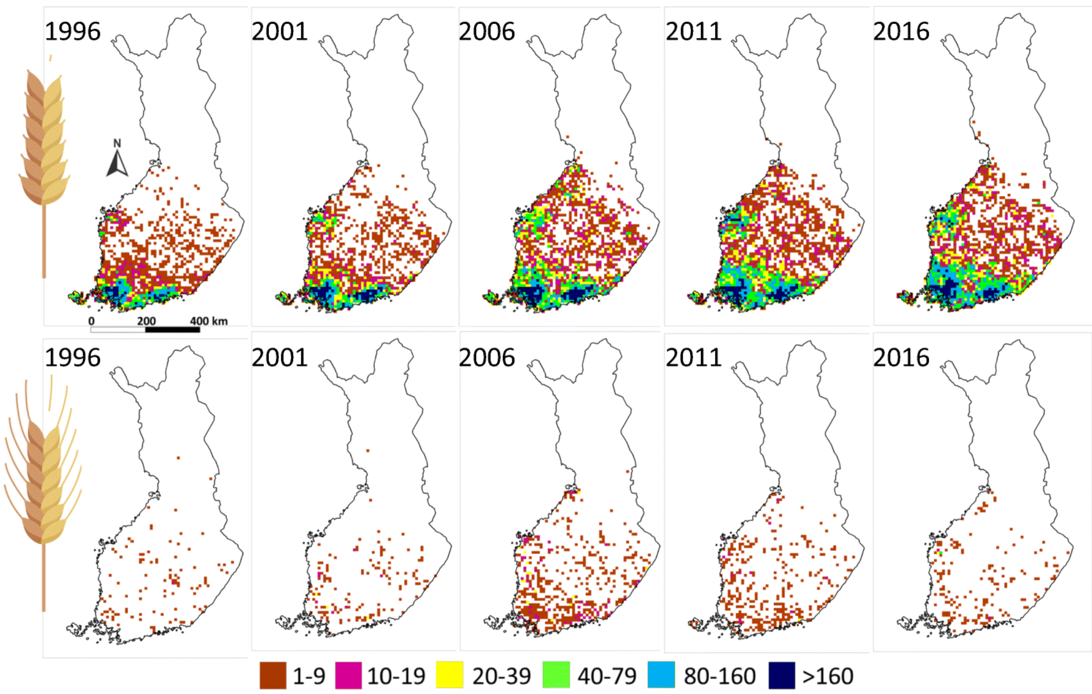

Figure 2.14 Maps indicating shifts in a 10 × 10 km grid in the number of field parcels with spring wheat (top row) and rye (bottom row) under cultivation in 1996, 2001, 2006, 2011 and 2016. The number of parcels is shown with different colours. White means that there are no parcels in the grid with the crop in question (Source: Peltonen-Sainio and Jauhiainen, 2020).

Pirttioja et al. (2015) examined the responses of a large ensemble of process-based crop models to systematic changes in temperature and precipitation, within plausible ranges of future changes. The analysis found wheat to be more sensitive to changes in temperature than precipitation in Finland. With current cultivars the highest yields are obtained close to baseline temperatures. With changes to any direction the yields start to decline. This shows how present-day cultivars are bred to develop and mature under location-specific ambient conditions.

Based on a number of studies applying both statistical and crop simulation modelling approaches, future changes in climate could lead to considerable increases in yield and above-ground biomass potentials of spring cereals in Finland. Achieving the higher yield potential is, however, reliant on e.g. yearly weather conditions, crop management efforts, dedicated breeding and cultivar responsiveness (Peltonen-Sainio et al., 2016). Tao et al. (2015) applied an advanced super-ensemble based probabilistic approach to analyse the projected impacts of future climate change on wheat productivity in Finland, conditional on a set of SRES-based scenarios. The results suggest that by 2050's, the yield of spring wheat is projected to increase substantially (on average by ~30.0% in the south to over 70.0% in the northwest with high probability). However, in parts of southern Finland, wheat production is likely to face increasing risk of high temperature and drought stress, resulting to an offset in the potential benefits of climate change on wheat yield. This is estimated to result in an increase in yield variability, together with an about 30% probability of yield decrease for spring wheat. The estimate increase in yield is in line with results of Purola et al. (2018), where an increase of 19–27% from baseline conditions (1971–2000) to 2042–2070 was found for spring wheat, when accounting also for economic and management considerations.

In Hakala et al. (2012) barley yields were found to respond negatively to drought, excessive rain early in the season and to high temperatures at various stages of development. Peltonen-Sainio et al. (2016) found spring barley yields to increase with time, assuming elevated CO_2, though under water-limited conditions the increase was less than for a potential (irrigated) production situation (Figure 2.15). However, with temperature increases exceeding 4 °C, positive effects on barley yields are likely to be reversed, with a high risk of noticeable yield losses (Rötter et al., 2011).

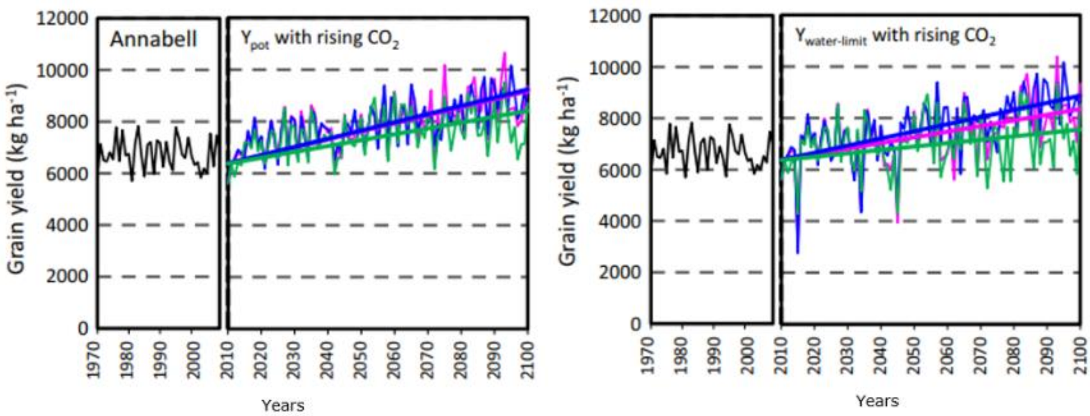

Figure 2.15 **Baseline period prior to 2010 and projected potential (Ypot) and water-limited grain yields (Ywater-limit) in currently cultivated barley cultivar Annabell with CO2 elevation accounted for, assuming A2 SRES scenario. Yields were estimated with the WOFOST model. Blue colour refers to model CNRM-CM3, red to BCCR–BCM2.0, and green to MIROC3.2 (medres)**

Pirttioja et al. (2019) found spring barley cultivars combining a short pre-anthesis and a long post-anthesis phase together with earlier sowing dates to produce the highest yield gains and smallest likelihoods of yield shortfall in Finland under future scenarios of climate change, conditional on RCP8.5. When comparing the responses of barley and oats to temperature and precipitation at key growth phases, it was suggested that while breeding has been more efficient with barely than oats, oats might adapt better to a changing climate. The predicted increase in precipitation and increased risk of heavy rains is expected to threaten barley more (Hakala et al., 2020).

While growing season is projected to prolong, the anticipated warmer autumns are unlikely to benefit spring cereals, in particular with earlier sowing. Even with the most late-maturing wheat cultivars, maturity will be reached prior to early autumns, suggesting that harvest will take place even earlier than currently, though interannual variation may remain high (Peltonen-Sainio et al., 2018). Cover crops undersown in a cereal field in spring such as winter turnip rape and oilseed rape may offer a viable win-win option. They scavenge soil nitrogen, produce soil cover and biomass, even harvestable yield in the following season, and thereby reduce erosion, soil compaction and nutrient leaching (Peltonen-Sainio et al., 2018; Tuulos et al., 2015).

Oilseed crops

Turnip and oilseed rape are the main oilseed crops cultivated in Finland. Due to lower production risks compared to those of summer oilseed rape (*Brassica napus L.)*, summer turnip rape (*Brassica napus L.)* has been the dominant oilseed crop in Finland. However, with the projected increases in temperature accumulation, favouring oilseed rape, the relative importance of the crops could be reversed in the future (Peltonen-Sainio et al., 2009a). This is already starting to show in the observed shifts in the cultivation area of the two crops, where turnip rape is seen to have dramatically declined it its primary production areas, while oilseed rape has expanded in the southernmost regions and into new areas (Fig. 2.16).

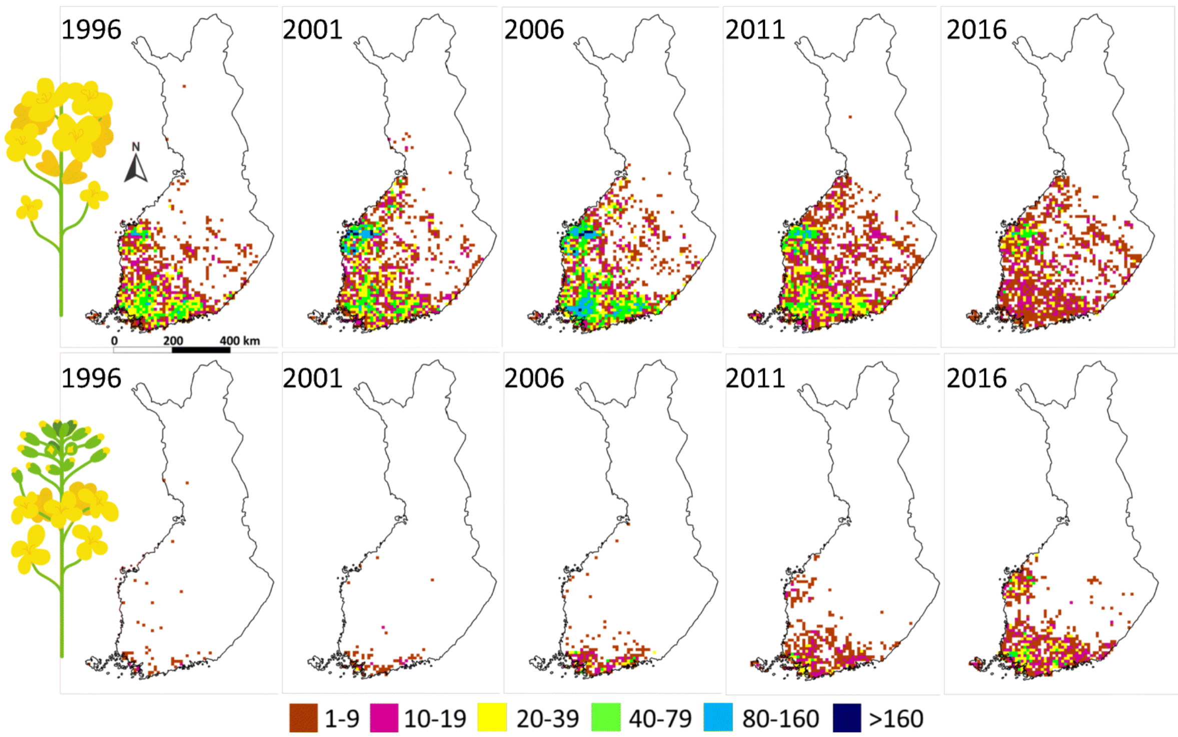

Figure 2.16. Maps indicating shifts in a 10 × 10 km grid in the number of field parcels with spring turnip rape (top row) and oilseed rape (bottom row) under cultivation in 1996, 2001, 2006, 2011

and 2016. The number of parcels is shown with different colours. White means that there are no parcels in the grid with the crop in question (Source: Peltonen-Sainio and Jauhiainen, 2020).

Similarly, as with spring cereals, projected climate change could lead to considerable enhancement in yield and above-ground biomass potentials of rapeseed in northern European growing conditions. Late-maturing oilseed rape with its high demand for degree-days from sowing to ripening is estimated to benefit from the longer growing seasons, resulting to gains in the yield potential (Peltonen-Sainio et al., 2016).

Grassland

Grass-based dairy and meat production are a key feature of agriculture in Norther Europe, including Finland. Largest part of the forage grass on Nordic farms is stored as silage and consumed over winter. As there is most often no market for silage, farmers try to minimise the risk of silage deficit. Grass is most often harvested in two separate cuts. Drought poses an considerable risk as such events will decrease the yields irrespective of the amount of fertiliser applied. Irrigation is rarely an option due to high costs relative to expected reduction in risk of yield loss (Kässi et al., 2015). Höglind et al. (2013) assessed the impact of climate change on two grass species, timothy and ryegrass, at locations across Northern Europe, including Finland for a 2040–2065 scenario (based on an ensemble CMIP3 climate models) compared to a 1960–1990 baseline. The results of the study indicated an increase in yield throughout the study area, mainly due to increased temperature during the growing season. The yield response was slightly less in non-irrigated conditions, as in Finland, compared to irrigated areas (11% and 14%, respectively) due to water deficit. The yield increase was found to be increased mainly because of an increased number of cuts per year rather than higher yields in individual cuts. In fact, simulations indicated in many cases a decrease in the yield of the first cut.

Opportunities for crop production

The agricultural sector in Finland and more widely in the Nordic countries can potentially be considered both a winner and a loser with respect to climate change. With effective adaption and proper management, climate change could lead to increased productivity. Based on a review by Wiréhn (2018), the opportunities brought about by a warming climate in combination with other factors, such as the increase in the atmospheric CO_2 content, generally refer to increased yield potential and the possibilities to introduce new crops or varieties. Table 2.3 gives an overview of the climate-change related opportunities identified for the agricultural sector from literature.

Table 2.3 Overview of agricultural opportunities associated with climate change in the Nordic region. Table adapted from Wiréhn (2018)

Area	Specific opportunity	Climate change driver	Source
Yield	Increased number of harvests per year	Prolonged growing season and higher mean temperature	1-4
	Increased quality	Climate change; combined aspects	5
	Compensate for climate change challenges	Elevated atmospheric CO2 concentration	6,7
	Favours perennial crop production	Climate change; combined aspects	3, 8
	Favour spring-sown crops in southern Nordic region	Temperature increase	7,9
	Shift from spring- to winter sown crops in nemoral zones	Climate change; combined aspects	10,11
	General crop yield opportunities	Climate change scenarios, specifically earlier sowing and increased number of growing degree days	3,8,12-14,19

New crops or varieties and northward expansion of current crops	Maize expansion	Climate change; combined aspects	4,5,15
	Ryegrass expansion	Increased winter temperature	16
	Winter wheat (and other cereals) expansion	Climate change; combined aspects	4,15,17
	Increased opportunities to grow peas, faba bean, oilseeds, soybeans, sunflowers, and C3 plants in general	Increased mean temperature and elevated atmospheric CO2 concentration	3,18

1. Uleberg et al. (2014); 2. Höglind et al. (2013); 3. Fogelfors et al. (2009); 4.Eckersten et al. (2008); 5. Eckersten et al. (2012); 6. Rötter et al. (2011); 7. Olesen (2005); 8. Rötter et al. (2013); 9. Olesen et al. (2012); 10. Trnka et al. (2011); 11. Peltonen-Sainio et al. (2010); 12. Rötter et al. (2012); 13. Kaukoranta and Hakala (2008); 14. Torvanger et al. (2004); 15. Elsgaard et al. (2012); 16. Thorsen and Höglind (2010); 17. Marttila et al. (2005); 18. Maracchi et al. (2005); 19. Lehtonen (2015)

However, there are many important challenges that relate both directly to climate change as well as to potential adaptation induced trade-offs. Failing to address these concurrent challenges, losses in productivity might impede potential gains and the possibility to capitalize on climate change in the long run. The review highlighted the need for recognizing and analysing the various important challenges as well as appreciations of potential adaptation-induced trade-offs that need to be accounted for in developing sustainable adaptation strategies (Wiréhn, 2018).

2.4 Relevant national policies

Production levels in agriculture and forestry have increased over past decades due to longer growing season, increasing temperatures and rain patterns, and higher CO2 levels in the atmosphere (NAS, 2015[1]; Forest strategy, 2019[2]). As showed in the previous section, this process is expected to continue also in the future due to further climate change, providing potentially more forest biomass both for industry and energy production. At same time less energy may be needed in Finland for heating (due to higher temperatures), lowering the need for biomass. However, climate variation increased and will continue to increase in the future, affecting forest management:

- biomass production and wood quality could put under pressure, for example due to more frequent storms and the spread of harmful organisms into new areas.
- Wood harvest (e.g. timing) and timber transport systems (water ways, roads) become more a challenge
- Wood quality could suffer by a higher moisture content

(NAS, 2015; Trinomics, 2021).

This carbon sink in the LULUCF sector of Finland varied between -14 and -33.7 Mt CO2 equivalent in the period 1990 and 2019 (NECP, 2019), compensating for 15 to 48% of its total CO2 emissions. In 2021 the LULUCF sector in Finland turned even into carbon source (LUKE, 2022). Regarding the fluctuation, climate had only a limited role. The most important reason for fluctuating C sinks is the level of wood harvest/net removals of roundwood. In years with much harvest, the LULUCF sink decreases, and vice versa.

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1 https://www4.unfccc.int/sites/NAPC/Documents%20NAP/Adaptation%20Strategies%20and%20Plans/Finland%27s%20National%20Adaptation%20Strategy%20-%20an%20integral%20part%20of%20the%20National%20Energy%20and%20Climate%20Strategy.pdf

2 https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/161739/MMM_17_2019_National%20Forest%20Strategy%202025%20final_.pdf?sequence=1&isAllowed=y

Finland aims to be the world's first fossil-free welfare society, i.e. carbon neutral by 2035, carbon negative soon after that (NECP, 2019). The NECP addresses all five dimensions of the EU Energy Union: decarbonization (incl. sinks), energy efficiency, energy security, internal energy markets and research, innovation and competitiveness. Relevant here is that agriculture is the second most significant source of greenhouse gas emissions in Finland. In 2019, agricultural emissions accounted for 12% (6.6 Mt CO2 eq.) of total emissions (NIR, 2021[3]). Agricultural policies should both increase the production and reduce the emission (NECP, 2019[4]). Moreover, measures in the agricultural sector could also reduce emissions from other industries (e.g. through promotion of biogas production, NECP, 2019). In addition to climate objective, several projects and actions have been defined and implemented to fulfill also other requirements as, for example, been set in the Global Sustainable Developments Goals (SGDs). Affordable and Clean Energy is one of these (SDG7).

Biomass is the most important source of renewable energy in Finland. Today around 85% of renewable energy is from biomass, and biomass contributes around about 30% of Finland's total energy supply and is as such more important than some other sources like coal and nuclear (IEA, 2021). The current main application of biomass is in renewable heat. The objective is to increase the fraction of biomass in the future energy supply (NECP, 2019). A longer growing season could support this objective.

As being a forest-dense country, the forestry sector is an important sector for Finland. Sustainable forests, both from an economic and ecological perspective are of great importance for the country. This includes sustainable forest management (to increase the C sink in forests) and wooded biomass production. Wooded biomass is the most important biomass source in Finland (about one fourth of total energy consumption, NECP, 2019). Wooded biomass (especially solid) is also exported to other parts of especially Europe (mainly in form of wood pellets and tall oil, IEA, 2009). Wooded biomass production is largely integrated into forestry and forest industries. As such, these biomass flows originate not only from forests (either as primary production or residue), but a major share is derived from residues and waste flows within the forest industry. Next to wood, peat is also an energy source in Finland (although not allocated as renewable). The policy objective is to halve its use in the national energy production by 2030 (NECP, 2019). More upcoming is the use of agricultural biomass (with high cellulose content) as energy source. And animal manure is used for energy by converting to biogas. All this means that bioenergy can be produced from various types of biomass and by using many different techniques, but wooded biomass is clearly dominating in Finland.

Policies and documents relevant in context of biomass

The Ministry of Economic Affairs and Employment is responsible for the coordination of the work on the energy and climate in general, particular the National Energy and Climate Plan (NECP). In relation to energy and biomass, the NECP is one of the main policy documents. In order to realize its ambition of becoming carbon neutral by 2035, actions and plans (incl. monitoring) as included in the NECP (2019) have been taken by every ministry in Finland and transformed into strategies. Related to the topic of this report, the Ministry of Agriculture and Forestry is responsible for the biomass part in the national energy plans, as well as for the land use, land-use change and forestry sector (LULUCF

[3] https://www.stat.fi/static/media/uploads/tup/khkinv/fi_nir_eu_2019_2021-03-15.pdf
[4] https://energy-poverty.ec.europa.eu/discover/practices-and-policies-toolkit/publications/finlands-integrated-national-energy-and-climate-plan_en

sector)[5]. Finland has adopted various acts and strategies to support this process and to initiate funding schemes for a sustainable biomass production. Some of these acts are more sectoral oriented, others more integral/cross-sectoral, and even multi-national.

- Climate & energy related: Climate act and NECP (2019), that promotes the use of biomass as (i) fuel; (ii) low-carbon construction material
- Climate Programme for Finnish Agriculture (2014) (http://extwprlegs1.fao.org/docs/pdf/fin165298.pdf)
- National Inventory Report (NIR) to UNFCCC
- Climate Adaptation: The National Adaptation Strategy for Climate Change (2015) and National Action Plan (NAP) for Adaptation to Climate Change;
- The Finnish Bioeconomy Strategy (2014, updated 2022) to steer the Finish economy in 'right' direction
- Forest legislation[6]: Forest act, the Forest Management Associations Act; Timber Measurement Act; Act on the Financing of Sustainable Forestry; National Forest Strategy (revised 2019[7]). Enumerate objectives to be achieved until 2025 by the wood-based industries and activities
- Nature conservation: Nature Conservation Act
- Building code to promote low-carbon construction

Lessons learned from policy documents in Finland with respect to biomass

Climate change (impacts) on forest and agricultural production have been addressed in many of the listed policy documents. When assessing these documents we can distinguish three entry points:

- The effect on the production of biomass and Carbon sequestration
- The effect on the use and applicability of biomass
- Side-effects of using biomass (either synergies or treat offs)

The production of biomass and Carbon sequestration

Finland has various policies -both agriculture and forestry related- that support the production of biomass and/or policies that aim to maintain carbon sequestered within the land or to increase the carbon uptake. For example, Finland aims to maintain the LULUCF net sink to be on average 20 Mt CO_2- equivalent, which is needed to reach carbon neutrality by 2035 (NECP, 2019). And the productivity of ecosystems, including forests should remain or even increase where possible, despite the changing climate (National Adaptation Strategy, 2015, National Forest Strategy, 2015, 2019). All in line with the latest updates of the EU Renewable Energy Directive (REDII[8] and REDIII[9]). In detail, agricultural policies, like included in the Rural Development Programme and the implementation of the EU's CAP, are targeted towards:

- More sustainable cropland management to increase biomass production and to reduce emissions by changes in:.

[5] The ministry is- together with Ministry of the Environment also responsible for the national adaptation plan for climate change and compiling the annual climate change report.
[6] https://mmm.fi/en/forests/legislation
[7] https://mmm.fi/en/nfs
[8] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC
[9] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0557

    - crop management, for example, by stimulating multi-annual/perennial crop cycle on organic soils, plant cover in arable land in winter and the use of organic cover for horticulture plants and seed potatoes.
    - Soil management, e.g. incorporation of slurry into the soil, recycling of nutrients and organic matter environment management of grasslands, and stimulate low tillage
- Establishing financial subsidy system and payment system for
    - More controlled subsurface drainage, for efficient C storage in soils, treatment and use of manure
    - investments in energy efficiency and sustainable energy, such as biogas plants.
    - direct aid and greening payments that affect the C storage in soils
- The abovementioned measures should reduce emissions from the agricultural sector by approximately 1.15 Mt CO2 equivalent by 2030 (NECP, 2019).

Finland has also legislation and monitoring systems in place to maintain the forests' health and ability to grow (which is a basic requisite for their capacity to sequester more carbon) and to minimize the risk of unsustainable forest biomass production, like the *Forest Act*, and the *Forest Damages Prevention Act*. These acts aim to protect (certain) forests, to make the forest more climate resilient and to secure sustainable use. Thus they include objectives for both climate mitigation (=maintain current sequestration) and adaptation (more resilient forests). This by:

- A general starting point of, for example, the Forest Strategy is that active forest management and use will maintain the forests' ability to grow, which is a basic requisite for their capacity to bind carbon.
- Protecting more forests in Finland. Currently, roughly 2.7 million hectares of forests in Finland are protected or under restricted use (= 12 % of the total forest area, including forest land and poorly productive forest land). The *National Forest Strategy* and *The Forest Damages Act* include strategic projects/actions to.
    - to increase this percentage to make Finnish forests more climate resilient
    - to reduce the risks of extreme weather events to forest health. The Action Plan on Climate Adaptation includes, among others, actions to limit forest damages and to secure forest biodiversity.
- Stimulating reforestation of degraded areas especially on drained peatland (about 4 Mha of Finland's peatland has been drained for forestry purposes, of which a small fraction is degraded). Notion that the effect of this stimulants could be limited as Finland has only limited degraded areas.
- Supporting Resource-efficient and Sustainable Forest Management to increase carbon content and harvest. The *National Forest Strategy* states that climate change should become an integral part of forest management. As result of the strategy, for example, a tree breeding program has been initiated to improve productivity and resilience of trees to respond better to the changing weather and climate conditions.
- Stimulants to improve the knowledge basis on carbon storage and sequestration in forests.
- Legislation like the *Forest Act*, *Forest Damages Prevention Act* and accompanied monitoring systems should minimize the risk of unsustainable forest biomass production.
- Providing forest guidance instruments and incentives, and practical tools. For example, forest owners, operators and authorities need to carry out risk assessments to assess current and future risk of climate change (Forest Strategy)

- Improving the financial system, i.e. setting up pilots for new carbon sequestration and storage markets
- Putting monitoring systems in place to minimize the risk of unsustainable forest biomass production, e.g. mentioned in *Forest Act* and *Forest Damages Prevention Act*.

Altogether, the forest strategy includes 10 strategic projects/actions, including (i) Resource-efficient and Sustainable Forest Management; (ii) Climate Sustainable Forestry (improving C storage); (iii) New Wood-based Products (new high value added fiber and pulp products as well as on in the use of wood in wood building and timber products.). Important in this respect is that the wood harvest in Finland is still (far) less than the annual increment of the forests, resulting in 38% increase of the standing forest biomass over past decades (NIR, 2021).

The Nature Conservation Act[10] is a key instrument to safeguard the biodiversity of Finnish nature, including many forests. Likewise the Climate Adaptation Strategy and accompanying Action Plan stress the importance of the Finish natural environment. Next to measures to protect the nature and limit greenhouse gas emissions (e.g. raising water tables in peatlands, resulting in more carbons storage), these acts and strategies also promote the sustainable use of natural resources including biomass.

Renewable energy policies and the use of biomass

As mentioned, biomass is important for the energy system in Finland.

- In forestry a major share of wood fuels is derived from logging residues, and residues of the forest industry
- In agriculture, the energy production lies especially in utilising biomass-based side streams of agriculture for Combined Heat and Power (CHP) generation and for transport fuel. Plus biogas from farming (current only utilized in minor extent, due to costs) (Trinomics, 2021)

Finland has the ambition to increase the contribution of wood fuel in near-term future (e.g. Action Plan for Adaptation to Climate Change, ….). For example, the contribution of liquid biofuel in transport should increase from 18% in 2021 to 30% in 2030 (Act on Promoting the Use of Biofuels in Transport). To achieve this ambition, the use of wood-based fuels as a whole is promoted in multiple ways (e.g. ETS system, operating aid for electricity, ….):

- The use of bioenergy should be even more integrated in the forest sector/industries.
- Funding schemes will be set up (both subsidies and taxation) to promote the use of renewable energy in general and biomass in particular. E.g. an aid is granted to compensate for the higher production costs when using forest chips in combined heat and power generation (CHP) (related to the ETS prize).
- An Act on Promoting the Use of Biofuels in Transport has been in force since 2008
- Initiating research in food and wood science to increase energy and material efficiency and reducing emissions per liter or kilo of production.

New, climate resilient markets for wood-based products will be developed , for example, in building industry (see Action Plan for Adaptation to Climate Change, and new Bioeconomy Strategy, 2022)

[10] https://ym.fi/en/reform-of-the-nature-conservation-act
https://finlex.fi/en/laki/kaannokset/1996/en19961096.pdf

2.5 Adaptation

Finland is in the process of developing its 2nd National adaptation plan extending until 2030. The plan aims at managing risks associated with climate change and increasing the capacity to adapt to the changes across the society. Projected changes in climate and increased likelihood of extreme weather events causing disruptions to biomass production, along with changes in the socio-economic setting affecting for example market prices place a need to increase the resilience and adaptive capacity in both forestry and agriculture. Diversity in biomass production is today reduced largely to the cultivation of a narrow selection of dominant species and crops. As a consequence, other species and crops of local and/or regional importance have lost ground. There is now great need to increase diversity for making future agriculture and forestry more sustainable and resilient under projected changes and risks to production (e.g. Kahiluoto and Himanen, 2012; Massawe et al., 2016).

Forests

Time span of the boreal forest growth from young seedlings to mature forests is long compared to the speed projected changes in climate. At the same time, the future projections of forest growth under abiotic and biotic risks are very uncertain. This makes the current decision making of forest management practices a challenging task.

Currently, the forest management in boreal forests is focused on conifers, despite their future growth projections and vulnerability for several climate change caused abiotic and biotic damages. Thus, there may be a need to adapt the choice of main tree species in forest regeneration, considering the uncertainties related to the projected climate change in different time spans. Scots pine and birch or mixtures of conifers and broadleaves should be favoured especially in south Finland. This may also increase biodiversity and recreational values of the forests (Torssonen et al., 2014; Pukkala, 2018; Kellomäki et al., 2018; Kalliomäki et al., 2018). Forest vulnerability for biotic damage may be increased by a preceding abiotic damage, e.g. severe drought, and multiple types of damage may accumulate. Uncertainty in projected damages and their spatial scale remains large, because the occurring damages (outbreaks and long term stress) are usually local and the spatial scale depends on the site conditions and structure. Overall, these damages may partially counteract the positive effect of climate change on forest growth (Reyer et al., 2017).

Agriculture

In agriculture, increasing diversity of plant species and genotypes in cropping systems through for example crop rotation, intercropping and cultivation of underutilized crops provide many benefits: farmers' adaptation options are widened, valuable genetic material is conserved and various ecosystem services are sustained (Himanen et al., 2013). Additionally, biodiversity insures ecosystems against disturbances by increasing the chances that if some crop fails, others may still maintain functioning (Yachi and Loreau, 1999).

As a concrete example from Finland, cultivation of specialty crops such as caraway, flaxseed and camelina, alongside cultivation of cereals, has been found to improve farm's resilience and adaptive capacity to various changes by increasing flexibility and securing productivity of the farm in the long run. Caraway, in particular, has shown considerable promise. As a primarily biennial crop it increases plant cover and develops extensive roots which aid in improving soil quality, enhancing nutrient intake, and providing additional security under extreme weather events such as heavy rains, floods and heat waves that are projected to increase in the future. Further, cultivation of caraway balances work peaks of the farm as it is sown later than cereals and harvested earlier and diversifies income sources (Mäkinen et al., n.d.). Cultivation of caraway has become popular in the 2000s in Finland and is among the crops that have since 1996 most substantially gained new areas (Peltonen-Sainio and Jauhiainen, 2020). In its capacity of demonstrating how a minor crop can become a high-quality niche crop in norther climates of considerable importance, it can be seen as a true success story (Galambosi and Peura, 1996). By supporting an enabling the expansion of caraway, emerging industries (www.transfarm.fi and www.carawayfinland.fi) have aided in making Finland now a key player in the world’s caraway markets (Peltonen-Sainio and Jauhiainen, 2020).

3 Case study France

3.1 Biomass from agriculture and forestry in France

France is a main cereal producing country in the EU (AGRESTE, 2021). The country has suitable crop growth conditions and has important potential for biomass growth. Around half of the land area in France is agricultural land and one third is forest land. Around 60% of renewable energy in France is from biomass (IEA Bioenergy, 2021). France committed to become carbon neutral by 2050. The French Environment and Energy Management Agency (ADEME) assessed future scenarios for this, concluding this cannot be achieved without plants, soils and forests as natural sinks (ADEME, 2022).

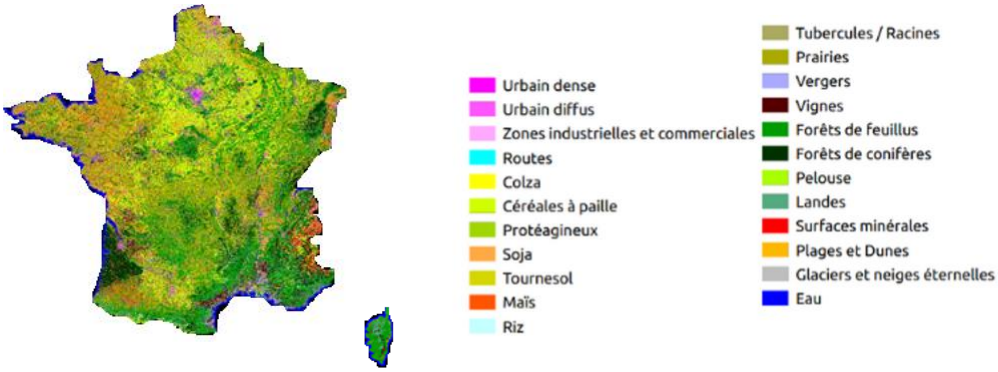

Figure 3.1 France land cover map 2020 (source: https://www.theia-land.fr)

Agriculture

More than half of the country's arable land is used for cereals, mainly wheat and maize. The area used for agriculture in 2020 amounted 28,580 million hectares (AGRESTE statistical handbook 2021) and the main crops are provided in Table 3.1. While the actual number of farms is decreasing, the cultivated area is stable over the past decade (down 1% compared to 2010), see Table 3.2.

Table 3.1 Main crops France, developed area in ha (source: Agriculture census AGRESTE)

Main crops	2020	2021
Maize	1 720 949	1 547 120
Soft wheat	4 267 497	4 982 767
Durum wheat	252 278	294 282
Barley	1 974 155	1 730 399
Oats	98 406	107 219
Sorghum	93 581	67 931
Total cereals	8 903 284	9 307 467
Rapeseed	1 112 928	980 126
Sunflower	777 344	698 330
Total oilseeds	2 119 095	1 878 886
Protein crops (beans)	388 403	381 885
Sugar beet	420 668	402 162
Potatoe	216 185	211 425
Vines	753 861	751 262

Table 3.2 Crop areas between 2000 and 2020 in Metropolitan France (source: AGRESTE statistical book 2021, March 2022)

Areas in thousand hectares	2000	2010	2020
Field crops	13,459	13,136	12,697
Forage crops	14,691	14,339	14,357
Permanent crops	1,141	1,011	1,013
Others	517	440	512
Total utilised agricultural area	29,807	28,926	28,580

Forestry

Forest cover in France amounts to 17,253 million hectares in 2020 which is 31% of the land area (Science for Environment Policy 2021, data from Forest Europe, 2020). The majority of the French forest is privately-owned and deciduous (70% of forest area) and 30% of the forest area is coniferous, with main areas show in Figure 3.2. For more than a century, the French metropolitan forest area is increasing (IGN, 2021). Based on an inventory between 2015 and 2019, the growing-stock volume (volume of standing timber) of the French forests was estimated at 2.8 billion cubic meters[11] (National Forest Inventory, 2022, IGN 2021).

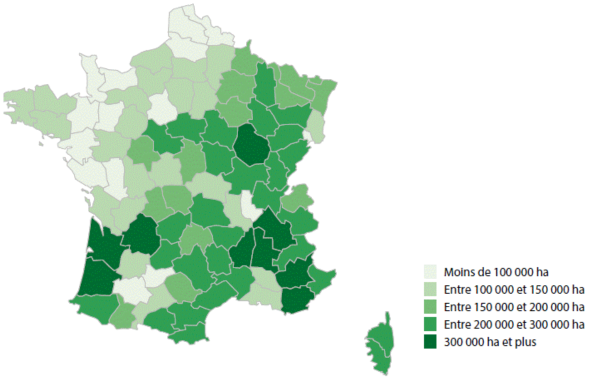

Figure 3.2 Main forest area in 2020 (*Institut National de l'Information Géographique et Forestières* IGN, 2021)

According to the Office National des Forêts (ONF), the condition of French forests deteriorates due to climate change. A study by INRA and IGN on the French forestry sector towards 2050 confirms the role of the sector in climate change mitigation. But severe weather events and threats are likely to increase in the future (storms, forest fires, pest outbreaks) and may dramatically reduce gains in carbon storage in forests (Roux and Dhôte, 2017).

3.2 Observed trend of biomass production major crops and tree species

Trends in biomass production were looked at by VITO from observations for the past 20 years, based on Copernicus productivity data (see Annex 1 for methodology):

- Gross primary productivity (GPP, in kg DM/ha/year) maps were prepared which quantify the actual photosynthesis rate.
- GPP trends are 'positively biased' by CO2 fertilization factor (global trend), hence adjusted trend maps were prepared to show the remaining trend more reflecting anthropogenies impact.

Forest and woodland trends

Trends for forest and woodland between 1999 and 2019 show that (Figure 3.3):

- There is an overall stable, increasing trend in GPP in last 20 years. This is in line with the fact that since 1990, due to a better protection as well as a decline in farming, France's overall wooded or forested areas have increased by nearly 7% (e.g. The Economist 2019). The area of forests in France is on the rise and the expansion for the period 1990- 2020 is shown in Figure 3.4. The above ground biomass increased at 1.4% per year between 2010 and 2020 (State of European Forests, 2020).

[11] Stock based on volume of trees with diameter at breast height >= 7.5 cm, including stump, bole up to 7 cm diameter and bark

- One region in the southwestern part (Landes de Gascogne) is stable to slightly decreasing in GPP, even when the CO2 fertilization effect is included (orange/red area in Figure 3.3). In this area (old) maritime pine forest is present, and the storms of 1999 and 2009 affected the South-West severely. These created approximately 70 million cubic metres of windthrow damage (Mora et al 2014).This may explain the distinct trend.

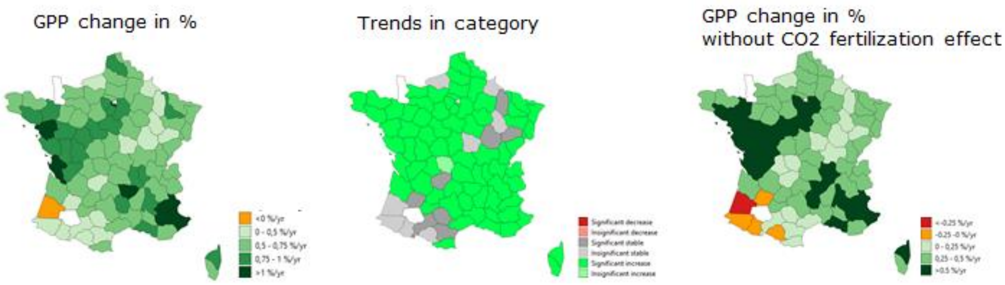

Figure 3.3 Forest and woodland GPP trend results from 1999-2019 per NUTS-3 level for France. For the blank regions no trend could be calculated, because less than 1% is occupied by forest (maps by VITO, 2022)

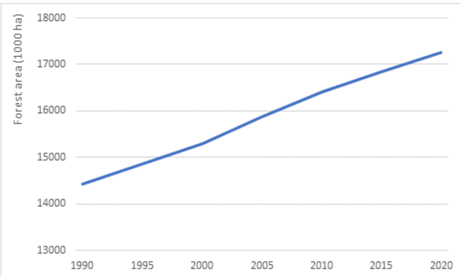

Figure 3.4 Forest area between 1990 and 2020 (data from State of European Forests, 2020)

Cropland trends

Trends for croplands 1999-2019 show that (Figure 3.5):

- There is an overall stable GPP trend in the last 20 years. The trend shows a less pronounced increase in GPP as compared to forests. This is in line with stagnation trends for cereals (see below).
- In the central to northeastern part (mainly field crops area with cereals, few areas grasslands), the GPP trends show a slight decrease of biomass production when excluding CO2 fertilization effect (orange and red parts in Figure 3.5).

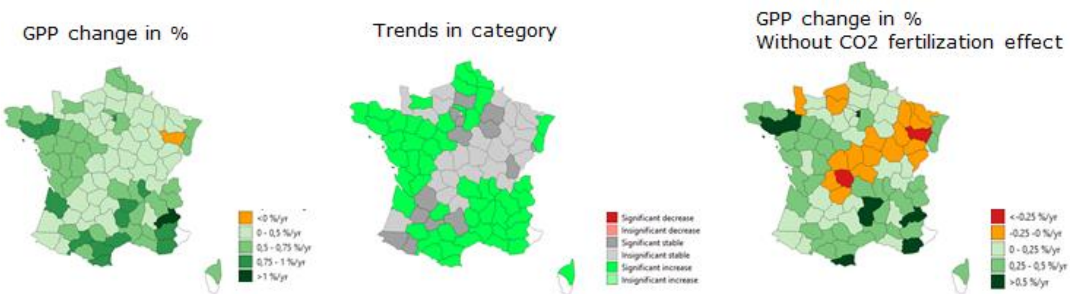

Figure 3.5 Cropland GPP trend results from 1999-2019 per NUTS-3 level for France. For the blank regions no trend could be calculated, because less than 1% is occupied by forest (maps by VITO, 2022)

There has been consensus on wheat yield stagnation in France since around 1996-1998, also confirmed by Schauberger et al., 2018. They studied yield trends for 1900-2016 at NUT3 level from national statistics to better understand this. Mean yields have grown rapidly over the second half of the 20th century, but stagnation for crops (winter wheat, barley, oats, durum wheat, sunflower and wine) is seen since the end of the nineties. Stagnation is more likely in departments with high average yields (northern parts with higher mean yields due to better growing conditions). The stagnation is caused by different factors, i.e. the yield potential is reached, climatic conditions, political decisions and crop management. Further research for the cause(s) is needed, currently impeded by lacking data. Maize shows no evidence for stagnation.

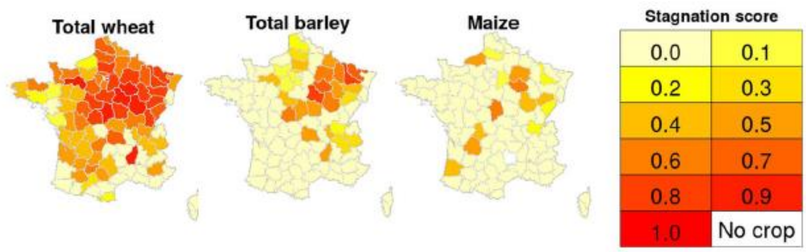

Figure 3.6 Likelihood of stagnation in recent years (1997–2016), expressed as stagnation score (extracted from Schauberger et al., 2018)

3.3 Future Agriculture and forestry under a changing climate

3.3.1 Climate change France up to 2030/2050

Increased air temperatures are one of the most noticeable changes in climate change in France. The Observatoire National sur les Effets du Réchauffement Climatique (ONERC) reports an average temperature increase for mainland France of 1.14°C for the decade 2000-2009 (compared to reference 1961-1990).

Near future (to 2050)

For the near future (2021-2050), Meteo France (2020)[12] reports an increase in average temperatures between 0.6 and 1.3°C (higher in the South-East in summer) for mainland France and an increase in the number of heat wave days in summer. ONERC reports as already visible and future impacts by 2050 (Figure 3.7):

-Average rise in temperature of 1,5 degrees for France
-Increased chance of forest fires
-Increased droughts
-Yield stagnation for crop yields (wheat) after 35 years of growth

[12] Meteo France 2020, https://meteofrance.com/changement-climatique/quel-climat-futur/le-climat-futur-en-france

Figure 3.7 Observed or future impacts by 2050 (source: ONERC[13])

There is a large seasonal contrast with larger increase in summer temperatures, mainly in southern France. To assess climate impacts, Climator prepared a set of climate projections at a finer scale over France, following scenario A1B for the 21st century. For 2020-2050, projections agree about:
- a mean heating of about 1.6 °C for the period 2020-2050 compared to the reference;
- a general reduction in annual rainfall, with a big drop in the spring and summer, particularly in the southwest. Trends in precipitation are less pronounced than temperature. The summer rainfall will decline over the whole country whereas the changes in winter rainfall is more uncertain.

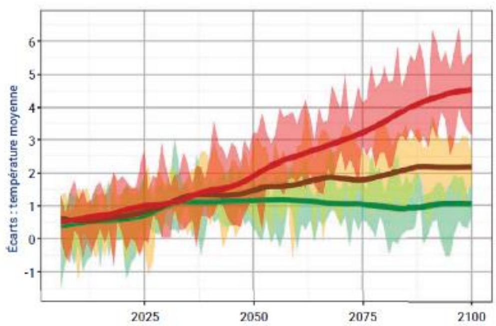

Figure 3.8 Evolution annual average temperature difference (compared to reference 1976-2005) for the three scenarios RCP2.6 in green, RCP4.5 in orange and RCP8.5 in red (in: Soubeyroux et al., 2020).

End of century (to 2100)
Recently a new dataset was prepared by the *National Climate Service DRIAS* to analyse climate change in France during the 21st century (DRIAS-2020[14]). Figure 3.8 shows the expected warming in France for three RCP scenarios. The warming trend is similar until 2040, after that it varies significantly according to the RCP considered (Soubeyroux et al., 2020).

3.3.2 Projected crop yields and forest growth up to 2030/2050

Types of biomass most vulnerable to climate change impacts
Climate change is expected to bring longer, warmer summers to France. The main influential factors are increased temperatures, changed rainfall patterns (overall less rain is expected), and higher evaporation. This results in different, sometimes conflicting effects to crops. Temperature has a

[13] ONERC, https://www.ecologie.gouv.fr/observatoire-national-sur-effets-du-rechauffement-climatique-onerc#scroll-nav__3
[14] DRIAS climate projections France, available from http://www.drias-climat.fr/

complex effect on crop phenology and yield; Increased temperatures can be beneficial or harmful. In general it can be stated that:

Crops that will be moderately affected by climate change in France are e.g. wheat, forage crops and sunflower. For these crops, yield formation takes place in spring or autumn. Damaging effects of climate change during summer are balanced by a lengthening of the growing period in spring and/or autumn. For sunflower, higher temperatures reduce problems associated with cold.

Crops that are likely to be significantly affected by climate change in France are annual summer crops and perennial crops, e.g. maize, wine yards and forest production, for which summer climatic conditions are decisive to yield, quality, and indeed the long-term survival of the crop (forest). Climate change could mean moving the production zones further north.

Regional differences - North and South of France: Where in general climate risks are more limiting in the south of France, warmer temperatures in the North may favor the growing season resulting in better yields.

Other drivers impacting yields
France has a high regional variety in biomass types and climate, making yield projections complex. Ceglar et al (2020) highlighted that approaches to model crop yields driven by observed climate have proven highly challenging in France. This is especially due to a high regional diversity in climate but also due to a variety in environmental and agro-management factors. Climate change is only one driver shaping agriculture, while food productivity is strongly related to technology development.

Climate change impacts to agriculture main crops / forest types
Projected impacts to crop yields vary for France across different studies. An extensive study on climate change impacts for crop and forests in France cited here is CLIMATOR (Brisson and Levrault). In the study yield projections were simulated using the atmospheric model ARPEGE based on SRES B1, A1B and A2 emission scenarios, then downscaled, for the near future (2020-2049) and the distant future (2070-2099).

Below climate change impacts to main crops for the near future are described.

Wheat and barley
Soft wheat occupies more than half of the cereal acreage in France, used for human and animal feed. Wheat is a winter crop, while barley is to a large extent a spring crop. The crops are primarily rainfed. Wheat and barley as C3 plants[15] are good in exploiting the increase in CO2 concentration. Simulations from Climator suggest that wheat yields could increase in the near future due to the effect of increasing CO2, but response are very variable. The increase in temperature results in an

[15] C3 and C4 crops are two types of crops with different mechanisms of CO2 consumption and a different response to climate change. The majority of crop plants are C3 plants. Examples of C3 crops are wheat, soybean, barley and examples of C4 crops are maize, sugarcane and sorghum. The efficiency of photosynthesis in C4 plants is higher than its efficiency in C3 plants. C4 crops are better adapted to deal with high temperatures than C3 crops, and C3 crops can benefit from increased CO2 concentrations better than C4 crops.

advancement of the developmental stages and a shortening of the life cycle which limits some of the stresses, which could allow an increase in the number of grains per m2. Also, fungal diseases tend to decline.

Lanaaia et al (2016) simulated biomass growth in France to assess climate change impacts as part of the Regional Observatory for Agriculture and Climate Change (ORACLE study). Their results show a production increase of 17% for above ground biomass for straw cereals for the near future.

Increases in wheat yields for France are also mapped by the JRC PESETA-IV project which analysed climate change projections for 2050 (RCP8.5) for 1.5 °C and 2 °C warming conditions, see Figure 3.9 (Hristov et al., 2020). There are large uncertainties in the estimated impacts of climate change, connected to highly variable projections of precipitation.

While several studies report positive impacts, Gammans et al (2017) describe negative effects of warming on wheat and barley yields. They concluded that projected yield declines range from 3.5% to 12.9% for winter wheat and 2.3% to 12.1% for winter barley across all models and all scenarios for the medium term 2037-2065. On the positive site, they conclude that continuing technology trends would probably counterbalance effects of climate change. Winter barley appears more resistant to warming than spring barley. As such, a possible pathway of adaptation could be shifting from spring to winter varieties (Gammans et al 2017).

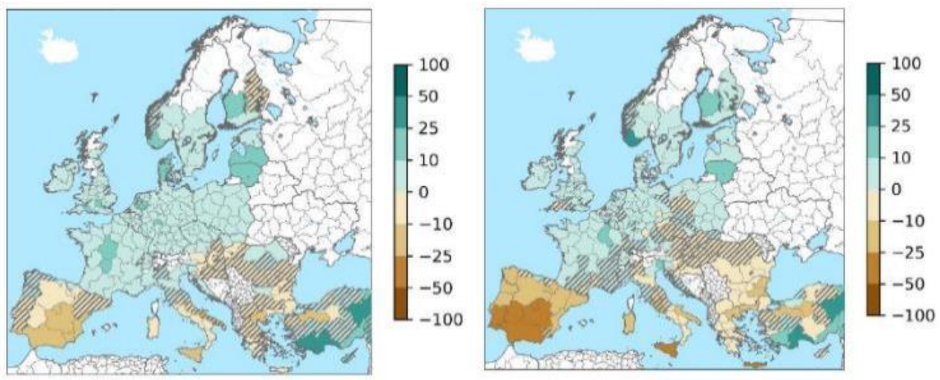

Figure 3.9 From Hristov et al 2020: Ensemble mean changes of wheat yield (% relative to the historical period) projected under the RCP85 for 1.5°C (left) and 2°C (right) warming under rain-fed conditions

Oilseed crops: Sunflower, rapeseed

There is a more favourable trend for winter crops (rapeseed) compared with summer crops (sunflower):

Oilseed rape (C3 crop): Oilseed rape is a major crop in France, used for food (human and animal) and biofuel production. Rapeseed has advantages when faced with climate change. In general, rape yield tends to increase in the near future. This increase is particularly large in the eastern regions in France and in the mountains, traditionally colder in autumn and winter. With a reduction of frosts in winter, the north-east and centre-east will become suitable for the crop. Rapeseed is able to sustain droughts during grain filling but is sensitive to droughts at early stages (source: Climator).

Sunflower (C3 crop): Sunflower is the second largest oil crop after rapeseed in France. It is used for human consumption and animal feed as well as for biofuel. Sunflower responds rather well to climate change. Increased temperatures will advance development phases but the crop may suffer from a reduced seed filling phase. In the near future, yields are not expected to change much, but an expansion of growing regions is expected into the north of France. Yield gains are expected in northern France as climate change may increase the growing period and make crop growth conditions more favourable (Climator). Agriadapt (2017) reports potential decreases in sunflower production for the south of France. The future of sunflower in Europe is related to its potential adaptation to climate change but also to its competitiveness and attractiveness for food and energy (Debaeke et al 2017).

Maize and sorghum

Maize (C4 crop), irrigated: Maize is mostly used for animal feed (about 30%) and export. The use of maize for energy (bioethanol production) is currently still quite small. Grain maize is projected to be the most affected crop by climate change in Europe. Maize is a summer crop and climate change causes a shortening in the grain-filling period which is expected to lead to yield losses, and climate change will increase the irrigation demand. Yield reductions are estimated by the JRC PESETA-IV project upto 2050 for most producing countries in Europe, including for France (Hristov et al 2020). The Climator study showed a lowering of yield of irrigated maize in the near future in current production regions (south-east, south-west, west and north-east) due to a shortening of the grain-filling. This can lead to yield losses of about 1 t ha-1 for the near future. A similar result is described in Agriadapt (2017): To 2030, yield decrease can be more than 25 % in the South (even with additional water supply). Small yield increase (with an additional water supply) is expected for the center and north part of France.

Sorghum (C4 crop), mostly rainfed: Sorghum is mostly used for animal feed. Grain sorghum (a 'hot weather' cereal) areas have increased in France mainly for fodder supplies. Only 25% of sorghum is irrigated. The crop is able to respond positively to the effects caused by climate change. It withstands drought better than maize and has deep roots. For rainfed sorghum, yield reduction due to the deterioration in water supply is less marked than for maize, with even the prospect of an increase in the northern zones (Figure 3.10).

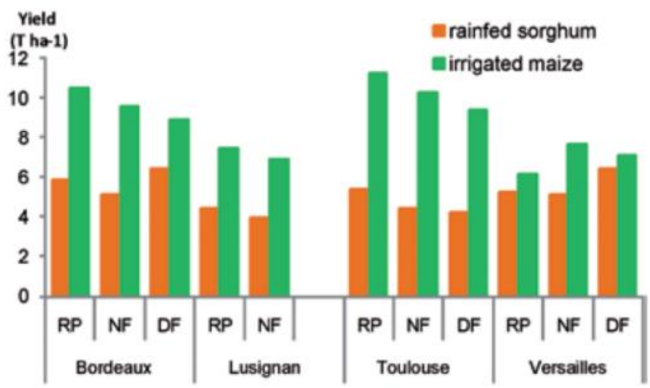

Figure 3.10 Comparison of the change in yield of irrigated maize and rainfed sorghum in France for Reference Period, Near Future (2020-2049) and Distant Future (2070-2099). Source: Climator

Grassland

Grasslands are an important part of French forage systems. In general climate change will have a moderate positive impact on the levels of forage production from grassland in France. The Climator study shows a change in the distribution of the yield throughout the year for the near future. Trends show an acceleration of production in winter and spring until the available soil water is used. In summer then a fall will occur in daily yield due to the more frequent drought episodes. The study predicts an increase of about 5-20% in forage production between now and 2100. However, a deterioration in the water and nitrogen status of grasslands can occur. Also Lanaaia et al (2016) report that in spite of the increased water deficit at summertime in France, grasslands (first cut) should be slightly more productive at the end of the century than today, in relation to earlier leaf onset dates.

Vines

Due to climate change an advancement of phenology and harvest dates is seen in the recent past for French vineyards. The most important impact from climate change limiting vine yields is summer water stress. Drier weather is expected to cause a decreased annual yield up to 2030, unless efficient irrigation is implemented. But the warmer climate allows moving wine production further north (Agriadapt 2017).

Climator reports impacts to yields in near future as highly variable. In general the sites where yields increase for several crops are mostly in the north-east, centre-north and west zones (Mirecourt, Mons-en-Chaussée, Rennes), or in the mountains (Clermont). Climate change will impact wine *quality*: Higher temperatures increase sugar concentration which may affect quality of the grapes. Kurtural and Gambetta (2021) report for two top wine regions in the world (France and USA) which have warmed substantially over the past 60+ years, that until now this warming has contributed to increases in the average wine quality so far but a tipping point may be reached.

Forest

Metropolitan French forest species are C3 plants. The majority of the French forest is deciduous (70% of forest area) and 30% of the forest area is pine. About 4% of French total primary energy supply is from wood (State of European Forests, 2020). According to the Office National des Forêts (ONF), the condition of French forests deteriorates due to climate change, mainly due to drought conditions.

The Climator study concludes that both deciduous and coniferous can be affected by climate change in the near future and significantly in the distant future. In the short term (up to 2030 and 2050) the expected impact on wood production will be more or less positive. In the long term (up to 2100), because of more frequent extreme events, the effects to wood production will be clearly negative. Due to the uncertainty in climate scenarios, the extent to which the positive impact of CO_2 increase will counteract the negative impact of reduced summer precipitation remains an open question (ref. climatechangepost).

Loustau et al (2005) analyzed climate impacts on potential forest production for France. All models predicted a slight increase in potential forest yield until 2030–2050, followed by a plateau or a decline around 2070–2100, with overall, a greater increase in yield in northern France than in the south. Laanaia et al (2016) conclude that forest productivity in France up to 2100 is affected by large uncertainties.

Pines

Pines are a special case: The rise in temperatures is unfavourable for pine. The yield of pines falls in the near future (4.6%) in France and more strongly in the distant future. There is uncertainty associated with these results, mainly due to the method of climate downscaling (reference Climator).

Beech forest

The probabilities of the presence of beech diminish in the near and distant future, indicating a possible regression of the species in France. There is however climatic uncertainty. According to the Office national des forêts (ONF), adapting forests to a future climate will involve a diversification of species. This may mean fewer beech trees, which are especially sensitive to climate impacts across Europe. Future growth trends for beech forests in Europe were predicted by Martinez del Castollo et al (2022), showing growth declines for France (Figure 3.11) depending on the scenario used (i.e. CMIP6 SSP1-2.6 and SSP5-8.5). The more realistic SSP5-8.5 scenario leads to dramatic decreases in beech productivity in Europe. From 2020 to 2050, decreases of 20–30% are expected to affects most forests in central Europe, even including some elevated sites in northeast France.

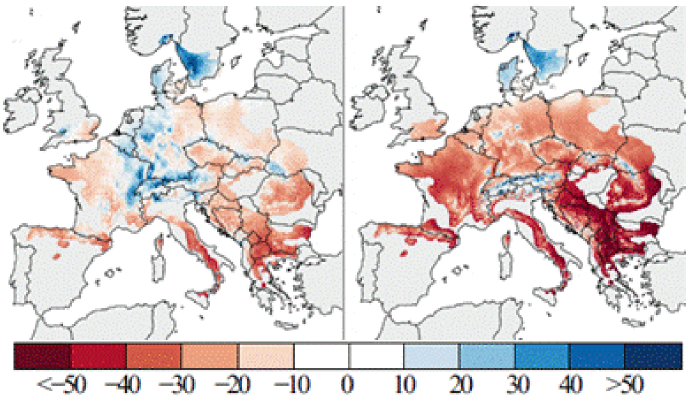

Figure 3.11 Relative changes in beech forest tree growth for 2020-2050, SSP1-2.6 (left) and SSP5-8.5 (right). Basal area increments (BAI) changes expressed in percentage of change compared to the 1986–2016 period. In: Martinez del Castollo et al, 2022

<u>Opportunities from climate change</u>

Climate change can represent also opportunities for France:

- New cropping opportunities due to climate change: e.g. for viticulture, the increasing temperatures can steadily extend the growing regions to the whole of northern France.
- Possible increase in yields when water stresses are avoided or made up for by growth in stress-free periods for winter crops, grassland and perennial crops.

3.4 Relevant national policies

<u>Climate and Energy</u>

Today, biomass is an important (sustainable) energy source in France. For example it covers 60-70% of renewable energy (IEA, 2021). This includes the use of biomass in industrial biomass plants for heating, renewable heat production, and wood used by households (e.g. in stoves and boilers) (NECP, 2020). Likewise, the bioenergy sector produced 7.7 TWh of electricity, representing 1.6% of total electricity consumption (NECP, 2020). France aims to become net carbon neutral by 2050. To start this transition, France launched an updated *National Low-Carbon Strategy* (NLCS)[16] in 2020, describing its ambition to mitigate greenhouse gas emissions and secure energy supply. The NLCS includes, among others, policies to:

- Increase carbon in forests and agricultural land through defining guidelines and setting up a monitoring system
- Increase the production and use of biomass in a way that it is in balance with food production, carbon sequestration in ecosystems, and other environmental concerns like air pollution needs to be considered as well (see also NECP. 2020).
- maximize the effects of carbon substitution and storage when using biomass (incl. more efficient use of biofuels and substituting energy-intensive materials)

Stimulate the development of new technologies to process biomass (e.g. gasification of wood fibre materials, or a better digestion for biomethane) and better recovery of energy from bio-based products. Together with the Multi-annual Energy Plan (MEP) the NLCS form the basis for the *National Energy and Climate Plan* (NECP)[17] of 2020. The NECP describes the French climate targets, both national and sectoral. Regarding agriculture and forestry, the NECP assesses different measures and trajectories on how the LULUCF sector could contribute to the decarbonization of the economy. It raises the challenge of balancing agricultural and forest biomass for energy production (clear trajectories on biomass supply and demand have been defined) versus substituting fossil-based materials, or enhancing CO2 storage in forest ecosystems (CO2 uptake should be enhanced by 2050). Next to the NECP, various other policy documents exist in France that address the current and possible future relevance of biomass and bioenergy, like the National Biomass Mobilisation Strategy (SNMB), 2018[18] and underlying regional biomass schemes (SRB). The SNMB includes 72 recommendations for increasing the mobilisation of biomass, to cover as many identified biomass needs for energy purposes, for construction or biomaterials, and for green chemistry (see details in the NECP, 2020).

The policy objective in France is to increase the total supply of biomass by 2028 by 40% (251TWh) compared with 2016 (179 TWh) The contribution of biomass to the total electricity production in France should increase by 63-73% in 2028, compared to 2016 (NECP 2020, SNMB, 2018). This includes both considerable sustainable mobilisation of solid biomass and development of biofuels/biogas of both agricultural and forest origin. About 40% of increase should come from forestry, half from agriculture and 10% from waste (SNMB, 2018). Agricultural biomass should mainly come through the use of crop residues and intermediate crops for energy purposes, and partly through agroforestry and, to a lesser extent, by perennial crops (SNMB, 2018). By 2050 nearly *two-*

[16] https://ec.europa.eu/clima/sites/lts/lts_fr_fr.pdf
[17] https://energy.ec.europa.eu/system/files/2020-09/fr_final_necp_main_en_0.pdf
[18] https://www.ecologie.gouv.fr/sites/default/files/Strat%C3%A9gie%20Nationale%20de%20Mobilisation%20de%20la%20Biomasse.pdf

thirds of the biomass should come directly or indirectly from the agricultural sector (NLCS, 2020). This all should be done in a sustainable manner (see also B*ioeconomy* Strategy *for France, 2017* [19]*).*

Ambroise et al (2022) assess how the forestry sector, including the issue of biomass is framed in French policy documents. Changes in forest management, revitalization of forests and more optimized wood use for multiple purposes, including biomass and material substitution are considered when comparing different strategies (including one to mitigate climate change). Wooded biomass (both for energy and material substitution) and increased carbon sequestration have become a priority to achieve climate targets for 2050. The forest area has to increase (by nearly 10% in 2030 compared to 2010 (National Forest Accounting Plan, 2020), and more sustainable forest management should preserve the current carbon uptake of forests, and enabling an gradual increase of the wood harvest. (see also Sergent, 2014). The NLCS (2020) and NECP (2020) set out a target of increasing wood harvest from 48 Mm^3 in 2015 to 59-65 Mm^3 in 2030 and 75-83 Mm^3 in 2050. Likewise the *National Forestry and Timber Plan* defined a target of mobilising an additional 12 million m3 of marketed wood for the period 2016–2026. All this is considered as a win-win objective that contributes to environmental, climate and economic objectives. At the same time it is recognized that it requires substantial mobilisation efforts especially in private forests. And the National forest act and National Forest Programme have been implemented, making also biological diversity and nature conservation a key issue in many parts of France. Smart management options like species diversification and taking an integrated and long-time perception are needed to optimize nature and climate objectives (National Forest Accounting Plan, 2020). Also the use of wood as a construction material is strongly encouraged (especially in form of long-lived products). For example, the French The National Recovery and Resilience Plan (NRRP)[20] defined requirements that new public buildings have to contain at least 50% wood in construction, and promotes the use of materials for insultation with low environmental footprints. Likewise a better collection of end-of-life wood products should increase the carbon sink in wood products. Similar messages for a promoting a more sustainable mobilization of wood are given by the “The Strategic Wood Sector Contract (2018–2022)” and the ‘Interdepartmental Plan for Stimulating the Forestry and Wood Sector (2018)’. The NECP also addresses the importance of using biomass to encounter for negative emissions (BECS, e.g. by 2050 10 MtCO2 equivalent of negative emissions annually on installations producing energy from biomass) and includes policy and measures to reduce GHG emission from agricultural soils, that could, partly be accompanied by additional C sequestration.

Overall, the annual natural sink by the LULUCF sector should increase from about 30.7 Mt CO2eq in 2019 to 42 Mt around 2030 and about 60 Mt in 2050 (Ecologic, 2022) (see Figure 3.12). This is mainly due to the uptake in newly established forests and the sink in wood products, and in existing forests caused by intensified wood harvest, despite a drop in the current carbon sink. Furthermore, agricultural measures should result in more soil carbon and less emissions, and soil and water policies should preserve/improve carbon sequestration in soils including peatlands.

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[19] https://www.alpine-space.org/projects/alpbioeco/newsletter/201903/bioeconomy-strategy-plan-till-2020-france.pdf

[20] https://www.aft.gouv.fr/en/french-recovery-plan

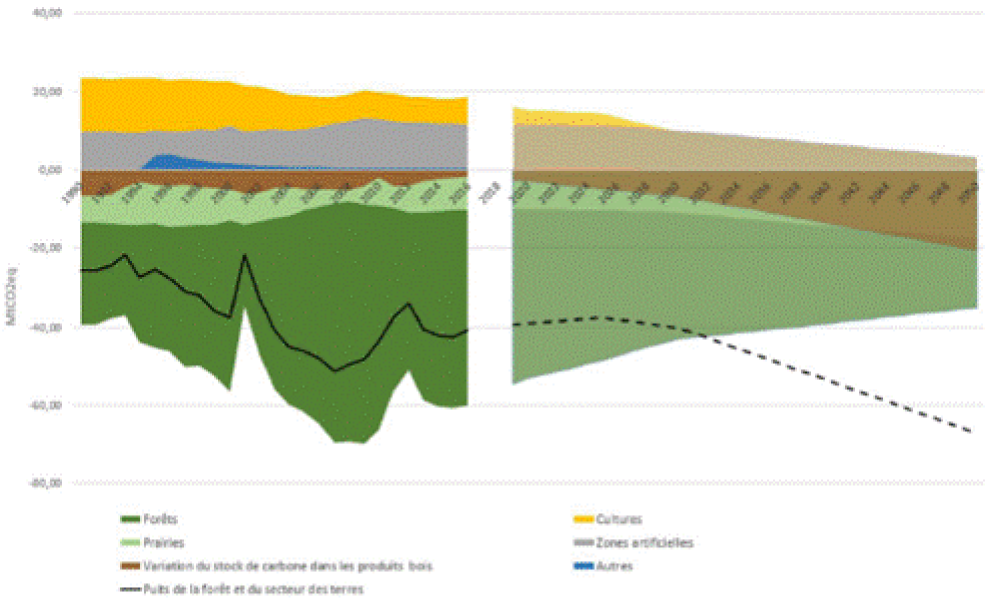

Figure 3.12 Carbon fluxes and historic (solid line) and projected (dotted line) carbon sink of the LULUCF sector in France, between 1990 and 2050 (source NECP, 2020)

Climate adaptation

France adopted its 2nd *National Adaptation Plan* (NAP-2) in 2016, covering the period 2018-2022 and considered that the *National Adaption Strategy* (NAS) of 2006 was still relevant. The general objective of the NAP-2 is to implement actions necessary to adapt, by 2050, the French society (= resilient people, economy and environment), including overseas France, to projected changes in climate and climate extremes. The biomass issue in the NAS and NAP includes recommendations on protecting natural ecosystems and making them more climate resilient in order to preserve proper functioning and production, including carbon sequestration (e.g. reducing risk for forest fires). The water issue has been defined as one of the main issue that needs to become assessed interdisciplinary.

Agriculture and forestry[21]

Agriculture contributes up to 18% of the emissions of greenhouse gasses in France (NIR, 2022). The CO2 sequestration in forests currently compensates for 13% of the national emissions (MinAgri, 2018). At the same time the agriculture and forestry sector is also vulnerable to climate change (e.g. droughts). Policy plans to improve both (=more climate resilient and less emissions) are included in the Agri-Environmental Plan for France and the National Forest Strategy. The overall target is to reduce the agricultural emissions by two third by 2050 (compared to 1990). Different policy measures, actions and tools are proposed:

- Agricultural measures to reduce fertilizer use and improve nitrogen management. (e.g. optimizing fertilizer inputs, co-planting leguminous crops)
- Livestock measures to reduce methane emissions and improve waste management and feed production.

[21] see also 20181130_panorama_de_laction_climatique_pour_lu2019agriculture_lu2019agroalimentaire_la_foret_et_la_bioeconomie_version_anglaise_bd.pdf (gouvernement.fr)

- Soil and water policies and actions should preserve/improve carbon sequestration in soils (forests, agriculture, peatland). E.g. stimulating agroforestry, low-tilling techniques, soil protection measures (e.g. agroforestry Development Plan)
- Land-use conversions more towards grassland, as these contain more carbon in the soil than agricultural sites (the Bio2022 programme)
- Promoting more sustainable forest management (e.g. by providing financial tools, guidelines) to increase carbon sequestration and to stimulate biodiversity in forests, and also wood harvest (National Forest and Wood Programme, also recent NRRP, see above))
- Policies to accelerate afforestation at abandoned agricultural land

In addition, the Government's Major Investment Plan (GPI) includes an agricultural pillar aimed at reducing greenhouse gas emissions by financing the development of tools and to start pilots that address abovementioned actions.

<u>Biomass and circular economy</u>

Finally, different national strategies and plans have been adopted in France for a more sustainable use and reuse (through more cascading) of biomass as substitutes for energy-intensive materials (National Bioeconomy Strategy, 2017, National Forest and Wood Programme, NECP, 2020). The basis here is that biomass resources are rare resources. Therefore a prioritization scheme has been defined: First food uses, then bio-fertilisers, then materials, then molecules, then liquid fuels, then gas, then heat, then electricity (SNMB, 2018, NECP, 2020). Furthermore, these strategies and plans stimulate the development of 'advanced' second-generation fuels produced from wastes and residues, instead of using fossil fuels and agricultural crops (NECP, 2020).

3.5 Adaptation

France is aiming for effective adaptation with its 2nd national adaptation plan (2018-2022). Adaptation will be needed to face challenges from climate change and its impacts, e.g.:

- A shift in production areas to the north (e.g. for maize or vineyards) due to production difficulties which may arise in the south.
- Shifts in sowing dates and choice of varieties, such as a shift from spring to winter varieties. For instance, winter barley is more resistant to warming than spring barley. Water plays an important role in adaptation to climate change. Adaptations to temperature increase will depend on the capacity of the water resource to cope with it. This applies to both rainfed and irrigated crops.
- Crop diversification and integration of woody vegetation and crops such as in agroforestry systems (see example below).

Combine trees and crops, case Montpellier

Climate change is expected to impact agriculture in Montpellier through more frequent droughts and increased temperature. The make the agricultural systems more resilient, a mixture of trees and crops as in agroforestry was introduced, as part of the SAFE (Silvoarable Agroforestry for Europe) project, funded in support of the European Common Agricultural Policy and coordinated by INRA. A French national scheme for planting half a million hectares of agroforestry during the next 20 years was implemented as a combination of walnut trees and wheat cultivation. This has advantages over a monoculture. The complementarity between trees and crops allows a more effective exploitation of the available resources. Agroforestry helps to better control soil erosion and increases the sustainability and resilience of agriculture. It allows for diversification of farm activity and makes better use of environmental resources.

Benefits obtained are:

- Agroforestry is less vulnerable to climate change. Trees provide shelter to crops and reduce damages due to high spring temperature.
- Production from one hectare of walnut/wheat mix is the same as for 1.4 hectares with trees and crops separated (corresponding to a 40% increase in productivity).
- Biodiversity is increased, enhanced controlling of pests and enhancing pollination.
- Farmers can diversify products and improve soil and water quality, reduce (wind) erosion and prevent damage due to flooding.
- Properly designed and managed agroforestry systems may help to increase the sequestration of atmospheric carbon, improve soil quality and soil conservation.

More information: https://climate-adapt.eea.europa.eu/metadata/case-studies/agroforestry-agriculture-of-the-future-the-case-of-montpellier/#websites

4 Case study summary

A synthesis for the case studies of Finland and France is provided below.

Box 4.1 Case study Finland

Case study Finland summary

Current situation agriculture and forestry production

Finland is the most forested country in Europe based on the proportion of forest area to total land area, covering about 75% of Finland's land area (~26 million hectares). Most of the forest area is in commercial use. Roughly 2.7 million hectares of forests in Finland are protected or under restricted use. The main tree species in the managed forests of Finland are Scots pine, Norway spruce and birch. About 7% of the land area is agricultural land (~2.27 million hectares in 2021). Cereals are cultivated on roughly half of the agricultural area with spring varieties of barley, oats, wheat and rye cultivated on a wider scale. Production is primarily rain fed. While Finland's grain yield is small compared to the global scale, it is one of the largest producers and exporters of oats in the world.

Observed productivity trends over the past 20 years

- Satellite-based estimates of trends in gross primary production suggest for both forestry and agriculture an increase across most of the regions in Finland. The most significant increases are found for the southernmost regions.
- For forestry, the result is supported by a comparison against statistics from the National Forestry Inventory.
- For agriculture, observed grain yields from individual areas suggest rye to have increased most while wheat has declined. When analysing shifts in cultivation areas, it is found that farmers' crop choices have changed since the mid 1990's. The most widely cultivated cereals, barley and oats have decreased in cultivation area, while spring wheat has become more popular.

Agriculture and forestry under a changing climate

- Climate change could potentially cause both negative and positive impacts to biomass production
- Global warming is likely to extend the growing season and together with elevated atmospheric CO_2 levels enhance gross primary production (GPP) and growth. Precipitation is more likely to increase than decrease in all seasons, but to be spread more unevenly leading to increased drought. Already by the year 2050, yearly drought days are projected to increase by 20 days in the south and by 5 days in the north. Wind damages are likely to increase with warming winters as tree anchoring soil frost decreases.

National studies suggest the following impacts of climate change on future (tree or crop) yields/growth:

- The effect of the elevated CO_2 alone is assumed to increase GPP in all main tree species.
- Forest gross primary production is assumed to increase by ~30% for the mid-century under all climate scenarios, only after which different climate scenarios make difference in GPP. growth in Scots pine is projected to benefit under all scenarios, especially in the north, independent on the site fertility. In the south, moderate increases in GPP are found for fertile and medium fertile sites. Scots pine also has lower probability of wind damage compared to other species. Growth in Norway spruce and birch is projected to increase on the country level but decrease in drought affected areas. Increasing temperature is projected to benefit GPP most in birch in comparison to other species.
- Depending on the study, the enhanced growth is projected to support sustainable harvest levels even up to 80 million m3 year-1 with intense forest management. However, these projections do not include the increased risks of different types of biotic and abiotic damages, which will play a bigger role in the warming climate and may substantially affect the GPP level.

- Although projections about future changes in crop yields may vary across national studies, they suggest increased potential for achieving benefits. Considerable increases in yields of spring cereals, rapeseed as well as grass, particularly in the northwest, could be achieved with favorable yearly weather, dedicated breeding and management efforts and responsive cultivars. For spring wheat this could mean on average a ~30.0% increase in the south to over 70.0% in the northwest. However, failing to address the concurrent challenges brought about by climate change, losses in productivity might impede potential gains and the possibility to capitalize on climate change in the long run.
- For barley, it has been found, that positive effects are likely to be reversed with temperature increases exceeding 4 °C and that oats might better adapt to a changing climate. Wheat has been found to be more sensitive to changes in temperature than precipitation in Finland.

National policies

- Finland aims to be the world's first fossil-free welfare society, i.e. carbon neutral by 2035, carbon negative soon after that. LULUCF and biomass are important components of the Finish Climate policy. Carbon sink in the LULUCF sector of Finland varied between -14 and -33.7 Mt CO2 equivalent in the period 1990 and 2019 (NECP, 2019), compensating for 15 to 48% of its total CO2 emissions. In 2021 the LULUCF sector in Finland turned even into carbon source due to increased harvest.
- Currently biomass is the most important source of renewable energy in Finland. Today around 85% of renewable energy is from biomass, and biomass contributes to about 30% of Finland's total energy supply. The current main application of biomass is in renewable heat. The objective is to increase the fraction of biomass (wood fuel in particular) in the future energy supply and increase liquid biofuels in transport from 18% in 2021 to 30% in 2030 (NECP, 2019). In forestry a major share of wood fuels is derived from logging residues, and residues of the forest industry. A longer growing season for biomass due to changing climate conditions could support this objective.
- Land-related policies are targeted to increase biomass production (by establishing a new tree breeding programme to improve productivity and resilience of trees) to maintain a carbon sink in forests (by increasing the areas of forest with restricted use, stimulate reforestation) and to reduce emissions (e.g. from agriculture production and peatland). Policies are further targeted to broaden the portfolio of biomass sources in Finland such as more sustainable cropland management which should lead to a more and a broader availability of biomass.
- Finland has legislation and monitoring in place to maintain the forests' health and to minimize the risk of unsustainable forest biomass production. Policies include also the establishment of financial subsidy and taxation system to stimulate production and use of biomass, in agriculture and forestry.

Possible adaptation

Effective adaptation is needed to address challenges such as increased extreme events, erosion, and occurrences of diseases and pests in e.g. the European (spruce) bark beetle (*I. typographus*). The 2nd National Adaptation Plan, effective until 2030, aims at managing risks associated with climate change and increasing adaptation across society.

In forestry this may involve:

- adapting the choice of main tree species in forest regeneration,
- favouring scots pine and birch or mixtures of conifers and broadleaves in southern Finland.

In agriculture this may be achieved via e.g.:

- increasing diversity of plant species and genotypes in cropping systems via crop rotation and intercropping,
- cultivation of specialty crops such as caraway, flaxseed and camelina alongside cereals that improve resilience.

Benefits include increase of biodiversity, conservation of valuable genetic material, sustenance of various ecosystem services and recreational values, widening of farmers' adaption options and insurance of ecosystems against disturbances.

Box 4.2 Case study France

Case study France summary

Current situation agriculture and forestry production

France has suitable growing conditions and an important potential for biomass growth. Around half of the land area is agricultural land (28,5 million hectares in 2020) and one third is forest land (17,2 million hectares in 2020). France is one of Europe's major crop producers of wheat, barley, maize, rape seed, sugar beet, potatoes and wine. While the actual number of farms is decreasing, the cultivated area is stable over the past decade. The majority of the French forest is deciduous (70% of forest area) and 30% of the forest area is pine. For more than a century, the French metropolitan forest area is increasing while the condition of French forests deteriorates due to climate change, mainly due to drought conditions. More severe weather events are likely to increase in the future (storms, forest fires, pest outbreaks) and may reduce gains in carbon storage in forests.

Observed productivity trends over the past 20 years

- Trends in gross primary productivity (GPP) show a stable, increased trend for forests and stable results for cropland with some areas of decrease.
- For forestry, studies show an increase in forest area between 2000-2020 and the above ground biomass increased.
- For agricultural crops, studies show stagnated wheat yields since the end of the 1990s. The stagnation is caused by different factors, i.e. the yield potential is reached, climatic conditions, political decisions and crop management. Further research for causes is needed, currently impeded by lacking data. Maize shows no evidence for stagnation.

Agriculture and forestry under a changing climate

- Future conditions for agriculture will be more favourable in the north than in the south. Where in general climate risks (drought, heat) are more limiting in the south of France, warmer temperatures in the North may favor the growing season, as well the possibility to expand the cultivated area.
- In general there is a more favourable trend for winter crops compared to summer crops and perennial crops.
- Crops that will be moderately affected are e.g. wheat, forage crops and sunflower. For these crops, yield formation takes place in spring or autumn. Damaging effects of climate change during summer are balanced by a lengthening of the growing period in spring and/or autumn.
- Wheat yields could increase in the near future but responses are variable. There are large uncertainties. While several studies report positive impacts to yield, Gammans et al (2017) concluded that projected yield declines range from 3.5% to 12.9% for winter wheat and 2.3% to 12.1% for winter barley for the medium term (2037-2065). They conclude that continuing technology trends would probably counterbalance effects of climate change.
- For sunflower, overall yields are not expected to change much. Higher temperatures can reduce problems associated with cold and an expansion to the north of France is possible.
- Crops that are likely to be significantly affected are annual summer crops and perennial crops, e.g. maize, wine yards and forest production, for which summer climatic conditions are decisive to yield and quality. Climate change could mean moving the production zones further north.
- Grain maize is projected to be the considerably affected crop by climate change. A lowering of yield of irrigated maize in the near future is expected due to a shortening of growth cycle which

can lead to yield losses of about 1 t ha-1 for the near future (source: Climator). To 2030, yield decrease can be more than 25% in the South (even with additional water supply), and small yield increase (with an additional water supply) is expected for the center and north part of France (Agriadapt, 2017).

- For forests and wood production, both deciduous and coniferous can be affected by climate change in the near future and more significantly in the distant future. The expected impact up to 2030-2050 can however be more or less positive. Pine and beech species are an exception. Pine shows growth declines of 4.6% for the near future (source: Climator). For beech, decreases of 20–30% are expected to affects most forests in central Europe, even including some elevated sites in northeast France from 2020 to 2050 (Martinez del Castollo et al, 2022). In the longer term (up to 2100), effects for forests will be negative because of more frequent extreme events. There are however large uncertainties for the long-term effects.

National policies

- France aims to become net carbon neutral by 2050 and at least 83.3% emission reductions by 20501. Achieving this carbon neutrality implies a balance between the biomass use for energy production versus substituting fossil-based materials, or enhancing CO2 storage in forest ecosystems.
- Around 60% of renewable energy in France is currently from biomass. As expressed in multiple strategies and plans, the policy objective in France is to increase the total energy supply of biomass by 40% in 2028 and to increase the contribution of biomass to the total electricity production by 63-73%, both compared to 2016. About 40% of the increase in total supply should come from forestry, half from agriculture and 10% from waste (SNMB, 2018). Agricultural biomass should mainly come through the use of crop residues and intermediate crops for energy purposes, and partly through agroforestry and, to a lesser extent, by perennial crops.
- The use of wood for substituting energy-intensive materials is strongly encouraged also, for example by the construction sector.
- Wood harvest should increase from 44 Mm3 in 2015 to 59 Mm3 in 2030 and 75 Mm3 in 2050. This will require significant efforts to reverse current trends, notably in private forests.
- The annual carbon uptake by the LULUCF sector should increase from about 31 Mt CO2eq in 2019 to 42 Mt around 2030 and about 60 Mt CO2eq in 2050 (see also Meyer-Ohlendorf and Spasova, 2022). Changes in forest management should result in additional CO2 sequestration in existing and new forests and wood products, agricultural measures should result in more soil carbon and less emissions, and soil and water policies should preserve/improve carbon sequestration in soils including peatlands.
- The National forest act and National Forest Programme have been implemented, making also biological diversity and nature conservation a key issue in many parts of France. Smart management options like species diversification and taking an integrated and long-time perception are needed to optimize the nature and climate objectives (National Forest Accounting Plan, 2020).

Possible adaptation

France is aiming for effective adaptation with its 2nd national adaptation plan to face challenges from climate change and its impacts. Possible solutions include:

- A shift in production areas to the north (e.g. for maize, vineyards)
- Shifts in sowing dates and choice of varieties, such as a shift from spring to winter varieties. For instance, winter barley is more resistant to warming than spring barley.
- Crop diversification and integration of woody vegetation and crops such as in agroforestry systems.

- According to the Office National des Forêts (ONF), adapting forests in France to a future climate will involve a diversification of species. This may mean fewer beech trees, which are especially sensitive to climate impacts across Europe.

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Annex I Methodology trend analysis biomass production

VITO, May 2022

As part of ETC-CCA 2022 activity 2.2.3 Biomass, VITO created maps of yearly biomass production and their shift (loss or gain) based on a trend of minimum 20 Years and more particularly for forest and crop land types. The following requirements were agreed upon:

- Biomass production trends for cropland and forest for Finland and France
- Show trends at administrative level (NUTS regions) from 2000 - 2020
- Divide NUTS regions in gaining, stable or increasing biomass production per land cover class (e.g., cropland and forest) and if feasible per crop type
- Distribute the results in a spatial dataset that allows mapping the trends

Methodology

The task started the selection of the main input dataset to measure the quantity of biomass production. The period was shifted with 1 year (1999-2019) to minimize the sensor-switches in the main input dataset (GPP 1km). A dataset prior to 1999 (going to 1984) was evaluated but would result in a lower spatial resolution (4km) and more effort (GPP had to be calculated from the basic components being the Copernicus Climate ECV fAPAR and meteorological data). A higher spatial resolution dataset was available (GPP 300m) and compared to the 1km dataset. Since the period was only 5 years and did not prevail main benefits compared to the 1km dataset, it was not retained. For cropland, a very high resolution (10 or 20m) dataset would be beneficial however such dataset is not yet available but could be created using the Copernicus Land fAPAR and meteorological dataset as explained above. However the time-series of 4 years would be too limited to identify climate change trends and hence was not retained either. Based on the above analysis a first workflow was designed, as shown in Figure A.1:

- The Copernicus gross primary productivity (GPP) dataset at 1km spatial resolution based on Spot-VGT and Proba-V satellites for 20 years (1999-2019) was aggregated from 10-daily to yearly.
- The Corine Land Cover (CLC) Accounting layers was mapped to the ecosystem types forest and cropland (level-1). These ecosystem types were also further subdivided using CLC level-2 classes for forest into coniferous and broadleaf.
- The CLC ecosystem type map was then resampled to 1 km was conducted to match GPP's spatial resolution. Mixed pixels were removed during this resampling step, meaning only pixels with a homogeneous land cover were kept. For each 1 km pixel, the dominant CLC class was kept only if it covers at least 75% of the total area within it. Otherwise, the pixel was excluded from the trend analysis. This procedure was applied for the four CLC datasets available in the period 2000-2018.
- GPP values per ecosystem type were aggregated at NUTS level. For every year, the average GPP of all the pixels covering a certain CLC class in a NUTS region is calculated. The most recent CLC ecosystem type layer for a certain year is always used to filter on land cover. For example the CLC dataset of 2000 is used for the years between 2000-2005 until the next CLC dataset in 2006.
- NUTS level-3 was chosen to do the spatial aggregation, because the higher levels would mask out some more local based trends that are specific for certain areas.
- Classes that covers less than 1% of the total 1 km pixels in the NUTS region are not considered for the trend analysis within that region.
- The extracted GPP values per year should be subdivided in certain trend categories according to their change in GPP per year. The GPP change per year is the slope of the regression line fitted through the GPP values. The regression line was obtained by making use of the Theil-Sen estimator. Following thresholds were used to divide the slope into trend categories:
  - GPP increase/year above 0.5% → Gaining area
  - GPP decrease/year stronger than -0.5% → Red area
  - GPP change/year between -0.5% and 0.5% → Stable area

The selection of the threshold was based on a paper with a similar objective: https://www.mdpi.com/2071-1050/12/1/411/htm

- The significance of the observed trend was determined by applying the Man-Kendall test, which subdivides the rising or decreasing trend into significant or insignificant.
- The observed trend category, the significance as well the change of GPP per year for each CLC class and NUTS region in the country is written into a spatial dataset that allows mapping and querying the trends of interest in a geospatial software package (e.g. QGIS, ArcMap).

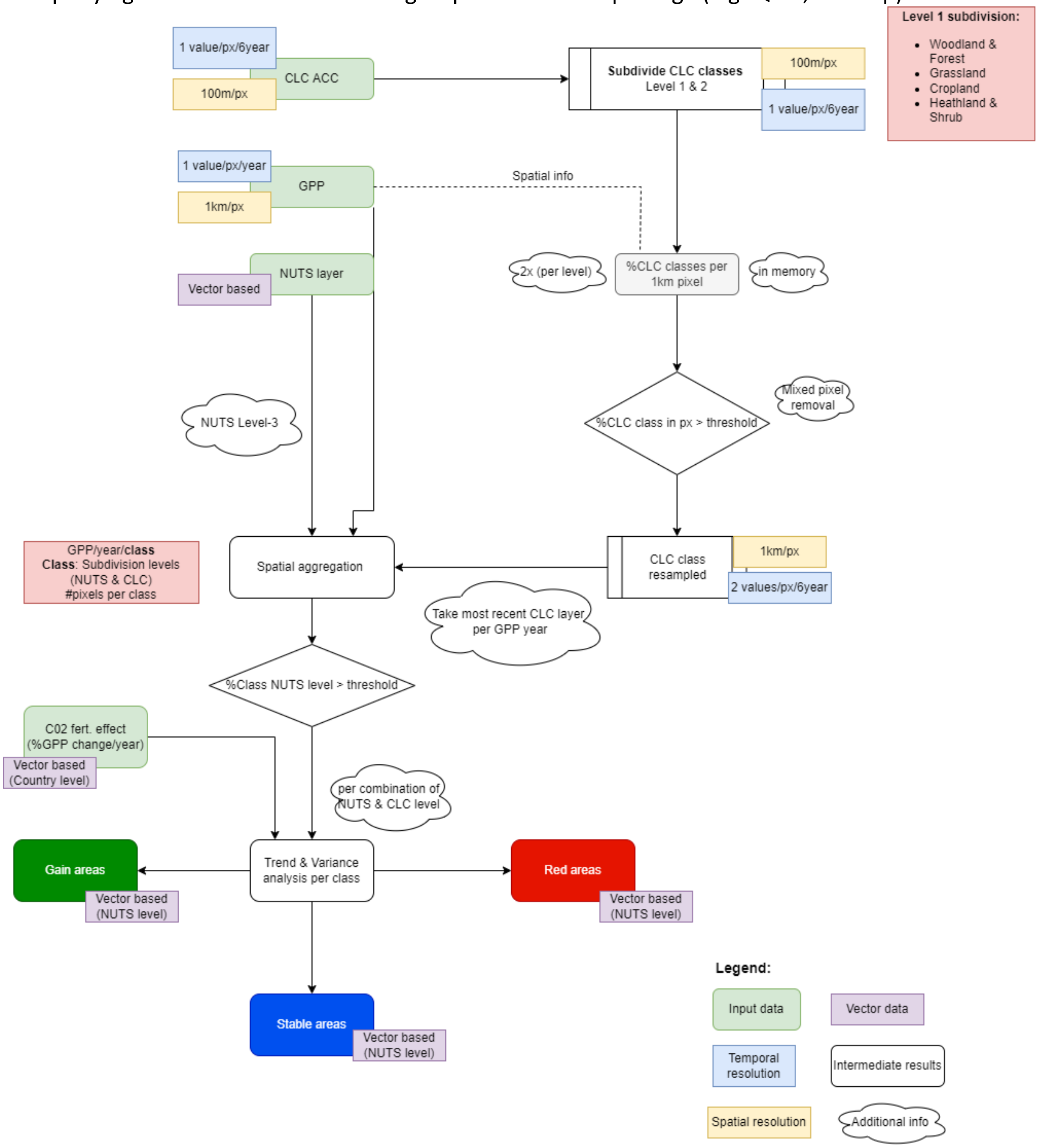

Figure A.1 Flowchart describing applied procedure for biomass production trend analysis at NUTS level.

Distinguish crop types

An add-on to the workflow was created to distinguish also the crop types to level-2 using the JRC CropMap layer, however only 1 timestep (2019) was available and the GPP layer per crop type per year did not generate clear statistics and hence was left out of these results.

CO2 fertilization factor in GPP model

The GPP model is based on 3 major components:

- Photosynthetic Active Radiation, estimated via incoming solar radiation
- fAPAR, the observations how much light is actually intercepted by vegetation
- Light Use Efficiency (LUE), to constrain the model to drivers: air temperature and atmospheric C02 concentration

The atmospheric C02 concentration is increased the last 20 years and hence result in an increase of the GPP at global scale. This phenomena is known as CO2 fertilization and can provide 'positive' bias trends at regional scale in GPP.

- The part of the GPP increase per year attributed to CO2 fertilization can be calculated by knowing the evolution in CO2 the last 20 years and the average temperature for this period, as shown in Figure A.2. The figure shows a raise in GP of 2.1% (5°C) to 7.7% (20°C) over the 2000-2020 period.
- For simplicity, the average temperature of the country was taken to calculate this correction factor. This simplification could especially for Finland restrict the trend results in the northern part of the country.
- Once the GPP increase per year attributed by the CO2 fertilization is known, it will be subtracted from the observed change in GPP per year.
- Removing this correction factor will allow to better highlight areas where real changes in biomass production are taking place. Furthermore, it will allow to better link the observed regional differences to anthropogenies impact like management practices.

- A correction of -0.3 GPP% increase/year was applied for France (assume average year Temperature of 14°C) and -0.15 GPP% increase/year for Finland (assume average year Temperature of 7°C).

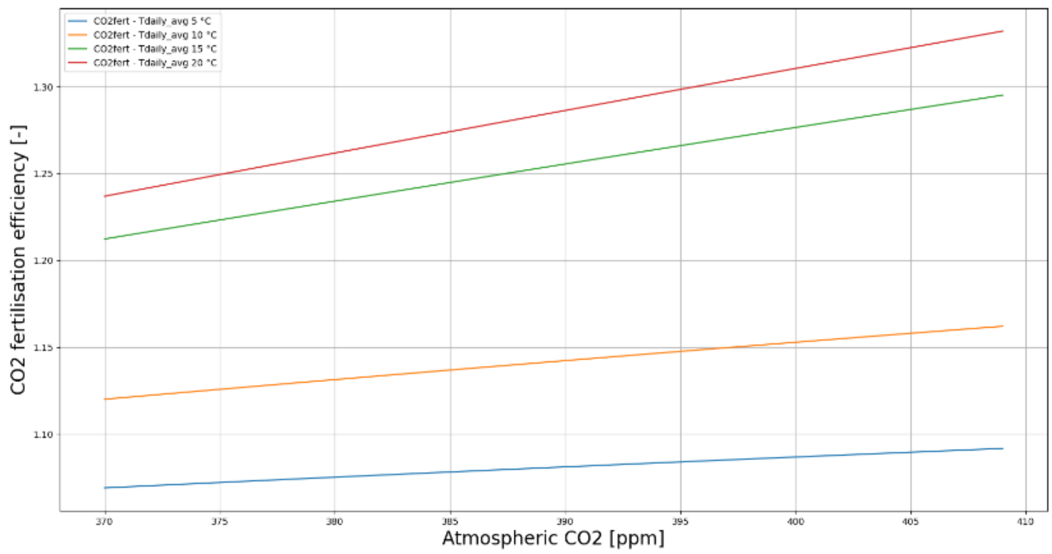

Figure A.2 CO2 fertilization effects

Annex 2 Uncertainty in future projections of biomass production

SYKE, September 2022

Uncertainties and the sources of uncertainty on biomass production are often neglected in the studies of future projections. Projections of future changes in biomass production typically rely on the use of process-based models. There, uncertainty in the results can arise from 1) input data, 2) model parameters and 3) model structure (van Oijen and Ewert, 1999; Wallach et al., 2014). Input data on aspects like weather, soil physical properties, crop/variety and management practices can vary between sites and/or years. Errors in measurement and limitations in data availability may affect values used as input to models. In contrast to input data that often can be measured, model parameters often need to be estimated, where the chosen estimation technique, quality of the data set used or expert bias may add to the uncertainty (Wallach et al., 2014). Model structural uncertainty results from the fact that no model can describe all relevant processes perfectly or a given process can be describe in many alternative ways. In climate change impact assessments additional uncertainty is added via scenarios of future radiative forcing of the climate, with projections of the climate conditional on this forcing, and techniques of downscaling these projections to the required spatial resolution (Giorgi, 2005; Olesen et al., 2007). There is also uncertainty associated with how the projected increase in CO2 will influence plant photosynthesis and water use (Porter et al., 2014).

As an example, on the uncertainties related to gross primary production, the source of all carbon in forest ecosystems, and heterotrophic respiration Kalliokoski et al. (2018) discovered that GCM variability was the major source of uncertainty until 2060, only after which the emission pathway became the dominant factor. Similarly, uncertainty in forest predictions have been shown to be most affected by climate models, RCP scenarios and management actions, while the ecosystem model parameters play a smaller role in projection uncertainty (Mäkelä et al., 2020). Vauhkonen and Packalen (2018) pointed out that the level and allocation of the future harvest cause considerable variation in the carbon stored and extracted. The management showed more influence on the projection uncertainty in the south than in the north in Mäkelä et al. (2020). They showed that the impact of climate models was relatively constant during the whole period until the year 2100, while the importance of RCP scenarios increased towards the end of the simulation period. The GPP and respiration trends show differences between RCP4.5 and RCP8.5 scenarios both in the south and in the north Finland starting from the year 2040, but the uncertainty of these differences with yearly variation remain large and overlapping until the end of the century.

Overall, the future projections of forest growth and carbon stock and balance depend highly on the modelling approach used. Projections of six different empirical and process based models were compared in Kalliokoski et al. (2018), and a large variety of predicted growth and carbon contents was discovered. Common with all the models was that the predictions of lowest harvest intensity scenario resulted in the largest carbon stock and carbon sink in given time periods (until 2065 or 2100, depending on the model). However, even the sign of the gross growth resulting from lower harvest intensity varied from increasing to decreasing, depending on the model. The conclusion on the model comparison was, that the scenario analyses of future must be built with as wide understanding as possible of the uncertainties entwined in the modelled predictions and settings. None of the currently available models of forest carbon state can alone reliably predict future growth. It is thus important to base climate policy actions on results from an ensemble of models.

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