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The land carbon sink of Lithuanian forests in the light of climate change
A model approach

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Abstract

Forests form the backbone of the European terrestrial carbon sink (State Forest Service & Ministry of Environment, 2018). As the European Union (EU) strives to become climate neutral by 2050, forests are accounted for the natural carbon absorption mechanism (European Commission, n.d.). Currently, the European net land carbon sink is decreasing largely due to forest ageing (Pilli et al., 2022), and increasing soil carbon emissions (Morales et al., 2007). Lithuania, a country composed of temperate-boreal forests located by the Baltic Sea, is witnessing a similar trend. Whilst Lithuania has demonstrated vast carbon sequestration rates over the past decades, the forest ecosystem, primarily composed of Norway spruce, Scot's pine and Silver birch, is becoming a carbon emitter (Ministry of Environment, n.d.; Mozgeris et al., 2021). To come in line with the targets set by the EU, Lithuania aims to expand its woodlands. With that, appropriate silviculture management practices could support higher carbon sequestration rates.

The scope of this study is to explore the behaviour of the three most common tree species and a so-called Natural stand in Lithuania, using a dynamic vegetation model LPJ-GUESS. For the first time the model has been applied solely in Lithuania. Following a baseline climate along with two Representative Concentration Pathway scenarios, RCP2.6 and RCP8.5, three major research questions were addressed: [i] the general response to climate change; [ii] species response to climate change; [iii] response to forestry management strategies. Regarding [i] by 2100 a majority of forests become carbon emitters, due to a higher net soil carbon release compared to carbon uptake by forests. With respect to [ii] broadleaf species were more favoured, whilst needleleaf trees did not exhibit particular sensitivities to the changes in simulated abiotic factors. Concerning [iii] both monoculture and silviculture plantations yielded similar carbon absorption rates due to the dominance of birch.

The modelled LPJ-GUESS results demonstrated that two of the three most common species in Lithuania, would not naturally grow at this specific ecoclimate. As a take home message, in order to improve forest land sinks, Lithuania and Europe as a whole, should consider mixed-age and mixed-species plantations in forestry management with a preference for native broadleaf trees in central Europe. Additionally, forests should be allowed to undergo successional development, with the avoidance of clearcuts. Eventually, since the net carbon sink of European forests altogether is weakening, all member states must be prepared to take supplementary initiatives in reducing GHG emissions as part of climate change mitigation.

Keywords: Climate change, forest sequestration, land carbon sink, Norway spruce, Scot's pine, Silver birch, monoculture, silviculture, NPP, NBP, ecosystem modelling, LPJ-GUESS.

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1 Introduction

Terrestrial carbon sequestration is the natural mechanism by which forest ecosystems remove carbon dioxide (CO_2) from the atmosphere. In the light of climate change, the land carbon sink is of great relevance, as it acts as a buffer between the terrestrial biome and the increasing atmospheric greenhouse gas pool (GHG) (Lindeskog et al., 2021). As the European Union (EU) seeks to reach climate neutrality by 2050, each member state has set respective emission reduction targets. Lithuania for instance should halve all GHG emissions before 2030 (Ministry of Environment, n.d.), by supporting natural means of carbon sequestration (European Commission, n.d.), whilst expanding forest coverage based on the principles of sustainable development (State Forest Service & Ministry of Environment, 2018).

In Lithuania alone, forests absorb 1/3rd of all annual GHG emissions (2017) (Ministry of Environment, n.d.). This absorption rate corresponds to a continuously growing forest cover which has expanded from 20% to 33.7% over the last century (Ministry of Environment & State Forest Service, 2020). Due to its geographical position, Lithuania is composed of mixed temperate-boreal forests, which are dominated by Norway Spruce (*Picea abies*), Silver birch (*Betula pendula*) and Scot's pine (*Pinus sylvestris*). Hence, about half of the country is made up of broadleaf species and the remaining of needleleaf trees which have evolved different climatic preferences.

Over the 21st century, Lithuania is projected to undergo a rise in average temperatures with likely increases in annual precipitation (Lithuanian Hydrometeorological Service, n.d.). Consequently, the temperate Silver birch should benefit from this change, whilst boreal Norway spruce and Scot's pine may decline or adapt to moderate changes at these latitudes (Ozolinčius et al., 2014; Paern, 2012; Reyer et al., 2014; Vitas, 2011). Furthermore, the globally increasing atmospheric CO_2 concentrations could promote photosynthetic activity for all three species (Riikonen et al., 2005; Wamelink et al., 2009). The level of acclimation by forest species will be witnessed in their potential to absorb carbon dioxide. Generally, even in the absence of climate change the forest cover present today is expected to show a decrease in productivity mainly due to ageing and increased timber production (Ministry of Environment & State Forest Service, 2020; Mozgeris et al., 2021). However, appropriate forest management practices can improve forest dynamics alleviating the negative effects of climate change (Biber et al., 2020).

Research finds that forests under a silvicultural maintenance system, containing mixed-species with varying ages, are more productive at carbon sequestration compared to forests under monoculture (Biber et al., 2020; Ruiz-Peinado et al., 2021). This is due to the species‘ varying life cycles and tolerance levels generating different productivity rates. However, up to this day uncertainties arise concerning specific multispecies interactions. With that regard, to sustain the forest land carbon sink in Lithuania, it is necessary to study the effect of different silviculture techniques, as well as, to predict how forests will adapt to climate change.

This paper will make use of a dynamic vegetation model LPJ-GUESS to assess species response to climate change by 2100. Eventually, the goal of this thesis is to provide a better impression of the future state of the Lithuanian land carbon sink.

2 Aim

This study aims to explore the-end-of-the-century terrestrial carbon sink of Lithuanian forests using a dynamic global vegetation model LPJ-GUESS. The aim will be fulfilled by computing Net Primary Production (NPP) and Net Biome Production (NBP) for the three most common tree species in Lithuania, as well as, as a so-called Natural vegetation cover. The results shall provide a quantitative indication to how individual species and their respective mixtures respond to changes in temperature, precipitation and CO_2 concentrations following two Representative Concentration Pathway (RCP) scenarios, RCP2.6 and RCP8.5.

The questions posed will attempt to answer:
i. What will be the future potential of forests in Lithuania as carbon sinks?
ii. Which species will be most benefited or most unfavoured by climate change?
iii. Does a mixed-forest generally generate higher productivity than pure species stands?

Abbreviations

RCP – Representative Concentration Pathway

EU – European Union

NPP – Net Primary Production

NBP – Net Biome Production

CO_2 – Carbon dioxide

GHG – Greenhouse gas

3 Background

3.1 Climate Change and the Carbon Cycle

To understand the effects of climate change on forests, it is fundamental to understand the carbon cycle. Carbon is a resource naturally stored in four major pools of the Earth, the lithosphere, hydrosphere, biosphere and the atmosphere. An exchange of carbon from one sphere to another occurs in a continuous flow, maintaining an equilibrium between the different pools, if no disturbances occur (Chapin III et al., 2011). Forests directly absorb carbon dioxide (CO_2) acting as natural buffers between the different spheres. However, climate change is disturbing the natural carbon cycle, causing a shift in the equilibrium of the land carbon pool.

Climate change is an anthropogenically induced disturbance caused by an excessive release of greenhouse gases (GHG) into the atmosphere (Intergovernmental Panel on Climate Change, 2015). The accumulation of atmospheric GHGs results in rising global temperatures, shifts in precipitation patterns along with increased frequencies and intensities of natural hazards. Carbon dioxide is the greenhouse gas that attracts most attention due to its disproportional release and long lifetime in the atmosphere (Pierrehumbert, 2014). In Lithuania alone, CO_2 is the most emitted GHG, on average representing 67% of all national emissions (State Forest Service & Ministry of Environment, 2021). Hence, as the release of CO_2 emissions is accelerating, amplifying the global warming effect and the associated positive feedback-loops, it is of great importance to study the response of terrestrial ecosystems in the light of climate change mitigation.

3.2 NPP, NBP and the carbon sink

To quantify the net carbon absorption of the terrestrial biosphere, two common measures are used, Net Primary Production (NPP) and Net Biome Production (NBP). As the name implies, NPP accounts for the difference between the carbon gain via photosynthesis and the release through autotrophic respiration. NBP indicates the net carbon exchange within the whole terrestrial biosphere, including carbon losses from heterotrophic soil respiration and from natural or anthropogenic disturbances (Kirschbaum et al., 2001, April 18-20). In order to minimise confusion NBP will be mostly referred to as the carbon sink (absorber) or carbon source (emitter).

That being said, geographically carbon sequestration is highest at the 50° - 60° latitudes (Wamelink et al., 2009). In Europe, these include temperate and boreal forests. The two exhibit vast physiological differences, making temperate forests better primary producers, compared to the boreal trees (Luyssaert et al., 2008). Nonetheless, with regards to carbon sequestration, ecosystems of the Northern Hemisphere contain the largest carbon storage, particularly distributed within the soil pool (Wamelink et al., 2009).

3.3 Natural and anthropogenic effects on vegetation

Naturally species have evolved specific adaptations allowing them to efficiently react to stressful conditions. As climate change amplifies climatic extremes, species are forced to adjust. In some cases, climatic changes favour species metabolism, whilst in others, species adaptation mechanisms are challenged. That being said, there is no one climate change-associated control which affects all species. With respect to ecosystem modelling, changing precipitation, temperature and atmospheric CO_2 concentrations are often analysed in the efforts to most appropriately represent ecosystem response to climate change (Wamelink et al., 2009).

3.3.1 CO_2 effects

Carbon dioxide, together with water are the two main reactants involved in photosynthesis. Generally, CO_2 fertilisation enhances plant productivity (Reyer et al., 2014). As long as no limiting factor is present (such as water, light or nutrient availability) then the increase in internal partial pressure of CO_2 increases light-use efficiency. Under this assumption, productivity increases as an increase in atmospheric CO_2 favours photosynthetic activity and plant growth (Ciais et al., 2008).

3.3.2 Temperature

Surrounding temperatures can greatly influence the speed of biochemical reactions. An increase in average air temperature, theoretically favours the inertia of plant organisms, influencing photosynthesis, vegetation seasons, respiration and evapotranspiration (Ciais et al., 2008). If the rise in temperature does not exhaust other growth limiting variables, particularly water demand, then a projected increase in future climates can increase forest productivity (Bukantis et al., 2015). However this statement does not hold true for all, as individual species are adapted to their specific climate range.

3.3.3 Precipitation

Access to water is a very important limitation for terrestrial plants. Sufficient soil water content promotes growth and productivity (Chapin III et al., 2011). Under moderate droughts, when water is scarce, photosynthetic rates are impaired, due to water-use-efficiency mechanisms which help regulate internal water levels at the cost of reduced productivity (Marozas et al., 2019). This is a result of the stomatal conductance during photosynthesis, where water and carbon dioxide molecules are exchanged at a cellular level. Hence, when the stomatal conductance is enhanced, the level of transpiration (water loss), as well as, carbon exchange is greater.

3.3.4 Ageing

An important factor determining forest productivities is age. Most species reach peak NPPs within the first 100 years of growth (Luyssaert et al., 2008). However, under ecological succession species have evolved specific biological characteristic which result in varying productivity rates. The following may include, being short-lived or long-lived, fast-growing or slow-growing, shade-tolerant or intolerant, to name a few. On evolutionary terms, broadleaf species generally reach higher photosynthetic maximums than conifers (Wyka et al., 2012). With that, the mentioned traits will be further addressed in this paper in relation to the varying degree of carbon absorption over a species' lifetime.

3.3.5 Forestry management

Adding onto climate change and ageing, forestry management brings another dimension which affects forest dynamics, through land conversion, forest composition control, as well as, clearcut and thinning regulation, composed of two or more species. In Europe 70% of forests are managed under silvicultural practices (Pach et al., 2018). Species coexistence increases the genetic biodiversity of woodlands, providing various ecosystem benefits in comparison to single-species forests (Hynynen et al., 2009). These can include complementarity, improved resource partitioning, species stabilisation, species resilience to natural disasters and resistance to beetle outbreaks (Bukantis et al., 2015; Ruiz-Peinado et al., 2021). Additionally, mixed -age and -species forest can sustain higher carbon sequestration rates (Biber et al., 2020; Pach et al., 2018).

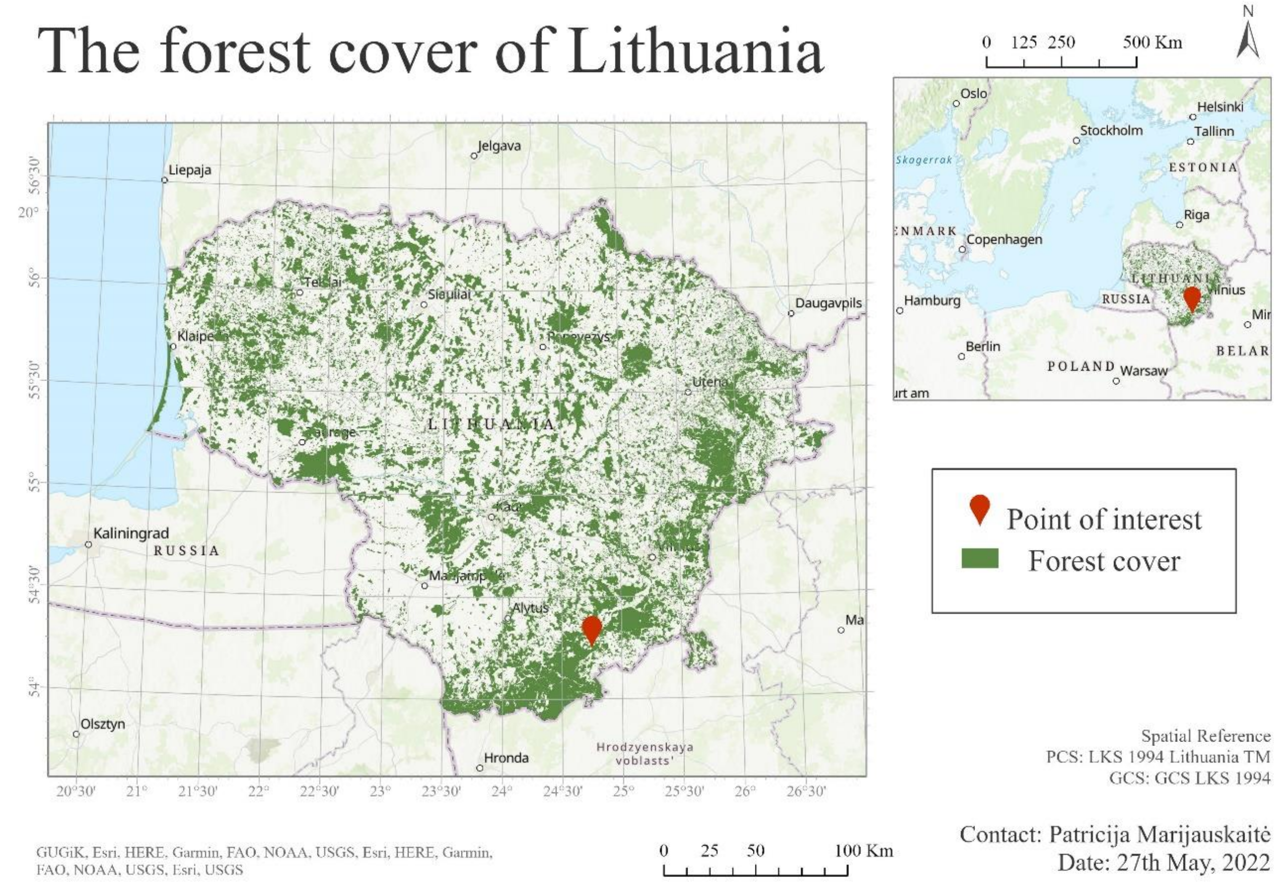
3.4 Lithuania and its forest cover

The upcoming sections will introduce Lithuania, its georaphical positon, climate, land use history, and the forest cover.

3.4.1 Geographical position and climate

Lithuania is the southernmost country from the three Baltic states. As the geographical name implies, it is located by the Baltic Sea, which has an effect on the local climate. Lithuania is 65,302 km^2 large, bordering Latvia, Belarus, Poland and Russia (Kaliningrad). The landscape is relatively flat with the highest point above sea level only reaching 293.8m (State Forest Service & Ministry of Environment, 2021).

According to the Köppen-Geiger classification, Lithuania is characterised by a humid continental climate, meaning that the country has mild summers and is wet all year around (Peel et al., 2007). The current average annual temperature and precipitation stand at 7.4 °C and 693mm respectively (Lithuanian Hydrometeorological Service, n.d.). Whilst temperature displays a continental variability further inland, precipitation is more varied. The highest rates appear by the coast reaching 900mm per year, whilst the lowest are located mid-inland exhibiting an average of 600mm annually. Concerning climate change, mean temperatures have risen by 0.5°C since 1981-2010, meanwhile average precipitation rates have slightly decreased throughout the country (Lithuanian Hydrometeorological Service, n.d.). That being said, the country is composed of organic soils (Biber et al., 2020), which paired with the regional climate, create favourable conditions for the establishment of a mixed boreal-temperate trees (see Fig.1) (Hickler et al., 2012).



Spatial Reference
PCS: LKS 1994 Lithuania TM
GCS: GCS LKS 1994

Contact: Patricija Marijauskaitė
Date: 27th May, 2022

GUGiK, Esri, HERE, Garmin, FAO, NOAA, USGS, Esri, HERE, Garmin, FAO, NOAA, USGS, Esri, USGS

Figure 1. Forest coverage of Lithuania in 2000-2005 retrieved from geoportalai.lt (n.d.).

3.4.2 Timber industry

In Lithuania, 71.4% of forests are designated for commercial purposes, whilst only 1.1% belongs to nature reserves under strict protective provision (Ministry of Environment & State Forest Service, 2020). With that regard, forestry practices control the rotational period, densities and species-mixtures within plantations. Thus, the composition of Lithuanian forests represents some of the most economically valuable tree species within the European wood production (Hynynen et al., 2009; Ruiz-Peinado et al., 2021). Thereafter, the three most-dominant species include, Scot‘s Pine (*Pinus Sylvestris*), Norway Spruce (*Picea Abies*) and Silver birch (*Betula Pendula*).

3.4.3 Land use history

Generally, the Lithuanian forest cover has been undergoing continuous growth. Since the 1940s the forest cover expanded from around 20% to 33.7% of the total national territory. Following the end of World War II, afforestation was highly promoted, initially prioritising spruce plantations, and shifting to pines in the 1970s (State Forest Service & Ministry of Environment, 2021). These newly emerging forests were based on an even class-age structure (Mozgeris et al., 2021). Following a governmental shift after the Restoration of Independence in 1991, afforestation continued, replacing needleleaf trees by encouraging broadleaf species plantations, such as birch (Bukantis et al., 2015; Kuliešis et al., 2017). Once Lithuania joined the EU in 2004, these plans gained great financial support. By 2020, the national forest territory mainly consisted of spruces (21.1%), pines (34.5%) and birches (21,9%). Hence, 56% of the forest cover today is composed of conifers, whilst the remaining 44% are deciduous trees (see Fig. 2) (Ministry of Environment & State Forest Service, 2020). A similar trend can be observed over northern and central Europe, with a high number of conifer plantations still present today (Reyer et al., 2014).

As mentioned, forests absorb 1/3rd of Lithuania’s GHGs, demonstrating a large carbon sink potential (Ministry of Environment, n.d.). However, whilst the plans are to reach a 35% forest coverage by 2030 (State Forest Service & Ministry of Environment, 2018), a recent increase in deforestation has corresponded to lowered emission absorptions throughout the 2010s (State Forest Service & Ministry of Environment, 2021). Furthermore, the once young spruce and pine plantations are becoming of old age, resulting in lower productivity in Lithuania, as well as, throughout the whole of Europe (Mozgeris et al., 2021; Pilli et al., 2022).

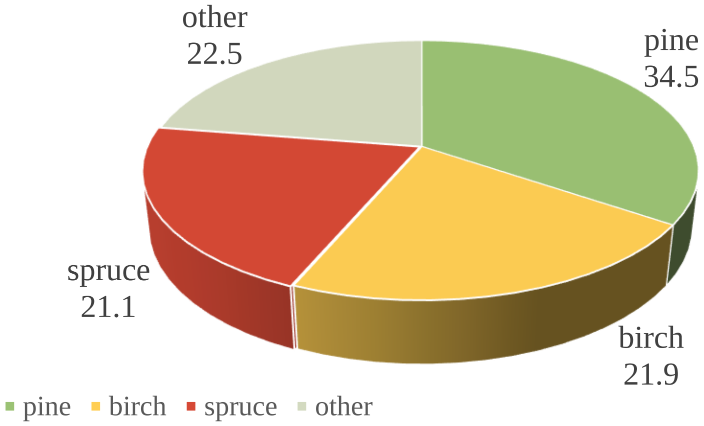


Figure 2. Forest stands by dominant tree species (%), retrieved from 2020 (Ministry of Environment & State Forest Service, 2020).

3.4.4 The species

The three species addressed in this report represent some of the most abundant tree species in Lithuania and throughout the continent, differing in their genetic makeup, photosynthetic preferences, adaptations to stress and growth cycles.

3.4.4.1 Norway spruce – Picea abies

Norway spruce is an evergreen needleleaf species found in boreal climate zones (Lindeskog et al., 2021; Wyka et al., 2012). The species is long-lived containing a shallow root structure and exhibiting shade-tolerance (Žemaitis et al., 2012). Norway spruce is more adapted to cold environments as it required below zero winter temperatures for proper establishment and development (Bukantis et al., 2015; Lindeskog et al., 2021).

Generally, Norway spruce is projected to be one of the most sensitive species to climate change (Mozgeris et al., 2019; Reyer et al., 2014). Both temperature and precipitation changes will impact the growth of the species. Warmer annual and seasonal conditions, particularly during winter, unfavour Norway Spruce; Whilst, its near-surface root network reduces access to deeper water sources, making the species also sensitive to water availability (Aldea et al., 2021; Läänelaid & Eckstein, 2012; Marozas et al., 2019). In other words, Norway spruce is expected to respond to either augmented temperatures or lower soil water availability (Žemaitis et al., 2012), while an increase in atmopsheric CO_2 could favour productivity (Wamelink et al., 2009).

Increased growth rates for the species are expected in northern latitudes, the opposite is seen in southern countries, making central Europe a transition zone with most unpredictable variations (Reyer et al., 2014). A couple of studies published by Lithuanian researchers have made opposing observations. A model study by Ozolinčius et al. (2014) concluded that even a 1 °C rise in average temperature will bring less suitable climatic conditions for Norway spruce in Lithuania. On the other hand, in-situ studies observing the growth of the species between 1976 and 2010, have found a positive relationship with the ongoing climate change, alluding enhanced growth with moderate climatic changes (Vitas, 2011). Perhaps Norway spruce will reveal a pronounced growth rate with slight temperature increases, where precipitation is not limited.

3.4.4.2 Scot's pine – Pinus sylvestris

Likewise, to Norway spruce, Scot's pine, is a long-lived, evergreen conifer. Scot's pine is a fast-growing tree during the juvenile stages of its development (Aldea et al., 2021; Ruiz-Peinado et al., 2021). The pine has a deep root system and is intermediately-shade tolerant. With that regard, Scot's pine is less sensitive to droughts, however more light-demanding than Norway Spruce. Whilst the species exhibits a high tolerance to seasonal variations (Marozas et al., 2019), its competitiveness decreases during winter months (Aldea et al., 2021), indicating that Scot's pine is more limited by the absence of light (Pukienė et al., 2020).

Overall, in Lithuania pines will likely be more benefited to climatic changes, associated with warmer seasons and increased total precipitation, lengthening its growth season (Paern, 2012; Pukienė et al., 2020; Rimkus et al., 2019). On top of that, similarly to spruce, elevated atmospheric CO_2 concentrations could increase the productivity of pines (Wamelink et al., 2009). On the other side of the spectrum, whilst Scot's pine is more resilient to rising temperatures, it will likely show a decline if extremes are reached (Galiano et al., 2010; Ozolinčius et al., 2014). Consequently, higher NPP rates are expected at least in the near future.

3.4.4.3 Silver birch – Betula pendula

Silver birch is the only deciduous species analysed in this study. This is a temperate summer-green tree exhibiting autumn senescence. Silver birch is shade-intolerant and is known to be an early successional pioneer species (Hynynen et al., 2009). Hence, Silver birch similarly to pines, is fast-growing during the early phases of development and is characterised by deep, intensive root systems (Hynynen et al., 2009).

As birch is a broadleaf it also exhibits greater genetic differences compared to conifers (Vitas, 2011). Due to a different leaf evolution and shorter life-span, deciduous trees contain a higher leaf nitrogen content, allowing them to exhibit higher maximum photosynthetic rates in comparison to needleleaf trees (Wyka et al., 2012). Regarding elevated CO_2 levels, the photosynthetic rate of Silver birch is expected to increase under such conditions (Riikonen et al., 2005). Adding on, out of the three species, birch displays best establishment in warmer environments (Lindeskog et al., 2021) and is least sensitive to humidity and temperature variations (Marozas et al., 2019). Hence, if adequate light, moisture and CO_2 is available, birch could demonstrate higher NPP rates with the ongoing climate change.

3.4.5 Species interactions

Temperate-boreal forests have displayed complementary effects under silviculture practices (Hynynen et al., 2009; Ruiz-Peinado et al., 2021). For example, the vertical stratification amongst differently sized species can create favourable conditions for shade intolerant species, such a birch or pine (Hynynen et al., 2009). Spruce on the other hand, is shade-tolerant and does not exhibit early development, hence it can be supressed by other pioneers, emerging during later stages of successional development. Whilst the differences in genetic traits of Norway Spruce, Scot's pine and Silver birch show certain positive mixing effects many questions remain at hand, regarding which species interactions function best, maintaining ecosystem services and most durable carbon sequestration (Aldea et al., 2021; Ruiz-Peinado et al., 2021).

3.5 Ecosystem modelling

Having introduced all of the above, ecosystem modelling provides the tools to build-on scientific knowledge and improve decision making regarding environmental policy and planning. In the light of climate change, modelling of forest carbon sinks into the future is of great relevance (Reyer et al., 2014). By utilising computational models one can modify spatial-temporal scales to assess changes in forest dynamics and the associated carbon pools (Reyer et al., 2015). That being said this paper attempts to better understand the response of Norway spruce, Scot's pine and Silver birch to climatic changes taking place in Lithuania.

4 Methods

The study was carried out using a vegetation model LPJ-GUESS. Most of the necessary settings were set in the default code, however to achieve the aims of the paper, certain parameters had to be adjusted. The output results were further analysed via Excel 2016.

4.1 A general description of the LPJ-GUESS model

LPJ-GUESS is a dynamic global vegetation model used to simulate the composition and development of forest ecosystems (Lindeskog et al., 2021). To answer the questions at hand, a European version of LPJ-GUESS was used as a tool to simulate potential NPP and NBP of various forest stands in Lithuania. The default of the model aims to represent a forest as it would establish itself without any human interference, where competition between species determines forest composition. Hence, throughout this paper a forest stand referred to as "Natural" will be such where species naturally compete for water, light, nutrients and space. LPJ-GUESS also allows simulating the development of a "New" planted forest, which are sown on clearcut or old pastoral/agricultural land. Thus, specific species parameters can be defined as desired and the successional stages of a forest can thus be distinguished. Thereafter, productivity rates of each tree species can be observed as they compete for valuable resources. A more thorough description of the model is provided by Lindeskog et al. (2021) and the model code can be made available upon request at Lund University.

4.2 Application of the model

LPJ-GUESS is composed of 0.5° x 0.5° grid cells. To run LPJ-GUESS, one site-specific coordinate served as the point of interest. For this purpose, 24.75°E and 54.25°N in south-eastern Lithuania was selected (revisit Fig. 2). This is a stand composed of a desired number of 0.1ha sized replicate patches which are designed to capture heterogeneity along the landscape, accounting for the effects of natural hazards, such as wind damage, droughts, insect outbreaks and wildfires. For this study, the number of patches was limited to 1 and natural disturbances, were not incorporated into the final code, as it was decided to investigate forest growth without their interference; following a similar set-up to Lindeskog et al. (2021).

To project forest growth into the future, 9 different climate change scenarios were delineated (see Table 1). These correspond to a plausible rise in global atmospheric CO_2 concentrations paired with average temperature and precipitation variations in Lithuania. Each scenario is applied to 8 different species combinations, explained further below. All simulations are run from 1900 until 2100, as the available precipitation and temperature data spans from 1900. Additionally, a supplementary investigation was conducted executing runs over 1900-2400.

4.3 Default data and adjusted parameters

The grid cells are fed meteorological, soil and vegetation data. The former is composed of global temperature, precipitation, atmospheric carbon dioxide, radiation, nitrogen deposition and soil map information. The latter consists of mechanistic representations of plant functional types (PFTs) for the most common European vegetated species.

All original meteorological inputs are found at a global scale. Monthly temperature, precipitation and radiation dating from 1901-2105 are retrieved from the station based CRU-NCEP data set (Wei et al., 2014). LPJ-GUESS further captures seasonality by interpolating monthly climate data into daily values. Atmospheric CO_2 contains historic annual carbon dioxide concentrations from 1900-2018, provided by the global carbon project (Le Quéré et al., 2018); meanwhile the CO_2 data following RCP2.6 and RCP8.5 were projected as annual values until 2100 (Riahi et al., 2007). Further, the soil map data is obtained from Batjes (2005) and the nitrogen deposition dates from 1850-2009 (Lamarque et al., 2011).

4.3.1 Climate change simulations

The adjusted future parameters include temperature, precipitation and carbon dioxide inputs. For this step, two RCPs from the Intergovernmental Panel's on Climate Change (IPCC) 5th Assessment Report (AR5) were chosen (Intergovernmental Panel on Climate Change, 2015). These pathways follow the trajectories of rising emissions depending on global efforts to manage GHG levels. RCP2.6 represents a more optimistic scenario comprising ambitious GHG reductions. On the contrary, RCP8.5 is a more pessimistic concentration pathway, involving low-effort GHG mitigation strategies. The two were selected to investigate species productivity under opposing yet possible future climate extremes.

A paper by Keršytė et al. (2015) was used as a base to determine the climate scenarios for Lithuania until 2100. This paper gathers temperature and precipitation trajectories from 24 model outputs which were utilised to formulate 8 future scenarios following climate change (depicted in Table 1). Each RCP is defined by the average of four climate projections corresponding to the lower- and upper-bound temperature and precipitation extremes per RCP. Further, in order to capture future interannual anomalies, the respective changes in temperature and precipitation were ramped according to a 30-year running average, instead of applying a uniform change. This allows to create more realistic climate simulations, where the last 30 years of annual historical undulations, are applied repeatedly starting from 2016, allowing to capture seasonal variations. That being said, Table 1 reveals a total of 9 scenarios (from a to i), which were grouped into 3 end-of-the-century climate projections: the baseline representing current conditions, an optimistic climate under RCP2.6 and a pessimistic climate under RCP8.5.

Table 1. Projected climate scenarios by 2081-2100, applied from Keršytė et al. (2015). LT refers to Lower-bound Temperature, UT refers to Upper-bound Temperature.

Scenario		RCP	Average CO_2	Temperature (°C)	Precipitation (%)
a		baseline			
b	L	2.6	426 ppm	+0.44	-1.34
c	T				+13.68
d	U			+2.68	-1.34
e	T				+13.68
f	L	8.5	850ppm	+3.72	+3.1
g	T				+18.84
h	U			+6.42	+3.1
i	T				+18.84

4.3.2 Species Combinations

This section describes which 8 species combinations were selected for investigation. As explained earlier on, in order to run LPJ-GUESS one has to select the species either by choosing Natural stands or New plantations. Altogether, the European version of LPJ-GUESS contains 21 PFTs representing tree species, 6 of which were not found in Lithuania. Hence, the Natural stand was composed of the remaining 15 species (left hand side of Table 2). This plot was the only stand containing reference data (1900-2015), which was later used as a historical comparison. Further on, to observe the development behaviour of spruce, pine and birch, New plantations were defined from 2016 onwards in the set-up code. The following include three monoculture and four mixed stands representing silviculture (Table 3). These procedures allowed to investigate which species would naturally grow at this ecoclimate, as well as, how the most common plantations, if sown in Lithuania today, would develop over the 21st century.

Table 2. The included and excluded LPJ-GUESS simulated species (PFTs), along with the chosen species compositions. Species name in bold have been chosen for the study.

All PFTs		Excluded PFTs	
Common name	**Scientific name**	**Common name**	**Scientific name**
European silver fir	*Abie alba*	Cade juniper	*Juniperus oxycedrus*
Boreal evergreen shrub		Mediterranean raingreen low shrub	
Silver birch	***Betula pendula***	Aleppo pine	*Pinus halepensis*
Downy birch	*Betule pubescens*	Kermes oak	*Quercus coccifera*
European Hornbeam	*Carpinus betulus*	Holm oak	*Quercus ilec*
Common hazel	*Corylus avellana*	Downy oak	*Quercus pubescens*
European beech	*Fagus Sylvatica*		
European ash	*Fraxinus excelsior*		
European larch	*Larix decidua*		
Norway spruce	***Picea abies***		
Scot's pine	***Pinus sylvestris***		
European aspen	*Populus tremula*		
English oak	*Quercus robur*		
Small-leaf lime	*Tilia Cordata*		
Scot's elm	*Ulmus glabra*		

Table 3. The 8 New species combinations.

Newly simulated species compositions	
Monoculture	**Silviculture**
Norway spruce	Spruce-pine
Scot's pine	Spruce-birch
Silver birch	Pine-birch
	Spruce-pine-birch

4.4 Analysis of results

The investigated results mainly focus on annual NPP and NBP values for all 8 species stands. These were analysed as averages over three specific periods: the Whole period (2016-2100), the Initial period (2016-2045) and the Late period (2071-2100). RCP2.6 and RCP8.5 served as the point of reference regarding climate change projections, allowing to assess changes compared to the baseline. This baseline was carried out for all species combinations, following the current climatic trend until 2100. Additionally, an experimental investigation was made for 1900-2400 to simulate more in-depth succession patterns.

5 Results

The modelled results provide an insight into natural species growth, as well as, species functioning under climate change throughout the 21st century. By fulfilling the aim, average Net Primary Production (NPP) and Net Biome Production (NBP) for Norway Spruce, Scot's pine and Silver birch, as well as, as a so-called Natural vegetation cover are computed. The main findings are presented within the following subsections: Natural effects, Climate change results and Long term effects.

5.1 Natural effects

To begin with, the analysed species will be addressed with respect to their natural development in pure stands and coexistence in mixtures.

5.1.1 Ageing

This section introduces the effects of ageing, as juveniles mature and surpass peak productivity. Over the first few years, Silver birch demonstrates a rapid spike in productivity, with a considerable decline commencing roughly 35 years after sprouting. Scot's pine follows a similar development, however with a steady decline after reaching maturity. The growth of Norway spruce is relatively delayed, starting at lower productivity rates, however once it stabilises spruce maintains constant average NPPs, demonstrating a steady rise until 2100. The abovementioned behaviour of all three species is portrayed in Figure 3. It is worth to observe the trends at the beginning versus the end of the simulation period.

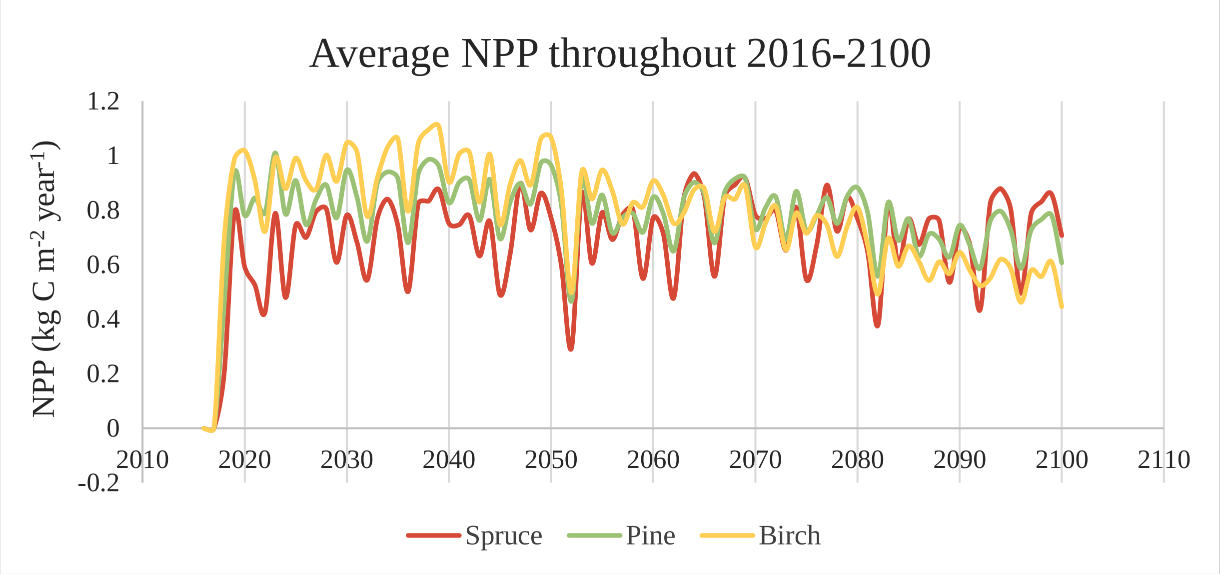


Figure 3. Graph representing the overall lifecycles of spruce, pine and birch using an average NPP of all 9 climate projections throughout 2016-2100.

Further, the absolute changes in NPP between the Initial and Late periods (2071-2100) were quantified (Table 4). Practically half of the stands revealed a decline in NPP towards the last 30 years of forest development, with the exception of Natural, spruce and spruce-pine forest stands. The most interesting observations demonstrate that Natural stands experienced a +9.7% rise in NPP with RCP8.5, whilst spruce revealed increased productivity under all scenarios, potentially augmenting from +7.2% to 18.6%. On the other hand, a slight reduction was noted at pine plots, meanwhile a pronounced decline was discovered within all birch-containing stands, ranging from a -17.8% to a -32.7% reduction. These results particularly denote the growth pattern of pioneers, such as pine and the short-lived birch compared to long-lived spruce trees.

Table 4. Absolute change (%) between the Initial (2016-2045) and the Late period (2071-2100). Arrows indicate an absolute increase (↑).

	baseline	**RCP2.6**	**RCP8.5**
natural	-3.4	-6.7	↑9.7
monoculture			
spruce	↑12.7	↑7.2	↑18.6
pine	-2.6	-9.1	-4.2
birch	-27.3	-32.7	-22.7
silviculture			
spruce-pine	↑2.6	-1.4	↑7.5
spruce-birch	-24.5	-30.3	-19.9
pine-birch	-23.5	-28.7	-18.5
spruce-pine-birch	-23.7	-28.9	-17.8

5.1.2 Succession

Further on monoculture, silviculture and the Natural simulations are addressed.

5.1.2.1 Monoculture

In 2016, monoculture stands of spruce, pine and birch were sowed via LPJ-GUESS. The modelled results reveal quite variable productivities over the century, ranging from 0.62 to 0.89 kg C m^{-2} year^{-1} (see Table 5 below). During 2016-2045, birch demonstrates the highest productivity rates, whilst spruce reveals the lowest. On the other hand, throughout 2071-2100, the inverse is noted, birch being the worst primary producer whilst both needleleaf species exhibit higher rates. These productivities relate to observations made under *3.3.4 Ageing*. Moreover, birch hols the highest NPP of all.

Table 5. A quantitative summary of average NPPs (in kg C m^{-2} year^{-1}) under the baseline, RCP2.6 and RCP8.5, following the Initial (2016-2045) and Late periods (2071-2100). For full values see Appendix A. Arrows indicate the absolute (↑) increase or decrease (↓) respective to TF1.

	2016-2045			2071-2100		
	baseline	**RCP2.6**	**RCP8.5**	**baseline**	**RCP2.6**	**RCP8.5**
natural	0.57	0.59	0.59	↓0.55	↓ 0.55	↑0.65
monoculture						
spruce	0.62	0.63	0.64	↑0.70	↑0.68	↑0.76
pine	0.76	0.78	0.80	↓0.74	↓0.71	↓0.76
birch	0.84	0.87	0.89	↓0.61	↓0.58	↓0.69
silviculture						
spruce-pine	0.70	0.72	0.73	↑0.72	↓0.71	↑0.78
spruce-birch	0.81	0.84	0.86	↓0.61	↓0.59	↓0.69
pine-birch	0.81	0.84	0.86	↓0.62	↓0.60	↓0.70
spruce-pine-birch	0.79	0.82	0.84	↓0.60	↓0.58	↓0.69

5.1.2.2 Silviculture

Species in mixed forests either coexist together in synergies or compete for resources. Overall, the model results reveal that species combinations with the presence of birch yield slightly higher NPPs through the Initial period, whilst the spruce-pine stand is relatively the most productive during the Late period (Table 5). The only tri-culture plot, spruce-pine-birch, follows a similar development to the birch-containing stands. Altogether, mixed-stands seem to yield similar NPPs as mono-forests. Moreover, different short-term and long-term carbon fluxes can be expected.

That being said, with slight deviations in NPP, the silviculture plots fall within a similar range of 0.58 - 0.86 kg C m^{-2} $year^{-1}$, due to the dominance of pine and birch. Overall, within all mixed-birch stands, both needleleaf species are initially suppressed. This observation is made clear within Figure 4 further below, as the spread and behaviour of all birch-related stands is practically the same. On the other hand, the coniferous spruce-pine stand exhibits growth of both species, with an earlier emergence of pine and a lower presence of spruce. This plantation also reveals the largest vegetated carbon pool by 2100. Further, it is worth noting that, Norway spruce and Scot's pine, do not reach the same productivity maxima as in their respective monoculture stands, alternatively Silver birch is as productive, even surpassing its pure stand NPP within the pine-birch plantation.

5.1.2.3 Natural forests

The Natural forest stands are the only simulations which were present prior to 2016. That being said, their growth and development was observed the longest and can be compared to the historical values from 1900-2015. As described under *3.3.4 Species Combinations,* Natural stands serve as an interesting reference point to all New plantations, as they aim to represent the actual species composition, adaptation to climate change, as well as, ageing effects under succession.

The modelled results demonstrate that instead of Norway spruce, Scot's pine and Silver birch, a different species composition dominates Lithuanian woods, mainly represented by deciduous species. These include English Oak, European ash, Scot's elm, European beech, as well as, Norway Spruce. The English Oak represents the highest carbon sequestration pool making up 46.1% of the total average NPP throughout the historic reference period of 1900-2015 (0.25 kg C m^{-2} $year^{-1}$). In the meantime, spruce covers 10.8% of the total average NPP (0.057 kg C m^{-2} $year^{-1}$), pine and birch, on the other hand, only share 0.67% and 0.29% respectively.

5.2 Climate change results

The upcoming paragraphs summarise the gathered findings from changes in NPP and NBP with respect to climate change.

5.2.1 Change compared to the baseline

Future projections relative to the baseline, reveal that carbon absorption under RCP8.5 will increase for all stands throughout the 21st century (Table 6). On the other hand, the relative change following RCP2.6, in most cases results in a productivity decline, particularly towards the end of the century. In other words, the underlying average NPP behind RCP2.6 displays a variability which could result in hindered productivities. Hence, the overall change in NPP by 2071-2100 could fall between -4.2% to +18.4%, the former displayed by birch, whilst the latter by the Natural stands.

On that note, regarding 2071-2100, the deciduous birch is more benefited by the extreme RCP8.5 scenario compared to needleleaf trees. This is seen at all birch-containing stands. However, the Natural stand, yields the highest increase compared to the baseline reaching +18.4% with RCP8.5 (Table 6). Whilst, over 1900-2015, Natural stands hold a NPP of 0.51 kg C m^{-2} $year^{-1}$, an increase up to 0.55 – 0.65 kg C m^{-2} $year^{-1}$ by 2100 could be expected (Table 5). This rise is generally observed with increasing productivity for European beech, English oak and somewhat Scot's elm, whilst European ash shows a successional drop, with a steady rise commencing afterwards. That being said, whilst the Natural stands yield lowest NPPs relative to other stands (Table 5), this forest is the least sensitive to climate change, as it is the least unfavoured by RCP2.6 and most benefited by RCP8.5

Table 6. Relative NPP change (%) to baseline with respect to the Whole (2016-2100) and Late periods (2071-2100). Arrow (↑) indicates a relative increase. For NPP per projection see Appendix A.

	2016-2100		2071-2100	
	RCP2.6	**RCP8.5**	**RCP2.6**	**RCP8.5**
natural	↑3.0	↑11.9	-0.4	↑18.4
monoculture				
spruce	↑0.5	↑7.5	-2.6	↑ 8.9
pine	↑0.2	↑5.1	-4.1	↑ 2.8
birch	-0.3	↑6.5	-4.2	↑13.1
silviculture				
spruce-pine	↑1.2	↑7.8	-1.5	↑ 9.0
spruce-birch	-0.3	↑6.6	-4.1	↑13.1
pine-birch	-0.1	↑6.7	-3.5	↑13.4
spruce-pine-birch	-0.2	↑7.0	-3.4	↑14.7

5.2.2 NPP variations within RCPs

To explain the distinct separation between NPP generated by RCP2.6 and RCP8.5, both scenarios have been addressed by referring to their respective projection extremes (revisit Table 1). Generally, it was discovered that the lower-bound temperature scenarios within RCP8.5 (f and g) corresponding to a temperature increase of +3.72 °C create the most favourable conditions for species development. Contrarily, the upper-bound temperature projections within RCP2.6 (d and e) representing a temperature rise of +2.68 °C are the most disadvantageous. In addition, comparing the baseline scenario with the lower-bound RCP2.6 (scenarios b and c, +0.44°C), as well as, the upper-bound RCP8.5 (h and i, +6.42 C) reveal relatively similar productivities. For visualisations see Figure 4 underneath; To view quantitative NPPs per projection see Appendix A.

Further, it was discovered that the worsened performance of RCP2.6 as an average, corresponds to a carbon dioxide restrain. The division between lower atmospheric CO_2 levels (426ppm in RCP2.6) and higher atmospheric CO_2 concentrations (850ppm in RCP8.5) creates unfavourable conditions for ecosystem functioning within climate scenarios d and e (revisit Table 1). Otherwise, temperature has a greater influence on biological reactions than precipitation. The latter only exhibits a more pronounced effect on NPP of Norway spruce and the Natural stand.

Figure 4 portrays all of the above-mentioned observations regarding NPP changes by species composition and different climate change projections. The boxes portray the spatial spread between the upper-bound (UT) and lower-bound (LT) temperature values for each RCP (revisit

Table 1), whilst the maximum and minimum values are represented by the vertical whiskers. The longer the whisker the greater the influence of precipitation. It should be noted that the yellow lines indicate the baseline value, which is often found within or above the spread of RCP2.6, pointing to the observation made under *5.2.1 Change compared to the Baseline.*

To give an example, the pure spruce stand reveals that [1] most of its future NPPs appear higher than the baseline, [2] RCP8.5 results in a greater NPP variability than RCP2.6, [3] as demonstrated by the extent of the whisker precipitation has a greater effect of NPPs compared to other species. In addition, a clear rise in variability is seen in Figure 4B, pointing to the effects of persistent temperature, precipitation and CO_2 changes modelled until 2100.

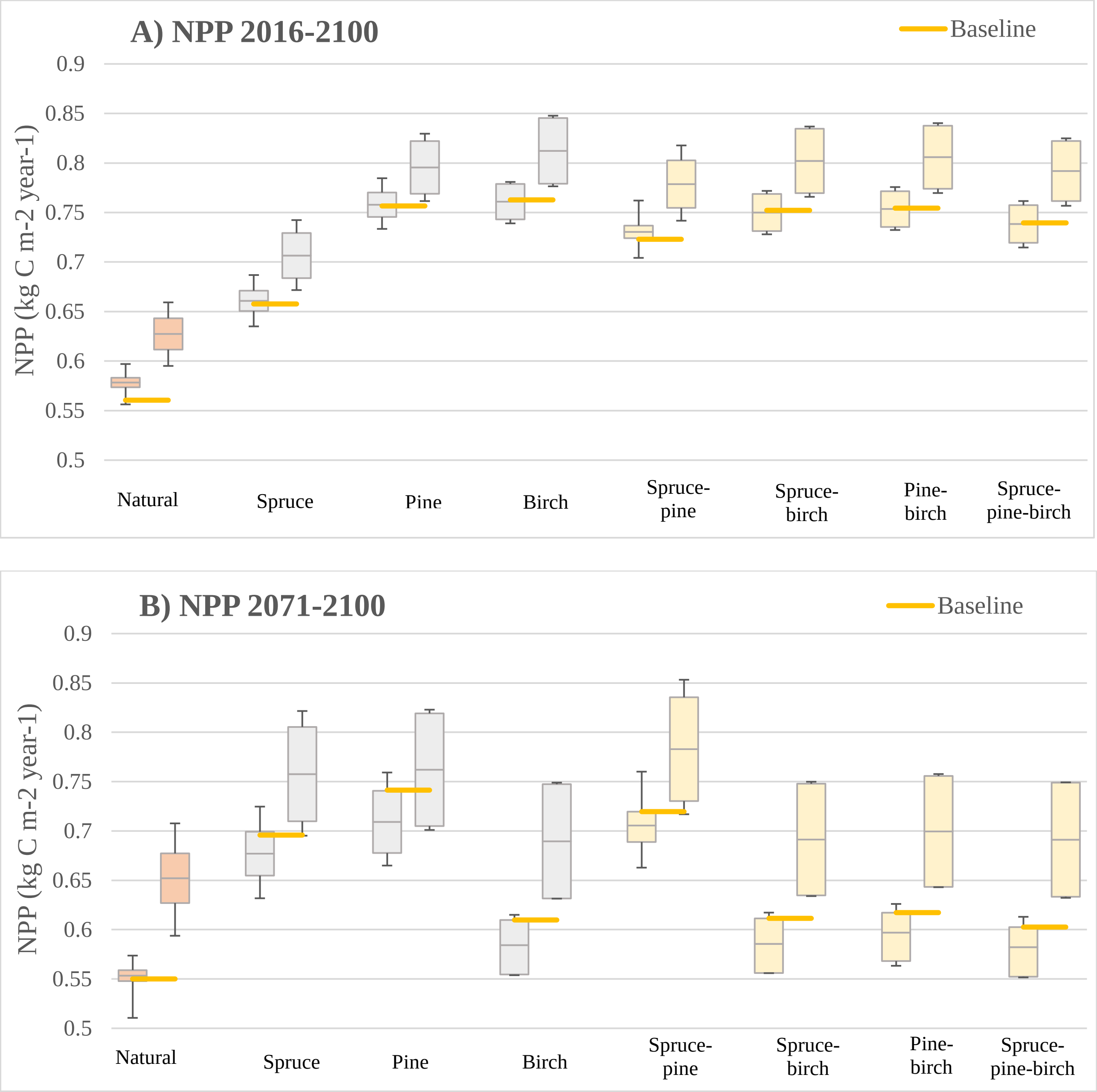


Figure 4. Box and whisker plot portraying the variability in NPP, including both RCP2.6 (left box) and RCP8.5 (right box). Graph A represents the Whole period, whilst graph B represents the Last. Natural stands are coloured orange, monoculture stands are grey, silviculture are yellow.

5.2.3 NBP

Net Biome Productivity describes if the whole ecosystem is a carbon sink or carbon source. Whilst forest NPP may foresee an increase depending on which climate change projection comes true, these modelled results reveal that forest ecosystems will likely become greater carbon sources by 2100, mostly due to a higher soil carbon release.

Throughout 2016-2100, all stands with the exception Natural forests, appear to be carbon emitters (Table 7). By 2071-2100, there is a slight shift in the net carbon exchange. The Natural stand only remains an absorber according to the baseline, whilst eight additional forest stands became net sinks: all pine, spruce-pine and spruce stands, with the exception of spruce under RCP8.5. That being said, initially all New stands are carbon emitters, since in 2016 space was cleared for New plantations. Consequently, a substantially high soil-atmosphere carbon flux from decaying litter that is oxidised after a forest is felled. Contrarily, Natural stand is the only stand which does not exhibit this net carbon loss, as it is simulated from 1900 and is not clearcut.

In addition, whilst modelled NPPs are projected to increase with moderate climate change, the overall carbon sink was also associated with a diminishing soil and litter carbon pool. With almost each climate projection the soil returned a greater carbon flux into the atmosphere. This relationship becomes more apparent with RCP8.5, especially towards the end of the century (Table 8), which was also noted by a gradual decrease in the carbon invested into leaves and roots. Lastly, supporting the above-mentioned observations, the soil carbon flux is the lowest under Natural forests relative to New stands. To conclude, a growing NPP represents an expanding vegetation carbon pool, however there is a shift in equilibrium within the system, due to a magnified net carbon release from the soil and litter by the end of the 21st century.

Table 7. NBP flux (in kg C m^{-2} $year^{-1}$) for the Whole and Final periods. For values see Appendix B.

	2016-2100			**2071-2100**		
	baseline	**RCP2.6**	**RCP8.5**	**baseline**	**RCP2.6**	**RCP8.5**
natural	sink	sink	sink	sink	source	source
monoculture						
spruce	source	source	source	sink	sink	source
pine	source	source	source	sink	sink	sink
birch	source	source	source	source	source	source
silviculture						
spruce-pine	source	source	source	sink	sink	sink
spruce-birch	source	source	source	source	source	source
pine-birch	source	source	source	source	source	source
spruce-pine-birch	source	source	source	source	source	source

Table 8. The soil carbon flux (in kg C m^{-2} $year^{-1}$) throughout the Whole simulation period.

		2016-2100	
	baseline	**RCP2.6**	**RCP8.5**
natural	0.47	0.50	0.55
monoculture			
spruce	0.57	0.60	0.65
pine	0.60	0.63	0.69
birch	0.62	0.65	0.70
silviculture			
spruce-pine	0.57	0.60	0.66
spruce-birch	0.61	0.64	0.69
pine-birch	0.61	0.64	0.69
spruce-pine-birch	0.60	0.63	0.68

5.3 Long term effects

After having analysed the results, it was decided that an 85-year simulation period leading up to 2100, was not fully representative of all species' development, since birches are short-lived, whilst spruces and pines are long-lived species. Consequently, the combined NPP does not portray all species equally. For this reason, an additional investigation was made, prolonging the simulation period until 2400, by gradually applying the same climate change projections as described under *4.3.1 Climate change simulations.*

The results reveal that in most mixed-culture scenarios a re-emergence of another species should be observed around 2150, approximately 140 years into succession. Regarding di-stands, the spruce-pine interactions are most balanced, where both species eventually result in similar average NPPs. Paired with birch, the conifers begin their development phases after birch subsides, although at more constant and lower rates than the broadleaf. The tri-culture stand of spruce-pine-birch yields greater variations between scenarios, resulting in more inconsistent successional development patterns with the ongoing climate change. The NPPs, as a whole, is similar to the ones of silviculture stands.

Regarding pure stands, eventually Norway spruce and Scot's pine reveal a reduction in NPP. Silver birch displays multiple short-lived cycles of regeneration. Altogether, all monoculture stands yield similar NPPs to 1900-2100 simulations. Lastly, the Natural plot maintains a constant mean NPPs, stabilising after the increase of 2016-2100.

6 Discussion

Three aspects regarding species productivities have been assessed in this model study: the effects of ageing, mixed management practices and climate change. Three species, along with a so-called Natural stand, were selected with the intention of representing the dynamics of Lithuanian woodlands. Overall, the aim of this paper was to investigate the-end-of-the-century terrestrial carbon sink of forests using a dynamic global vegetation model LPJ-GUESS at a chosen location in Lithuania. Thus, three major research topics were addressed and will be further discussed throughout the following paragraphs: [i] General response to climate change; [ii] Species response to climate change; [iii] Response to forestry management strategies.

6.1 LPJ-GUESS study comparisons

Observational NPP data for Lithuania was not available, therefore the gathered results shall be compared to other existing literature regarding the topic. This is reasonable, as LPJ-GUESS is well-constrained to simulate boreal-temperate forest transitions (Smith et al., 2014). In addition, the model was recently successfully evaluated on the account of forest management for Europe by Lindeskog et al. (2021).

That being said, the modelled NPPs are consistent with NPPs published within older reports involving LPJ-GUESS at the beginning of the 21st century, coming to ~0.6 – 0.8 kg C m^{-2} $year^{-1}$ (Smith et al., 2014). This range varies depending on the exact forest type; however, the overall temperate-boreal and mixed ecosystem NPPs are found within this spectrum.

Furthermore, future NPPs were compared to a study conducted by Pilli et al. (2022) which ran a hybrid of four land-climate models using LPJ-GUESS-simulated PFTs. The paper explores regional NPP changes at a European country-specific level following RCP2.6 and RCP6.0 until 2091-2100. Due to a lack of data availability, RCP8.5 was assumed to be similar to RCP6.0. The LPJ-GUESS modelled results reveal that following RCP2.6 needleleaf trees are slightly overestimated by Pilli et al. (2022), whilst with the more extreme RCP needleleaf species meet the range. On the other hand, birch, representing deciduous species, is found within the range of both RCP projections.

6.2 General response to climate change

Generally, the study was based on the assumption that as long as the change in climate does not reach extremes then Norway Spruce, Scot’s pine and Silver Birch could reveal greater growth rates in the future (Galiano et al., 2010; Marozas et al., 2019; Ozolinčius et al., 2014; Vitas, 2011). The outcome results indeed confirm that both the temperate and boreal trees analysed yield greater NPPs than the baseline, following a moderate increase of temperature, precipitation and carbon dioxide concentrations, under the average RCP8.5. As explained under section *5.2.2 Variations within RCPs,* carbon dioxide and temperature determined productivity rates more than precipitation.

That being said, forest photosynthesis is mainly curbed under two circumstances. During the first, carbon dioxide levels are not sufficient to meet the respective rise in temperature (UT) under RCP2.6, restraining light-use efficiency as described by Reyer et al. (2014). On the other side of the spectrum, the highest rise in temperature within RCP8.5 exceeds the tolerance thresholds or the availability of other limiting factors, resulting in a productivity decline. To conclude, under certain RCP2.6 scenarios, Lithuanian forests could become worse primary producers compared to the baseline. Alternatively, all three species could be favoured by a moderate rise in temperature, with sufficient water and carbon dioxide availability, best represented by the lower-end of RCP8.5.

However, whilst the vegetation carbon pool is projected to increase under such environments, these conditions also favour soil heterotrophic respiration (Morales et al., 2007). The combined effect suggests that a majority of the simulated forests would become carbon sources, rather than sinks by the end of 2100. A recent study by Mozgeris et al. (2021) noted a similar trend. This is not applicable for all Newly planted stands, nonetheless the fundamental Natural stand, which represents forests of varied ages and species mixtures, eventually reveals a net carbon release. This indicates that even if temperate-boreal forests become more productive at carbon sequestration, as the climate in Lithuania becomes warmer, the equilibrium of the land carbon pool begins to shift. Hence, it is of uppermost importance to consider, not just the productivity of forests alone, but also the cumulative effects of the whole ecosystem.

6.3 Species response to climate change

One of the targeted research questions of this paper was to investigate whether climate-change pronounced environments would favour temperate or boreal species. It was anticipated that needleleaf trees could reveal a more pronounced drawback (Bukantis et al., 2015). Nonetheless, with respect to the “New” plantations it seems that all three species exhibit the same response to the abovementioned climate extremes.

The study was also based on the assumption that birch would acclimate the best to climate change as it exerts a greater photosynthetic genetic variability and adaptability to warmer environments (Dubois et al., 2020; Wyka et al., 2012) than boreal trees. The modelled outcome over the century confirms this assumption, as birch-associated simulations yield the highest NPPs out of all plots (0.89 kg C m^{-2} $year^{-1}$). In addition, following research carried out by Malakauskiene (2020), the vegetation period of birch trees in Lithuania has already increased by two days due to the warming of the climate. However, as the results were analysed per simulation, increasing attention was drawn to the effects of ageing, as Silver birch is also the species showing the fastest decline, corresponding to a worsened carbon sink. This is so because the broadleaf is a relatively short-lived, shade-intolerant species portraying vigorous growth over the first 35 years of development (Hynynen et al., 2009). Thereafter, a decline was foreseen as portrayed by the averaged NPPs in Figure 4, making space for spruce or pine.

On that note, since both birch and pine are pioneer species (Aldea et al., 2021; Hynynen et al., 2009; Ruiz-Peinado et al., 2021), in pure stands pine demonstrates a similar development trend: quicker at the start with a steady decline commencing with reached maturity. Regardless, since pines live longer and are relatively good primary producers, the species can sustain high productivity rates over a longer period of time. Hence the pure pine and spruce-pine stands remain as carbon sinks throughout the whole simulation period.

Furthermore, a combination of all three species, as found by other researchers (Hynynen et al., 2009), firstly reveals an emergence of Silver birch, often followed by Scot’s pine and Norway Spruce in that particular order (Kuliešis et al., 2020). This could be explained by light availability, since Silver birch requires full exposure to sunlight, whilst Scot’s pine is an intermediate shade tolerant (Hynynen et al., 2009; Lindeskog et al., 2021).

Moreover, as it was mentioned in section *3.4.4 The species*, it was uncertain to which extent conifers, particularly Norway Spruce, would adapt to climate change at such latitudes (Reyer et al., 2014). Increasing temperature conditions or lowered soil water availability should have impaired the growth of spruce (Ozolinčius et al., 2014; Žemaitis et al., 2012). It’s important to note that these studies do not take carbon dioxide changes into consideration, which turned out to be the most determinant abiotic factor within this study. As far as New plantations are concerned, Norway Spruce is the only species revealing greater deviations with inter-varying precipitation projections, likely due its shallow-root structure (Aldea et al., 2021; Läänelaid & Eckstein, 2012; Marozas et al., 2019). However, whilst it does reveal slightly lower photosynthetic productivities, no particular sensitivity to other variables is manifested (Mozgeris et al., 2019).

Nevertheless, contrary to pine and birch, Norway spruce yields the lowest relative productivity rates during 2016-2045. However as spruce reaches maturity, it maintains gradually increasing average NPPs all throughout the 21st century. For this reason, spruce forests become better carbon absorbers towards the end of the simulation period. That being said, regarding adaptations to climate change, a simulation period of 85 years does not capture a representative development of spruce trees. In this case, the Natural stand could be more informative, where Norway Spruce only portrays a clear rise in carbon uptake under the baseline scenario. To conclude, new stands of Norway Spruce in Lithuania could benefit from moderate climatic changes in the near future, whilst older spruce forests will likely decline (Ozolinčius et al., 2014; Vitas, 2011).

Having touched upon the Natural cover, it reveals greater average NPPs relative to the historical period of 1900-2015. By 2100, the NPP could rise by as much as 0.04 – 0.14 kg C m^{-2} $year^{-1}$. This cover is generally composed of five species exhibiting successional shifts, where the rise in NPP is largely contributed by oaks, making up almost half of the forest's carbon sequestration. Such oak behaviour under climate change, can be confirmed by Reyer et al. (2014). In their study the English oak found in temperate forests revealed enhanced productivity under persistent CO_2 effects. Nevertheless, it's important to note, that whilst the overall NPP increases, the Natural ecosystem still becomes a carbon emitter by the end of 2100.

As a learning curve, having investigated the behaviour of pioneer species and the effects of ageing, the results point to the need to prolong future simulation periods. This would allow assessing successional changes at later phases of an ecosystem's development and to better understand species coexistence. Eventually, chosen timeframes depend on the horizon of interests.

6.4 Response to forestry management

Moving onto the third research topic, management, mixed forestry can bring many complementary, ecosystem-supporting benefits, promoting stabilisation, resilience against extreme events and partitioning of resources, to name a few (Ruiz-Peinado et al., 2021; Steckel et al., 2020). The obtained silviculture results bring about a couple points of interest. Firstly, mixed cultures seem to drive a similar land carbon sink as monocultures. Secondly, the Natural plot demonstrates that species which are most adapted to the natural ecosystems of Lithuania are not necessarily the species which are most often sown in European forestry today. Thirdly, clearing space for a "New" plantation initiates remarkably high emission rates generated by the soil carbon pool. These observations are relevant keeping in mind the need to meet timber demands, as well as, the desire to expand the Lithuanian forest cover by up to 35% by 2030 (Bukantis et al., 2015; Mozgeris & Juknelienė, 2021; State Forest Service & Ministry of Environment, 2018).

With that regard, it is important to study which species complement one another, to improve silviculture practices (Pach et al., 2018; Steckel et al., 2020). Overall, there is a greater availability of research concerning spruce-pine plantations. A paper by Žemaitis et al. (2012)

found that Norway spruce grows well when planted in pure stands, however Aldea et al. (2021) concluded that spruce does not exhibit any particular advantages nor disadvantages between its respective mono- or mixed- plots. Meanwhile the growth of Scot's pine paired with Norway spruce, is favoured as there's less competition than in single stands, supposedly allowing pines to grow faster, longer and increase in basal area (Aldea et al., 2021; Ruiz-Peinado et al., 2021). The modelled results did not display any particular difference in the commencement or length of pine's growth; Likely due to the parameter set up.

Hynynen et al. (2009) found that if birch grows in plantations with other deciduous species, it could become suppressed by neighbouring broadleaf pioneers. This pattern could be illustrated by the Natural simulations, where other broadleaf trees dominate and birch is outcompeted. Thereby, the growth of birch is favoured in mixed stands with Norway spruce or/and Scot's pine. The LPJ-GUESS modelled results even demonstrate that Silver birch reaches its highest maximum NPPs in a pine-birch mixture. Thus, if birch afforestation is desired, a pairing with conifers would be advised (Bukantis et al., 2015).

6.5 Natural disturbances

An aspect which was deactivated within the model code, and which brings many benefits with mixed-forestry practices, is the positive effect of increased resilience against natural hazards. These could include windstorms, snow blizzards, forest fires and droughts along with the commonly associated beetle attacks (Aldea et al., 2021; Ruiz-Peinado et al., 2021; Steckel et al., 2020). Regarding the latter, recurring large-scale bark beetle outbreaks on spruce trees have been recorded in Lithuania, as well as, the whole central Europe (Bárta et al., 2021; Zolubas et al., 2009). Keeping that in mind, spruce plantations in forest mixtures have a high potential of increasing resilience and shelter against such pests. Overall, pure needleleaf stands growing in sandy soils are particularly sensitive to the abovementioned hazards in Lithuania (Žemaitis et al., 2012). That being said, same-age monocultures are more exposed to natural disasters than mixtures. Hence, augmented resilience against natural disasters through silviculture should be addressed in forestry management (Bukantis et al., 2015).

6.6 The perspective forest carbon sink

To come in line with the targets set by the EU, Lithuania is aiming to become climate neutral by 2050 (Ministry of Environment, n.d.). As stated within the Lithuanian National Forestry Policy, emission reductions should come in hand with an even greater expansion of the forest cover area. However, it is deemed that the Lithuanian forest biome will become a greater carbon emitter by 2100 due to progressively increasing timber harvests and tree ageing (Ministry of Environment, n.d.; Mozgeris et al., 2021), as well as, an augmented soil flux (Morales et al., 2007). Therefore, the maintenance of current forests should not be disregarded.

Concerning forest expansion, the country is transitioning towards increasing mixed-age silviculture plantations, intermingling both needleleaf and broadleaf trees (Bukantis et al., 2015). The latter being more advisable (Biber et al., 2020; Bukantis et al., 2015). One of the suggested species by Bukantis et al. (2015) includes the European beech, which also contains the 2nd highest mean annual NPPs within Natural stands, falling between the English Oak and Norway Spruce. Oaks could also be considered in mixed-age silviculture plantations for a couple of reasons [1] the modelled results suggest that the Lithuanian ecoclimate is suitable for oaks, which play a key part as a primary producer; [2] studies such as the one by Steckel et al. (2020) also points to the positive trade-offs between oak plantations together with Scot's pine, as well as, the positive response of oaks to climate change (Wamelink et al., 2009). Further on, regarding needleleaf trees, it is estimated that pine resilience to droughts will likely increase their value in forestry management (Albert et al., 2015). Considering that Scot's pine remains to be the only species still sequestering carbon by 2100, and its positive effect on birch in mixed simulations, pine plantations could be acceptable.

Further, to achieve mixed-age plots, thinning is highly recommended. Whilst the effects of thinning practices is outside the scope of this paper, it must be noted that thinning creates space for species to further expand in basal area, allowing sunlight to reach lower canopies and reducing vulnerability against storms (Kuliešis et al., 2020). On that note, neighbouring countries such as Latvia, are also promoting silviculture under selective thinning (Bukantis et al., 2015). With respect to space availability, clearcutting is not advised, as it generates high emission rates, as well as, disrupts the soil carbon pool which takes a long time to regenerate (Chapin III et al., 2011). Thus, Lithuania plans to utilise abandoned or damaged agrarian lands to comply with new plantations (Bukantis et al., 2015).

All things considered, whilst carbon sequestration is highest at the 50° - 60° latitudes (Wamelink et al., 2009), Lithuanian forests alone only comprise a small part of the forests within the Northern Hemisphere. In order to mitigate climate change global efforts are necessary. The European Union is set to reach climate neutrality by 2050 (European Commission, n.d.), however to achieve this target, the net equivalent forest CO_2 sink will have to increase by 20% (Pilli et al., 2022). This means that all member states will have to significantly increase CO_2 absorption (Mozgeris et al., 2021), whilst minimising their respective GHG emissions (Mozgeris et al., 2019). In Lithuania, like elsewhere in Europe, however, the whole forestry sector is ageing. As a result, the forest sink is likely to decrease, even under the more optimistic RCP2.6 projections (Pilli et al., 2022).

6.7 Future studies

First, further studies should particularly focus on specific multispecies interactions. The species dominating the Natural stand could serve as a point of reference in Lithuania. Second, as LPJ-GUESS can mimic natural disturbances including bark beetle outbreaks, their effects should be investigated, since the response mechanisms between mono- and silviculture stands should be apparent. Third, further research should study successional dynamics, by increasing the simulation length or running multiple tree age classes. As it is pointed out under the section *Additional runs*, in the long-run mixed-forests are nearly as productive as the single-species plantations. In the light of climate change, this is of great relevance.

Further, seasonal variations should be accounted for, as drier summers in Lithuania lead to humidity deficits and all-drought related natural hazards (Bukantis et al., 2015), whilst warmer winters influence tree bud development, sensitivity to weather extremes and affects vegetation seasons (Bukantis et al., 2015; Ciais et al., 2008). In addition, further research should be conducted regarding soil heterotrophic respiration and the decline of the soil carbon pool with climate change. On that note, the effects of augmented CO_2 levels on terrestrial vegetation requires further attention, since CO_2 was one of the main determinants on forest NPP. As a final point, perhaps the Natural cover could be compared to the protected old growth forests comprising 1.1% of the national forest area, which would help evaluate the reliability of LPJ-GUESS in Lithuania.

6.8 Limitations and model uncertainties

With respect to limitations, multiple areas for improvement arise. Firstly, all meteorological and soil variables were applied as grid-cell specific 0.5° x 0.5° averages, which are rather large for a small country such as Lithuania. Secondly, there was no historic observational data for the

"New" stands, only allowing to carry out a comparison of results, rather than an evaluation. Thirdly, the modelled simulations only take into account one coordinate point, whilst 10 more are suitable with regards to the parameterisation of LPG-GUESS. Since LPJ-GUESS has not been applied solely within Lithuania, to obtain a better representation of the forest cover, multiple coordinates should be considered. This would allow to capture the climatic continentality, soil characteristics and the overall Lithuanian landscape spanning from the Baltic Sea, further inland. Lastly, having simulated the Newly stands, it would have been interesting to compare their absolute change in NPP to real forests in Lithuania, since the average forest rotational period within the commercial industry is of a similar extent.

Concerning model uncertainties, it should be mentioned that all New forest simulations followed a similar fluctuating pattern along the 9 climate projections. Whilst the general temperate-boreal response to these variables does come in line with additional literature, the magnitude at which temperature, CO_2 and especially precipitation influence individual species should be considered with caution. That being said, the reliability of estimated long-term changes in these climatic variables should not be disregarded. Furthermore, the results generated from RCP8.5 create a greater spread of productivities, as a consequence of a larger projection uncertainty. Moreover, perhaps one of the greatest model uncertainties is associated with the soil carbon flux due to undefined historical land-use management strategies. Hence, a prospective adjustment of the LPJ-GUESS model will likely include historical data allowing to create a better representation of the soil carbon pools (Lindeskog et al., 2021).

With regard to the multiple experimental runs made for 2400, whilst increasing the temporal scale would help understand forest dynamics, the over-manipulation of the timeframe increases mode uncertainties and the risk of misinterpreting reality. With that, LPJ-GUESS is useful at simulating the short-term developmental phases of forests, allowing to compute peak productivity. On that note, successional vegetation dynamics are difficult to model due to the complexity of biological interactions; Below-ground trade-offs are particularly difficult to study (Chapin III et al., 2011). Keeping in mind the modelled results, the behaviour of New Norway spruce plantations could have been overexaggerated, as many studies point to the recession of the species with climate change. On the other hand, the spruce trees within the Natural stand did reveal a decline, alluding that, young plantations behave differently compared to old forests. In addition, Scot's pine did not exert particular growth benefits from its respective silviculture stands, as explained under *6.4 Response to forestry management*, suggesting that the growth cohort parameters should be revised. Nevertheless, at the end of the day, it has been shown that LPJ-GUESS is good at representing both, the dynamics of succession and temperate-boreal forest development (Lindeskog et al., 2021).

On the less critical side, ecosystem modelling saves time and resources, whilst still improving targeted research gaps, since species growth can be observed computationally. With that, LPJ-GUESS brings multiple benefits. To name a few, the model provides a degree of freedom to select which and how many tree species should be simulated for assessment; Additionally, it allows free adjustment of any of the set-up parameters to explore specific sources of change.

7 Conclusions

In this paper, the growth of Norway spruce, Scot’s pine, Silver birch and a so-called Natural stand has been simulated using a global dynamic vegetation model LPJ-GUESS. Three major topics regarding forest productivity have been investigated; [i] The general response to climate change; [ii] Species response to climate change; [iii] Response to forestry management. Species adaptation was assessed by applying 3 end-of-the-century climate projections: the baseline representing current conditions, an optimistic climate under RCP2.6 and a pessimistic climate under RCP8.5. The main findings have been summarised to conclude that:

i. The net biome exchange becomes more pronounced with increasing climate extremes, and whilst under moderate climatic changes forest productivities are enhanced, the soil carbon emissions rise accordingly; fundamentally by 2100 the majority of forest become sources of carbon, particularly under RCP8.5.

ii. All species followed similar fluctuations in productivity with inter-varying projections, however regarding broadleaf and needleleaf trees, the former was more favoured by climate change simulated environments, represented by both, birch plantations, as well as, temperate species found within the Natural stand; meanwhile needleleaf trees did not exhibit particular sensitivities to the changes in abiotic factors.

iii. Both monoculture and silviculture plantations yielded similar carbon absorption rates due to the dominance of birch, as the chosen time frame does not fully grasp ecological succession of all three species together; with that, since natural disturbances were supressed, full multispecies interactions cannot be accounted for with certainty.

Having outlined all of the above, for the first time LPJ-GUESS has been applied solely to the country of Lithuania. The modelled results return various conclusions regarding forestry management and the rate of carbon fixation by individual species. With respect to future studies, a clearly defined time horizon should be delineated depending on, if one desires to assess species successional development under forestry management, or the species response to climate change. In addition, as the country aims to expand its forest cover in the efforts of reaching climate neutrality, decisive bodies should consider mixed-age and mixed-species plantations, composed of trees which are natural to the country’s flora, such as the English oak or European beech, whilst avoiding clearcut activities. That being said, modelled forest productivities between all climate change scenarios revealed varying results calling for the need to further improve scientific climate projections, to further explore multispecies interactions and to measure the effects of augmented carbon dioxide onto forest ecosystems. As a final point, since the net carbon sink of European forests altogether is weakening, all member states must be prepared to take supplementary initiatives in reducing GHG emissions as part of climate change mitigation.

8 Appendix A

Extended NPP tables containing averages of all 9 future projections for each simulation.

Table A1. Average NPP values (kg C m^{-2} year^{-1}) throughout the Whole simulation period, 2016-2100.

2016-2100									
			monoculture			silviculture			
scenario		natural	spruce	pine	birch	spruce-pine	spruce-birch	pine-birch	spruce-pine-birch
a	baseline	0.5605	0.6576	0.7566	0.7627	0.7231	0.7522	0.7545	0.7396
b	RCP2.6	0.5832	0.6711	0.7702	0.7788	0.7368	0.7687	0.7716	0.7574
c		0.5971	0.6869	0.7846	0.7809	0.7621	0.7718	0.7757	0.7616
d		0.5563	0.6350	0.7335	0.7390	0.7042	0.7280	0.7323	0.7147
e		0.5736	0.6506	0.7455	0.7431	0.7242	0.7313	0.7355	0.7193
f	RCP8.5	0.6432	0.7293	0.8221	0.8454	0.8028	0.8345	0.8377	0.8222
g		0.6593	0.7423	0.8296	0.8477	0.8177	0.8368	0.8402	0.8249
h		0.5951	0.6717	0.7616	0.7764	0.7417	0.7658	0.7697	0.7568
i		0.6116	0.6838	0.7689	0.7791	0.7546	0.7696	0.7740	0.7615

Table A2. Average NPP values (kg C m^{-2} year^{-1}) for the Initial simulation period, 2016-2045.

2016-2045									
			monoculture			silviculture			
scenario		natural	spruce	pine	birch	spruce-pine	spruce-birch	pine-birch	spruce-pine-birch
a	baseline	0.5695	0.6174	0.7614	0.8389	0.7011	0.8095	0.8072	0.7898
b	RCP2.6	0.5888	0.6344	0.7813	0.8626	0.7189	0.8353	0.8292	0.8142
c		0.5960	0.6399	0.7920	0.8734	0.7307	0.8482	0.8415	0.8271
d		0.5787	0.6246	0.7718	0.8645	0.7066	0.8333	0.8278	0.8107
e		0.5845	0.6303	0.7827	0.8750	0.7175	0.8448	0.8426	0.8228
f	RCP8.5	0.5940	0.6424	0.7954	0.8931	0.7288	0.8639	0.8571	0.8398
g		0.5998	0.6484	0.7955	0.9027	0.7390	0.8771	0.8710	0.8503
h		0.5872	0.6299	0.7862	0.8837	0.7192	0.8533	0.8486	0.8313
i		0.5944	0.6362	0.8059	0.8898	0.7310	0.8605	0.8581	0.8403

Table A3. Average NPP values (kg C m^{-2} year^{-1}) for the Late simulation period, 2071-2100.

2071-2100									
			monoculture			silviculture			
scenario		natural	spruce	pine	birch	spruce-pine	spruce-birch	pine-birch	spruce-pine-birch
a	baseline	0.5500	0.6959	0.7414	0.6098	0.7195	0.6114	0.6172	0.6025
b	RCP2.6	0.5590	0.6992	0.7407	0.6150	0.7222	0.6173	0.6260	0.6121
c		0.5737	0.7247	0.7592	0.6140	0.7601	0.6151	0.6258	0.6130
d		0.5106	0.6318	0.6649	0.5546	0.6628	0.5559	0.5682	0.5516
e		0.5477	0.6548	0.6777	0.5538	0.6888	0.5560	0.5634	0.5523
f	RCP8.5	0.6772	0.8054	0.8191	0.7490	0.8355	0.7499	0.7577	0.7492
g		0.7077	0.8215	0.8229	0.7474	0.8532	0.7479	0.7557	0.7490
h		0.5938	0.6952	0.7010	0.6316	0.7169	0.6340	0.6433	0.6322
i		0.6270	0.7098	0.7050	0.6314	0.7303	0.6347	0.6430	0.6333

9 Appendix B

Supplementary table containing average NBP values of the baseline, RCP2.6 and RCP8.5.

Table B1. NBP values (kg C m^{-2} $year^{-1}$) for the Whole and the Final simulation periods. Negative numbers in orange indicate a carbon source, whilst positive numbers in green indicate a carbon sink.

	2016-2100			**2071-2100**		
	baseline	**RCP2.6**	**RCP8.5**	**baseline**	**RCP2.6**	**RCP8.5**
natural	0.0317	0.0112	0.0054	0.0007	-0.0308	-0.0332
monoculture						
spruce	-0.0908	-0.0994	-0.1149	0.0539	0.0147	-0.0047
pine	-0.0436	-0.0557	-0.0765	0.0933	0.0444	0.0149
birch	-0.0567	-0.0727	-0.0765	-0.0501	-0.0901	-0.0622
silviculture						
spruce-pine	-0.0401	-0.0489	-0.0680	0.0938	0.0517	0.0233
spruce-birch	-0.0570	-0.0734	-0.0767	-0.0491	-0.0897	-0.0608
pine-birch	-0.0564	-0.0717	-0.0767	-0.0487	-0.0869	-0.0622
spruce-pine-birch	-0.0587	-0.0746	-0.0771	-0.0492	-0.0882	-0.0586

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