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Model-based optimisation of the trade-offs between biomass production, CO_2 balance and water consumption in short rotation coppice forestry

Optimalisatie van de trade-offs tussen biomassaproductie, CO_2 balans en waterconsumptie in korte-omloop hakhoutculturen, een modelanalyse

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Summary

The use of fossil fuels since the start of the industrial revolution has increased the CO_2 emissions into the atmosphere, and caused these to rise above the geological record maxima of about 300 ppm. As a consequence, average air temperatures have already risen by almost 1 °C, and are projected to keep rising. Furthermore, the global energy demand keeps rising, as the global population and development grows. Meanwhile, fossil fuels are being depleted faster than they can be replenished. It is therefore important to invest in resource exploration, energy production technology and renewable energy research.

Biomass for energy is one of the most interesting renewable energy sources, because it can provide a continuous flow of electricity and it can be converted into liquid biofuel. Biomass can be sourced from organic waste streams and residues, but it can also be grown specifically for this purpose. Short Rotation Coppice (SRC) plantations are carefully tended, perennial energy crops with fast growing tree species, mostly poplar (*Populus spp.*) or willow (*Salix spp.*), that are intensively managed in a coppice system. This type of biomass plantation allows a fast production of woody biomass. Theoretically, using this biomass for bioenergy production is carbon neutral, but in practice the operation and management of the plantations adds an extra cost which should be considered.

The objective of this thesis is to find an optimized management for SRC plantations throughout Europe, for the current climate, and for a future climate. In order to find the optimized management, the biomass yield, the CO_2 balance, the energy balance and the water use of a number of management scenarios are compared, to acquire a good yield, with a low environmental impact.

A computer model was used to predict the biomass yield and the CO_2 uptake of a poplar SRC plantation for a number of different management scenarios. To this aim, the land-surface model ORCHIDEE was modified to model SRC. Modifications were made to implement management, growth, allocation and parameterization typical for SRC. Using data from two existing Belgian SRC sites, the model modifications were evaluated. The biomass yield predicted by our model was well within the range of measured values. The model also gave good estimates for GPP and ecosystem respiration. The simulated latent heat flux fitted reasonably well with the measurements.

The CO_2 cost and energy cost of the management activities involved was gathered from the Ecoinvent 2.1 database. Per management scenario, the total CO_2 cost and the total energy cost were calculated. For all scenarios, the biomass was assumed to be used for electricity

production by gasification. A net CO_2 balance was calculated by adding the biogenic CO_2 uptake, the management CO_2 emissions, the CO_2 emissions from energy production and the CO_2 savings by substituting grid mix electricity with the produced bio-electricity. A net energy balance was calculated by subtracting the management energy cost from the electrical energy output of the gasification.

We selected 22 sites from the European Fluxes Database Cluster, spread across the geographical range of Europe, with a variety of soil types and climates. For each of these sites, we calculated the biomass yield, the net CO_2 balance, the net energy balance and the actual evapotranspiration for 20 different management scenarios under current climate (2001-2020) and future climate (2081-2100; RCP 2.6, 4.5, 6.0 and 8.5). The management scenarios were all combinations of 0, 50, 100, 150 and 200 mm of annual irrigation and 2, 3, 4 and 5 year rotation cycles.

The simulations and calculations showed that careful site selection is most important in establishing an SRC plantation. Plantations in a temperate climate performed better than plantations in a Mediterranean climate. To further optimize the plantation, short rotations of two years were recommended according to our data. Varying planting densities between 5,000 and 15,000 trees per hectare did not have an impact on yield, the net CO_2 balance or the net energy balance. On sites with a temperate climate irrigation is not advised, as it is too costly from an energetic point of view. In sites with a Mediterranean climate, however, the plantations have a limited supply of water and might not survive the summer drought. Therefore irrigation is advised at these sites. In future climate scenarios, the positive effect of increased atmospheric CO_2 concentrations on water use efficiency was stronger than the increasing drought. Therefore, the increased atmospheric CO_2 concentrations caused an increase in yield and CO_2 uptake from the atmosphere, making SRC an even more promising renewable energy option for the future climate.

Samenvatting

Het gebruik van fossiele brandstoffen sinds het begin van de industriële revolutie heeft de atmosferische CO_2-concentraties doen toenemen tot boven het geologisch vastgestelde maximum van ca. 300 ppm. Als gevolg is de gemiddelde luchttemperatuur reeds met 1 °C gestegen en wordt voorspeld dat deze nog verder zal stijgen. Ook de globale vraag naar energie blijft toenemen door de groeiende wereldbevolking en stijgende ontwikkeling. Ondertussen worden fossiele brandstoffen sneller uitgeput dan ze vernieuwd kunnen worden. Daarom is het belangrijk om te investeren in de opsporing van energiebronnen, de ontwikkeling van productietechnologieën en onderzoek naar hernieuwbare energie.

Biomassa voor energie is één van de interessantste hernieuwbare energiebronnen, omdat het een continue stroom van energie kan produceren en kan worden omgezet in vloeibare brandstof. Biomassa kan zowel van organische afvalstromen en residuen afkomstig zijn, als specifiek voor dit doel geproduceerd worden. Korte Omloop Hakhout (KOH) plantages zijn zorgvuldig beheerde, meerjarige energiegewassen van snelgroeiende boomsoorten, voornamelijk populier (*Populus spp.*) of wilg (*Salix spp.*), in een intensief hakhoutbeheer. Dit type van biomassaplantage laat een snelle houtige biomassaproductie toe. Bovendien is biomassa voor bio-energie theoretisch gezien koolstof-neutraal. In de praktijk hebben de exploitatie en het beheer van de plantages echter ook een kost die in rekening gebracht moet worden.

Het doel van deze thesis is om een geoptimaliseerd beheer te vinden voor KOH plantages doorheen Europa, zowel voor het huidige klimaat, als voor een toekomstige klimaat. Om dit geoptimaliseerd beheer te vinden, werden de biomassaopbrengst, de netto CO_2-balans, de energiebalans en het waterverbruik van verschillende beheerscenario's vergeleken, om een goede oogst te bekomen met een lage milieu-impact.

Een computermodel werd gebruikt om de biomassaopbrengst en de CO_2-opname te voorspelen voor KOH plantages met een aantal verschillende beheerscenario's. Hiervoor werd het model ORCHIDEE aangepast om KOH te simuleren. Aanpassingen werden gemaakt om beheer, groei, allocatie en parametrisatie typisch voor KOH te implementeren. Het model werd geëvalueerd aan de hand van twee bestaande Belgische KOH sites. De biomassaopbrengst voorspeld door het model lag binnen de spreiding van de gemeten waarden. Het model gaf ook goede waardes voor bruto primaire productie en ecosysteem respiratie. De gesimuleerde latente warmteflux kwam aanvaardbaar overeen met de gemeten waarden.

De CO_2-kost en energiekost van de geteste beheeractiviteiten werden verzameld uit de Ecoinvent 2.1 databank. Per beheerscenario werd de totale CO_2-kost en de totale energiekost berekend. Voor elk scenario werd verondersteld dat de geproduceerde biomassa omgezet werd in elektriciteit via vergassing. De netto CO_2-balans werd berekend door de biogene CO_2-opname, de CO_2-uitstoot van het beheer, de CO_2-uitstoot van de energieproductie en de uitgespaarde CO_2-uitstoot door substitutie van de standaard net-elektriciteit door de geproduceerde bio-elektriciteit bij elkaar op te tellen. De netto energiebalans werd berekend door de energiekost van het beheer af te trekken van de elektriciteitsproductie van de vergassing van de biomassa.

We selecteerden 22 sites uit de Europese Fluxes Databank Cluster, geografisch verspreid over Europa, met een variëteit van bodemtypes en klimaten. Voor elk van deze sites berekenden we de biomassaopbrengst, de netto CO_2-balans, de netto energiebalans en de effectieve evapotranspiratie voor 20 verschillende beheerscenario's in het huidige klimaat (2001-2020) en een toekomstig klimaat (2081-2100; RCP 2.6, 4.5, 6.0, 8.5). De beheerscenario's waren alle combinaties van 0, 50, 100, 150 en 200 mm jaarlijkse irrigatie en 2, 3, 4 en 5 jarige rotatiecycli.

De simulaties en berekeningen toonden dat een goede sitekeuze de belangrijkste factor was bij het opzetten van een KOH plantage. Plantages in een gemiddeld klimaat presteerden beter dan plantages in een Mediterraan klimaat. Om de plantage verder te optimaliseren, waren korte rotaties van twee jaar aangewezen volgens onze data. De plantdichtheid kon gevarieerd worden van 5 000 tot 15 000 bomen per hectare zonder invloed op de biomassaopbrengst, de netto CO_2-balans of de netto energiebalans. Op sites met een gemiddeld klimaat is irrigatie niet aangewezen, omdat het energetisch te veeleisend is. Op sites met een Mediterraan klimaat echter, hebben de plantages een beperkte watervoorraad waardoor ze de zomerdroogte mogelijks niet overleven. Daarom is op deze sites irrigatie wel aangewezen. In een toekomstig klimaat is het positieve effect van de verhoogde CO_2-concentraties op de efficiëntie van het watergebruik van de bomen sterker dan de ernstiger wordende droogte. Daardoor veroorzaken de verhoogde atmosferische CO_2-concentraties een verhoging van de biomassaopbrengst en de CO_2-opname uit de atmosfeer. Dit maakt van KOH een veelbelovende optie voor hernieuwbare energieproductie in het toekomstige klimaat.

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Chapter S Synthesis and discussion

1 General introduction

1.1. The global energy problem

Since the start of the industrial revolution, the demand for energy has increased drastically. For 2012, the International Energy Agency (IEA) estimated the total primary energy supply of the world to be 560 EJ (IEA, 2014). Because of transportation and conversion losses, only 67% (375 EJ) of this energy is consumed. Non-renewable sources were used for 86.5% of the energy production: oil (31.4%), coal (29%), natural gas (21.3%) and nuclear (4.8%). All except the latter are major sources of anthropogenic CO_2 emissions to the atmosphere.

Ice core data show that in the past levels of atmospheric CO_2 were not constant (Figure 1) (Etheridge et al., 1996; Indermühle et al., 2000; Lüthi et al., 2008; MacFarling-Meure, 2004; MacFarling Meure et al., 2006; Monnin et al., 2001; Pépin et al., 2001; Petit et al., 1999; Raynaud et al., 2005; Siegenthaler et al., 2005). For the last 800 000 years, temperature has fluctuated because of variations in solar energy input. A possitive feedback effect was caused by temperature induced increases in greenhouse gases, which amplied the initial warming. Greenhouse gases, such as CO_2, absorb certain wavelengths of infrared light, thus preventing the earth from radiating heat back into space. Higher concentrations of these gases cause more heat retention and an increase in temperature. During this period CO_2 concentrations have varied roughly between 175 ppm and 300 ppm.

The use of fossil fuels since the start of the industrial revolution has increased CO_2 emissions into the atmosphere, and caused the atmospheric CO_2 concentration to rise above the geological record maximum of about 300 ppm. Since 2013, summer values of atmospheric CO_2 concentrations recorded at Mauno Lao (Hawaii) exceed 400 ppm. Because of these increased CO_2 concentrations, the average land-surface air temperature of the Earth, compared to a base period of 1951 till 1980, has increased by 0.9 °C in 2014 (GISTEMP Team, 2015; Hansen et al., 2010). The temperature is projected to further increase up to 4.8 °C on average across the climate models by 2100 for the worst case scenario in the IPCC fifth assessment report (IPCC, 2013b).

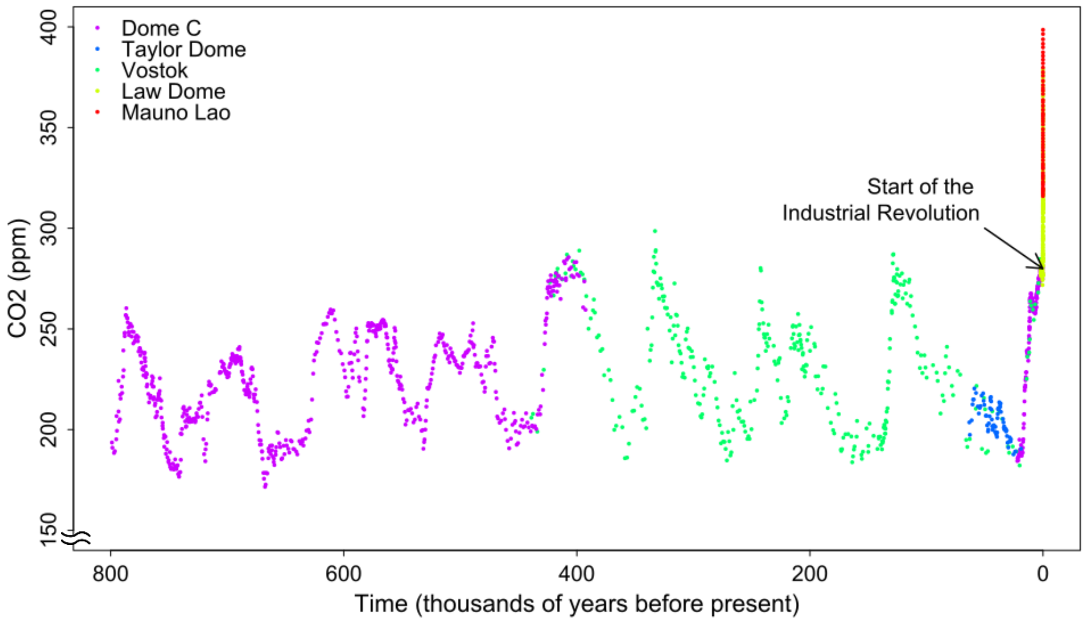

Figure 1: A history of atmospheric CO_2 concentrations from now until 800 000 years ago. The data was collected from ice cores on Antarctica: Dome C (Lüthi et al., 2008; Monnin et al., 2001; Siegenthaler et al., 2005), Vostok (Pépin et al., 2001; Petit et al., 1999; Raynaud et al., 2005), Taylor Dome (Indermühle et al., 2000) and Law Dome (Etheridge et al., 1996; MacFarling-Meure, 2004; MacFarling Meure et al., 2006); and from real time measurements on Mauno Lao (Keeling et al., 1976; Komhyr et al., 1989; Thoning et al., 1989). Note that the CO_2 concentration does not start at zero.

Global change affects natural and human systems on all continents and across the oceans. Changing precipitation or melting snow or ice alter hydrological systems, affecting the quantity and quality of water sources (IPCC, 2014b). In the most extreme cases, climate change will lead to desertification by droughts, or inundation by sea level rise. Many species alter their geographical ranges and migration patterns in response to the changing climate (IPCC, 2014b). This impacts for example the distribution and abundance of commercial fishing species, affecting human food supplies, and especially small local fishers in poor regions. High atmospheric CO_2 concentrations cause ocean acidification, which is harmful to roughly half of the ocean's organisms, from corals to phytoplankton (IPCC, 2014b). The acidifying ocean interferes with the calcification of the shells or external skeletons of these aragonite-forming organisms. Coral reefs are breeding grounds for a wide range of fish species. Phytoplankton plays a key role in deep-storage of carbon in the oceans.

Global change can activate multiple positive feedback loops. CO_2 is dissolved into ocean water, absorbed by phytoplankton and used in photosynthesis. When the plankton dies, it sinks to the bottom of the ocean and stores the carbon there (Sarmiento & Orr, 1991).

Warm water, however, can hold less CO_2 than cold water. Because of global warming, oceans are warming, and thus can take up less CO_2. This decrease in CO_2 uptake and the negative effect of ocean acidification on phytoplankton may result in a decreased oceanic CO_2 sink. The importance of this biological pump is, however still a topic of debate (Bouttes et al., 2011; Denman et al., 2007).

Another positive feedback loop is generated by permafrost. In high-latitude and high-elevation regions, permafrost is warming and thawing (IPCC, 2014b). This is problematic, because permafrost stores enormous amounts of carbon and methane (CH_4). Upon thawing, this CH_4 can be released directly into the atmosphere or converted to CO_2 by bacteria and then released into the atmosphere. CH_4 has a greenhouse effect 20 to 25 times stronger than that of CO_2.

The global energy demand keeps rising, as global population and development grow. Meanwhile, fossil fuels are being depleted faster than they can be replenished. New reserves are harder to locate and extract. It is therefore important to invest in resource exploration, energy production technology and renewable energy research (IPCC, 2014a; Rogner et al., 2012).

Because of the environmental and energy security concerns, governmental policies have been established to invest in renewable energy sources. In their advice to Government on future carbon budgets, the Committee on Climate Change indicated that the carbon intensity of electricity production should fall from the current level of 550 kgCO2 per million watt hours (MWh) to 80 kgCO2 per MWh by 2030 and 30 kgCO2 per MWh by 2050 (UK Environment Agency, 2009). In 2009, the European Commission approved the 20-20-20 targets, which aim at (1) a 20% reduction of GHG emissions in comparison to the 1990 levels; (2) a share of 20% renewable energy in the gross final energy consumption; and, (3) a 20% reduction of primary energy use through improved energy efficiency by 2020 (Directive 2009/28/EC). Individual goals were set for each country, based on their potential. Figure 2 shows the target renewable energy shares for the 28 member states of the European Union, and their 2014 actual renewable energy shares.

More recently, during the December 2015 Conference of Parties (COP21) in Paris, negotiators from 196 countries agreed to a global pact, the Paris agreement, which states: “In order to achieve the long-term temperature goal set out in Article 2 (well below 2 °C), Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty." (UNFCCC, 2015). In a model study, Walsh et al. (2016) found that in order to meet this target, a rapid transition to renewable energy sources is necessary. The window of time in which we can successfully reach this goal is closing rapidly. If the transition to renewable energy sources is not fast enough, implementation of large scale carbon capture and storage (CCS) and other negative emission technologies will be necessary.

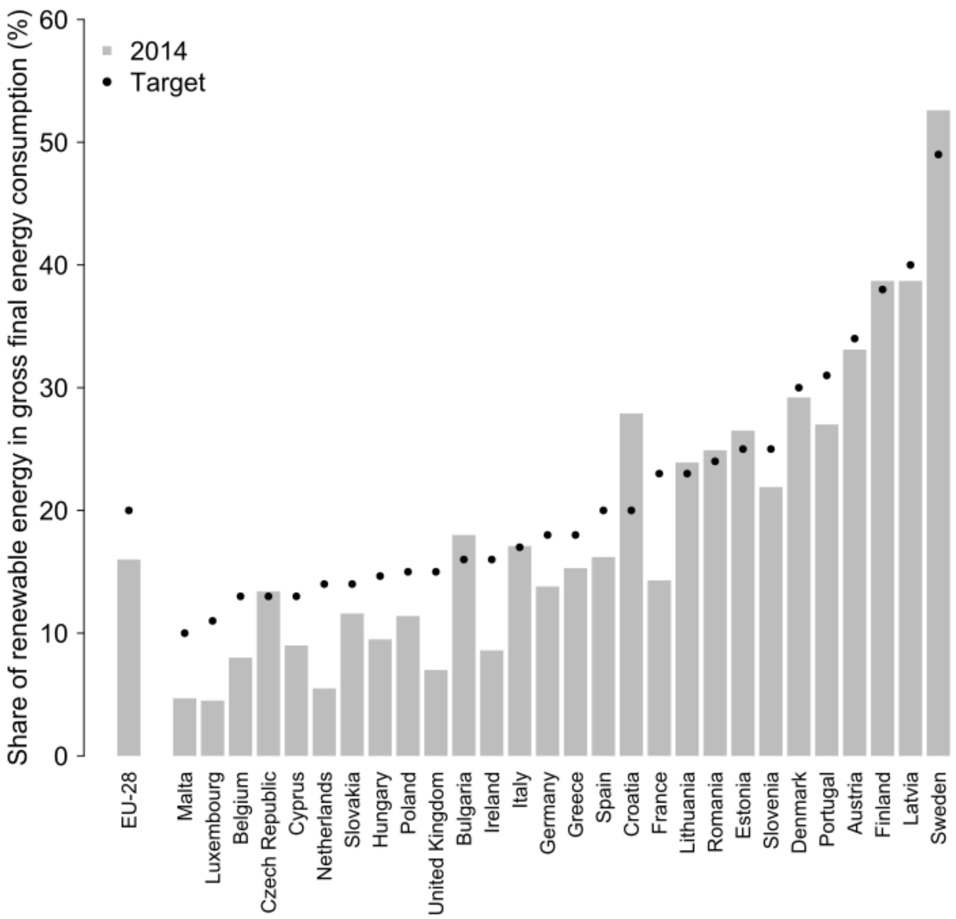

Figure 2: The share of renewable energy in the gross final energy consumption of the 28 members of the European Union. The grey bars show the share for 2014 and the black dots show the goals set by the EU Sustainable Development Strategy. Data acquired from Eurostat (2016b).

A number of possible negative emission technologies are (1) bioenergy with CCS (BECCS), (2) direct air capture (DAC), where CO_2 is extracted from ambient air by chemical reactions, (3) enhanced weathering of minerals (EW), where CO_2 is stored by accelerating the weathering of certain minerals, (4) afforestation and reforestation (AR), where atmospheric CO_2 is captured and stored in the wood, (5) biological or chemical manipulation of uptake of carbon by the ocean, (6) revising agricultural practices such as tilling, crop selection and nutrient management, (7) converting biomass to biochar and storing this char in the soil, and (8) soil carbon sequestration (SCS) where carbon stocks of degraded soils are restored.

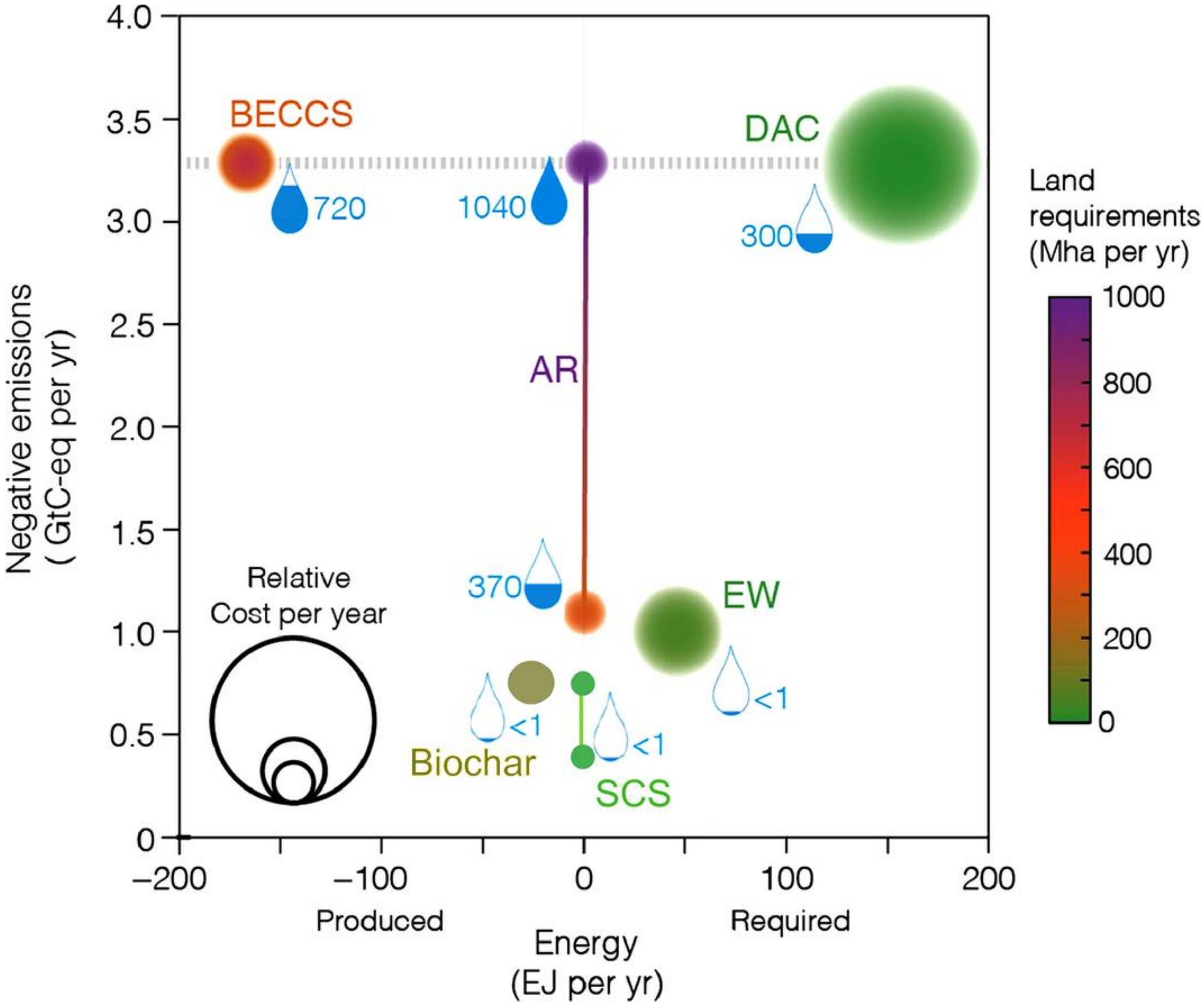

Figure 3: Comparison of the global impacts of bioenergy with carbon capture and storage (BECSS), direct air capture (DAC), afforestation-reforestation (AR), enhanced weathering (EW), soil carbon storage (SCS) and biochar. Water requirement shown as water drops with quantities in $km^3\ yr^{-1}$; all other units are indicated on the Figure. Adapted from Smith (2016).

Figure 3 shows that each of these technologies does have its disadvantages (Smith, 2016; Smith et al., 2016). DAC has good CO_2 uptake values and a low land requirement, but the costs and energy requirements are high. EW has a low CO_2 uptake potential, and the logistical costs might be a barrier. AR and BECCS have good CO_2 uptake potentials, but their water footprint is large and they may be limited by nutrient demand and land availability.

Changes in albedo, caused by AR, might also have a negative influence on the climate. While the water footprint, cost and land requirement of SCS and biochar is low, their CO_2 uptake is also low. Biochar might, just like AR, have a negative impact on the climate through albedo. Looking at BECCS, we can see that bioenergy has an interesting combination of high negative emissions and a high energy production. Many constraints still have to be overcome in order to enable BECCS to become a large-scale energy source and contributor to climate warming mitigation.

1.2. Renewable energy

The implementation of renewable energy options has an impact on land use. The introduction of these technologies competes with existing land services, like food and feed production, provision of housing and recreation, and nature conservation. Different technologies have a different impact on space.

A study on the future of solar energy in the US (Miller et al., 2015) found that 100% of the projected energy requirement of the US in 2050 could be produced by 33,000 km^2 of solar arrays, when distributed evenly across the US. When concentrated around the most efficient locations, this could be reduced to 12,000 km^2. In comparison, the US has an estimated total area of 20,000 km^2 of rooftops. If carefully sited, i.e. on rooftops and across parking lots, industrial brownfields, landfills, and other degraded lands, it might be possible to power a third of the US without measurably increasing the land use footprint. Solar energy is still the most expensive source of renewable energy, but prices are coming down and efficiency is improving (IRENA, 2015). Between 2010 and 2014, the average price for solar energy production halved.

Producing a third of the US's energy requirement with wind power would require 66,000 km^2 of wind farms (Brook & Bradshaw, 2015). However, wind farms contain a lot of empty space and mostly occupy the vertical space. Only 1% of the actual area can no longer be used for its previous land use (Denholm et al., 2009). Therefore, wind energy can cohabit with farming, grazing, industry, etc. Prices for onshore wind are low and competitive with the fossil fuel power cost, but offshore wind remains more expensive (IRENA, 2015).

Although the initial cost of establishing a hydroelectric dam is high, hydropower is the cheapest renewable energy source (IRENA, 2015). In addition, the production of electricity from hydropower has no GHG emissions. However, hydropower can have some other serious negative impacts on the environment. Dams act as barriers to fish and other aquatic species, and to sediment transport. Hydropeaks from temporary changes in the operation of the dam cause disruptions in organisms and their habitat (Fette et al., 2007).

The land requirement for bioenergy is much larger than that of solar and wind energy. Biomass has the advantage of being a non-intermittent power source and it requires less infrastructural modifications. Biomass is, after hydroelectric power, the cheapest renewable energy source (IRENA, 2015). Biomass, geothermal, hydropower and onshore wind are all in the lower range of the fossil fuel energy cost.

1.3. Biomass for bioenergy

Most forms of renewable energy production cannot be universally implemented as substitutes to fossil fuels. Solar and wind energy are dependent on the weather and time of day, and efficient energy storage for a continuous energy supply is not yet available. Hydropower and geothermal power can provide a continuous flow of electricity, but cannot directly substitute oil, which is the main energy source for the transportation sector. Biomass overcomes both these pitfalls, by providing a non-intermittent power generation, and the possibility to be converted into biofuel. Therefore, biomass is considered one of the most interesting sustainable energy options in the EU (EC, 2007).

Biomass can be sourced from organic waste streams and residues, but it can also be grown specifically for this purpose either as an annual or perennial crop. Bioenergy is also considered CO_2 neutral, as the CO_2 that is emitted by the combustion or gasification was first sequestered from the atmosphere during the growth of the biomass (Righelato & Spracklen, 2007). In practice, some extra CO_2 is emitted to the atmosphere by the handling and management involved in the production of biomass.

In order to reduce the net carbon emissions to below thresholds set by the Intergovernmental Panel on Climate Change (IPCC) and more recently COP21, a lot of biomass has to be produced. This biomass production will probably compete with food and feed production; land use change (LUC) effects will negatively influence the climate, negating part of the mitigation potential of bioenergy. Therefore, careful planning and implementation of bioenergy plantations is needed. Walsh et al. (2015) suggest a possible solution to this problem by using algaculture. Algaculture is a relatively new technology where phototrophic microalgae are produced, with yields of up to 100 dry tonnes of biomass per hectare. Algae production is limited by carbon availability, not climate, and possibly CO_2 from flue gases or DAC can be used for their cultivation. The protein rich algal biomass can be used to replace soy or fishmeal in feed. By relocating feed production to land with an unfit climate for biomass production using algaculture, more land is made available for bioenergy crops, lowering the negative impact of LUC on GHG emissions.

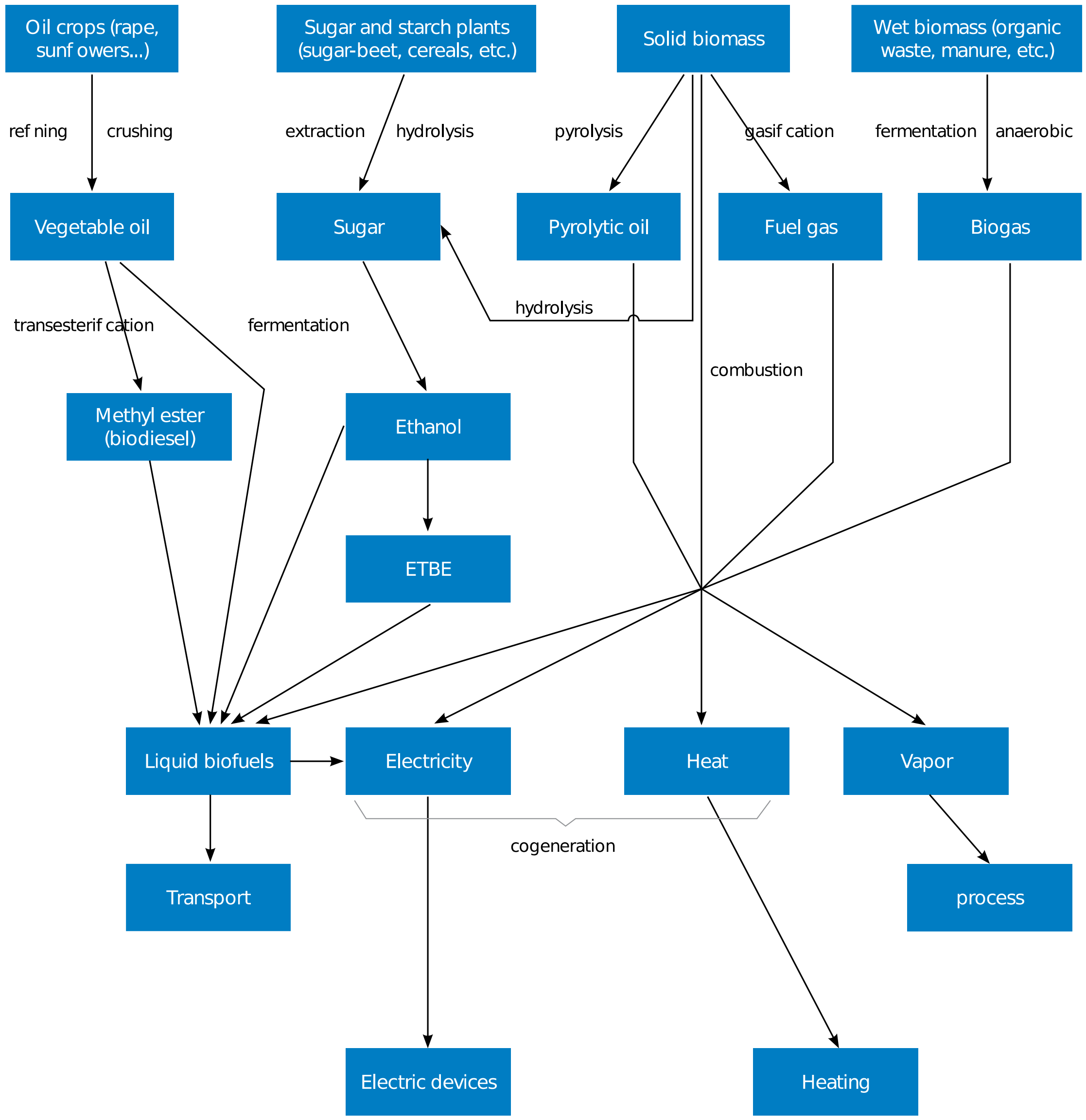

Figure 4: Overview of different biomass feedstock types and their applicable conversion technologies. Reprinted from (Kimble et al., 2008).

1.4. Comparison of biomass feedstocks

Different biomass feedstocks have a comparable energy density (McKendry, 2002). Therefore, the selection of the best biomass source is mainly dependant on other factors, such as chemical composition, biomass production rate and bulk density.

There are a lot of different biomass feedstocks and conversion technologies. The appropriate conversion technology is dependent on the type of biomass feedstock (Figure 4) (Kimble et al., 2008). The main categories are woody biomass, herbaceous biomass, aquatic biomass and manure. Manure and aquatic plants have a high moisture content, which makes them inefficient for use in pyrolysis, gasification or combustion, i.e. dry processing techniques. They are more suited for wet processing techniques, like fermentation (McKendry, 2002).

Another important factor is the cellulose-lignin ratio. Plants with a high cellulose content and a low lignin content are well suited for biochemical fermentation. Herbaceous biomass, like straw and switchgrass, matches these criteria. Biomass with a higher lignin content, like woody biomass, is better suited for dry processing, as lignin cannot yet be chemically converted using current techniques, but it can be converted into energy thermally (McKendry, 2002).

The ash content of the biomass has an important impact on the suitability for dry processing, especially combustion. At these temperatures, the ash can react to form a slag, which interferes with the functioning of the plant (McKendry, 2002).

The biomass production potential is another defining factor. Plants like *Miscanthus*, sweet sorghum and maize use a C4 photosynthesis mechanism, which is more efficient than the C3 photosynthesis of plants like poplar, willow, wheat and other cereal crops.

Woody biomass crops need less fertilization than herbaceous crops, as the wood that is harvested has a low nutrient content. Leaves, which have a higher nutrient content, are not harvested, thereby reducing nutrient exports as compared to herbaceous crops (Euring et al., 2014; Kostecki et al., 2015; McKendry, 2002; Overend et al., 1985). The resulting low fertilization need is an important feature, because of the relatively high GHG cost of fertilization and the associated risk of increased N_2O emissions (Zona et al., 2013b).

Biomass density is important for transport and storage. Biomass with a higher bulk density, such as wood, can be stored more compactly, making it more efficient. For straw to be competitive on the same density basis, it needs either to be baled, or processed into a cubed/pelleted form (McKendry, 2002).

Most of these biomass feedstocks can be grown as a dedicated energy crop, or they can come from organic waste streams and residues. An advantage of waste streams is the absence of land use change effects. No new land has to be designated to biomass production, because it is a waste product from an existing service. It is also preferable to reuse or recycle this waste, e.g. for energy production, instead of dumping it in a land fill. In case of forest residue use, care should be taken that not too much residue is removed from the forest, as too low levels of deadwood might negatively influence biodiversity (McKinsey, 2010) and may deplete soil organic carbon stocks, with negative effects on water and nutrient retention capacity. The composition of waste stream biomass can also be less consistent than dedicated crops, which is bad for conversion efficiency.

Looking globally at the production of biofuel from biomass, a recent study for the European Commission (Valin et al., 2015) also found differences in LUC emissions between different biomass feedstocks. Plants that are used to produce biodiesel from their oil content, like palm oil and soybean oil had high LUC emissions (63 – 231 g CO_2 MJ^{-1}), largely because of drainage of peatlands and deforestation in Indonesia and Malaysia. Plants for ethanol production, with high sugar or starch content, like maize and sugarcane, had lower LUC emissions (14 – 34 g CO_2 MJ^{-1}). For Short Rotation Coppice (SRC) and perennial crops, they found negative LUC emissions, because of the increase in the soil carbon stock. This increase, however, is only present in the short term. For their SRC scenario, they assumed a conversion to SRC from the prior land uses cropland (33%), grassland (5%), natural vegetation (43%) and abandoned land (19%).

The global LUC emissions from biofuels can be lowered by using more abandoned land, stopping peatland drainage and limiting deforestation. Putting a monetary cost on emissions from deforestation at a rate of 50 USD (t CO_2)$^{-1}$ should be sufficient to limit deforestation (Valin et al., 2015). To be effective, sustainability criteria must be implemented globally. To limit indirect LUC, sustainability criteria should also be extended to the food, feed and materials sector (Valin et al., 2015).

1.5. Short rotation coppice

SRC plantations are carefully tended, perennial energy crops with fast growing tree species, mostly poplar (*Populus spp.*) or willow (*Salix spp.*), that are intensively managed in a coppice system (Aylott et al., 2008; Herve & Ceulemans, 1996). This type of biomass plantation allows a fast production of woody biomass. The plantations are established, managed and harvested using agricultural and forestry machines. Therefore, the management intensity of an SRC plantation is higher than in traditional forestry, but lower than in food crop production (Hansen, 1991).

A traditional SRC starts with the planting of 20 to 30 cm long cuttings, which are reproduced vegetatively from the parent tree (Figure 5). Intensive worldwide breeding and selection programs since the early 1950's have yielded a wide range of fast growing, disease resistant poplar clones. These cuttings are usually planted in one of two layouts: (1) In the Swedish planting system, the cuttings are planted in a double row system. In this system, a wider and a smaller gap between the rows of cuttings alternate, resulting in a planting density of 8,000 to 15,000 cuttings per hectare (Bergkvist & Ledin, 1998). The rotation length in this system is typically between two and three years. (2) The Italian planting system consists of single rows of less densely planted cuttings, with a planting density of 2,000 to 7,000 cuttings per hectare (Spinelli et al., 2009). Because of the sparser planting, the trees in this system can grow bigger before competing with each other, and therefore are harvested after five years.

During the establishment phase of the plantation, when the cuttings are starting to root and sprout, they are very sensitive to weed competition (Dickmann & Stuart, 1983; Tubby & Armstrong, 2002). Proper weed removal will ensure a low mortality of the cuttings and a higher yield in the long run. Tree mortality after the initial establishment is generally low (Ceulemans & Deraedt, 1999; Dillen et al., 2013).

Coppicing follows during winter, depending on the chosen site design, when the cuttings have grown into trees for one up to ten years. The tree stems are cut at the base to about 10 cm above the ground (Berhongaray et al., 2013). From the left-over stumps, new stems will resprout into multi-stemmed trees during the following year, and so the cycle continues (Figure 5). After coppicing, herbicide is applied, to prevent weed competition during the resprouting of the stumps.

After harvesting, the trees are usually chipped, either by combine harvester, during harvest, or by a different machine at a later stage (Berhongaray et al., 2013). Combining the harvesting and chipping reduces the workload, but requires heavier machinery and smaller trees. The resulting wood chips can be dried and transported to a bioenergy plant for bioenergy production through combustion or gasification. Alternatively, the wood chips can be used for district heating, fibres or paper production.

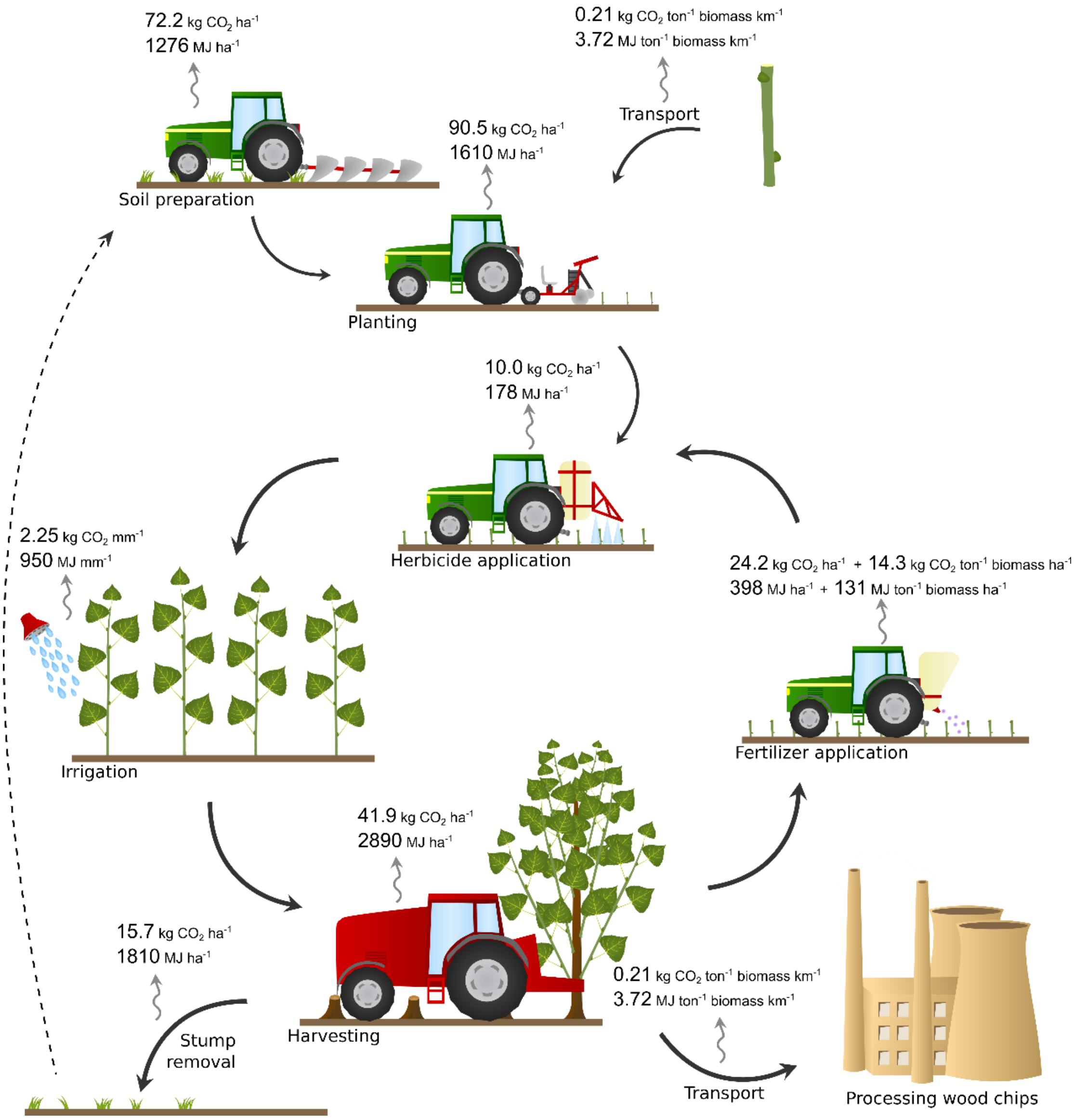

Figure 5: The life cycle and associated CO2 and energy costs of a Short Rotation Coppice plantation.

1.6. Bioenergy in a future climate

In a future climate, biomass production will most likely be affected by elevated CO_2 levels, higher temperatures and drier summers (IPCC, 2013a). It is therefore important to study SRC under these conditions, in order to make sound decisions on their implementation. Representative concentration pathways (RCP) were created by the IPCC as a standard for scientists exploring future climate impacts. The four RCPs represent different possible scenarios for atmospheric CO_2 emissions (Figure 6). In RCP 2.6 the atmospheric CO_2 concentration peaks around the middle of the century and thereafter starts to decline again (van Vuuren et al., 2007). For RCP 4.5 and RCP 6 radiative forcing stays under the long term target level, with the atmospheric CO_2 concentration stabilizing shortly after 2100 (Clarke et al., 2007; Fujino et al., 2006; Hijioka et al., 2008; Smith & Wigley, 2006; Wise et al., 2009). In RCP 8.5 the CO_2 emissions keep increasing, causing high atmospheric CO_2 concentrations (Riahi et al., 2007). The average predicted temperature anomalies roughly follow the same pattern as the predicted atmospheric CO_2 concentrations (Figure 6). Compared to 1986-2005, an average temperature difference of 1 °C, 1.8 °C, 2.2 °C and 3.7 °C is predicted for RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 respectively by 2081-2100 (IPCC, 2013a). These predicted changes are higher on land than over the oceans.

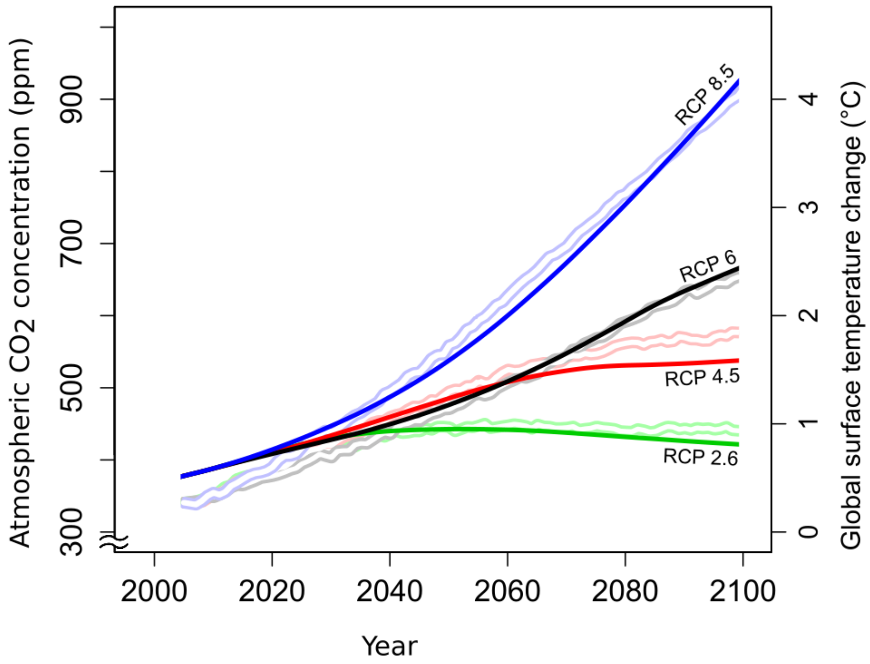

Figure 6: The atmospheric CO_2 concentrations (single lines) for the four IPCC RCP scenarios from 2005 until 2010 according to Meinshausen et al. (2011). And the global surface temperature change relative to 1986-2005 (double lines) for the four IPCC RCP scenarios from (IPCC, 2013a). Note that the CO_2 concentration does not start at zero.

2 Objectives of this thesis

The main objective of this thesis is to find an optimized management (combinations of rotation length, irrigation and planting density) for SRC plantations throughout Europe. The biomass yield, the CO_2 balance, the energy balance and the water use of different management scenarios are compared to elucidate good yields with low environmental impacts.

Direct upscaling of experimental SRC plots is not a suitable approach to reach the objective. Not all combinations of management and local conditions can be tested, and the experimental plots are typically very small. Small scale plots give unrealistic yields (Hansen, 1991; Mola-Yudego & Aronsson, 2008) and cannot be used for this experiment. Large scale experimental plots produce realistic productivity estimates, but are too scarce to allow extrapolation. Therefore, simulating SRC plantations with a well calibrated and evaluated computer model is the best option.

To achieve this objective, the following steps were taken in this study:

1. Modify the process-based model ORCHIDEE-FM (Bellassen et al., 2010; Krinner et al., 2005), to allow the simulation of SRC plantations, and evaluate the model (Chapter 1).
2. Combine the modelled data with life cycle analysis data to evaluate different management scenarios for two SRC sites in Belgium (Chapter 2).
3. Establish trade-offs to elucidate the optimal management of SRC plantations across Europe, using weather and soil data, for a range of European locations (Chapter 3).
4. Find the optimal management using future climate scenarios across Europe (Chapter 4).

3 Presentation and discussion of the main results

3.1. Modifying a process-based model to simulate short rotation coppice plantations

3.1.1 ORCHIDEE-FM

For the simulations presented in this thesis, we opted to modify the mechanistic land-surface model ORCHIDEE (Krinner et al., 2005), which stands for ORganizing Carbon and Hydrology In Dynamic EcosystEms). More specifically ORCHIDEE-FM (Bellassen et al., 2010), which is an extension to ORCHIDEE that adds forest management. A number of modifications were needed to implement the typical management practices associated with SRC and the fast growing poplar trees (Chapter 1).

ORCHIDEE consists of two main components: (1) Sechiba (Ducoudre et al., 1993), which is responsible for calculating the energy and water budget at a half-hourly timescale. (2) Stomate (Krinner et al., 2005), which calculates the carbon balance at a daily timescale (Figure 7).

The carbon (C) in ORCHIDEE-FM is distributed over three main pools, which are subdivided into a total of thirteen smaller pools. (1) The biomass pool consists of leaves, roots, above- and belowground sapwood, above- and belowground heartwood, fruits (i.e. both flowers and fruits) and a carbohydrate reserve. (2) The litter pool is composed of a structural and a metabolic litter pool. The former contains high-lignin litter, with a slow decay rate, while the latter contains low-lignin litter, which decays faster. (3) The soil carbon consists of a fast, a slow and a passive pool, corresponding to the time it takes for the C in these pools to become biologically available again.

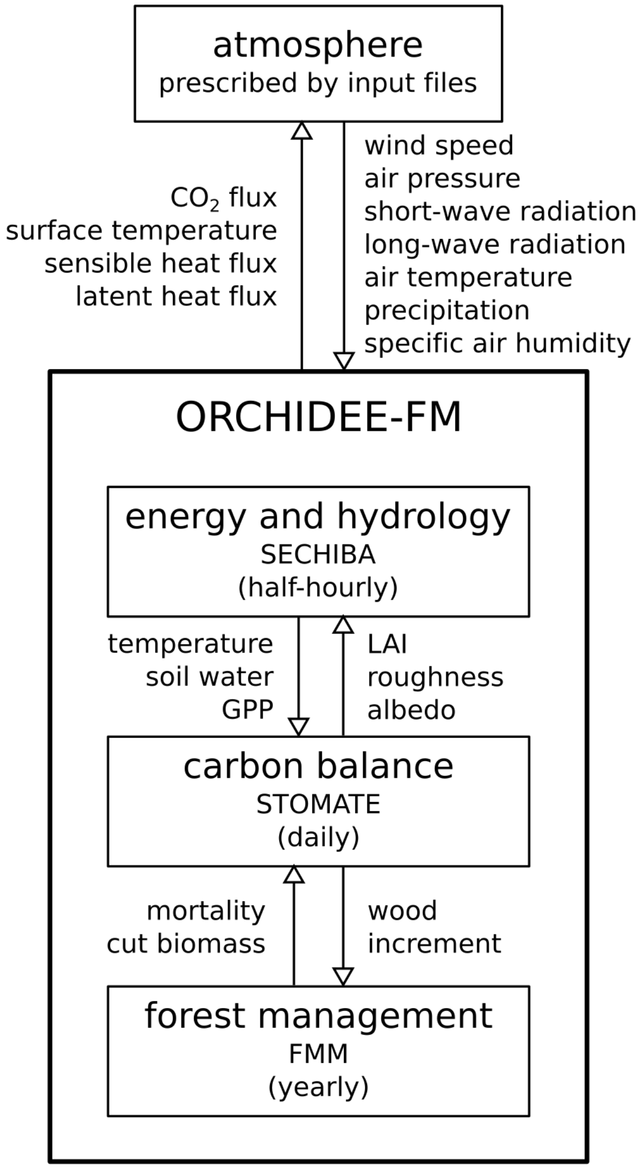

Figure 7: Structure of ORCHIDEE-FM and how the components interact.

The soil water is simulated using a two layer model, following the Choisnel scheme (Choisnel, 1977). The upper layer is dynamic and fills with rain water. In dry periods, the top layer disappears. This dynamic layer is implemented to simulate the easier evaporation of surface water after precipitation, compared to the deeper soil water pool.

ORCHIDEE uses twelve plant functional types (PFT), which combine plants with similar physiology. A thirteenth PFT simulates a bare soil scheme. Our modifications to the model are based on the "temperate deciduous broadleaf forest", as this PFT resembles the poplars grown in SRC plantations the best.

We opted to evaluate our modifications to ORCHIDEE-FM using in situ observations of biomass production, Gross Primary Production (GPP), Net Ecosystem Exchange (NEE), respiration (R), sensible heat (H) and latent heat (LE), as we used these measures of the biomass production, water balance and energy balance in the optimization of the management scenarios.

3.1.2 Management modifications

A first and essential modification to ORCHIDEE-FM was the ability to simulate multiple rotations, including the coppicing of trees. Contrary to the thinning in ORCHIDEE-FM, only aboveground biomass is removed in SRC plantations, with the stools remaining alive.

A second modification was made to the establishment of the plantation. In ORCHIDEE, trees start their lives as saplings. SRC plantations, however, are established using cuttings which don't have any roots or leaves. Therefore, ORCHIDEE was modified to grow SRC from these cuttings, which only have sapwood and a carbo-hydrate reserve.

3.1.3 Growth modifications

After coppicing a fast growing poplar resprouts as a multi-stemmed tree. The number of shoots with which the tree resprouts depends on the genotype. The variation in the number of stems resprouting after coppicing is very large, ranging from 1 to 25. Here, we adopted an average across the many genotypes of two main stems after the first coppicing and four main stems after subsequent coppicing. After the initial resprouting of the stems, the trees gradually undergo self-thinning, reducing the initial high number of small stems, favouring fewer big stems (Laureysens et al., 2005). This motivates our choice in the lower range of the reported values.

In ORCHIDEE, the senescence of the leaves and fine roots occurs simultaneously by the same phenological trigger. For SRC simulations, we decoupled root mortality from leaf senescence and included a turn-over time. The poplar fine roots now stay alive for six months after their formation. The onset of fine root growth remains coupled with the phenological trigger for leaf growth.

3.1.4 Allocation modifications

A poplar tree can become sexually mature from the age of five onwards. Because the duration of most SRC rotations is under five years, SRC-grown poplars will never produce flowers or seeds. The same age threshold holds for the sapwood to heartwood conversion. To account for this in the model, no carbon is allocated to the reproduction-pool, and no aboveground sapwood is converted into heartwood when the last coppicing was 5 years or less ago.

The tree species used in SRC plantations are fast-growing tree species that reach a large leaf area as fast as they can. Therefore, we adapted the Maximal Leaf Area Index (LAI_{max}) in the model such that it is only limited in the first year, and allowed to reach the PFT-specific LAI_{max} from year two onwards.

After coppicing, poplar trees allocate almost no carbon to the growth of coarse roots. To simulate this effect, the trees in the modified ORCHIDEE model maintain a fixed, structurally logical, root-shoot ratio. When the root-shoot ratio deviates from this ratio by more than 10%, such as after removal of the entire shoot biomass, 95% of the C allocated to wood production is allocated to the aboveground part.

3.1.5 Parameterization

ORCHIDEE-FM uses five allometric relations to convert stem biomass into stem volume, stem volume into stem biomass, circumference into stem volume, stem volume into circumference and circumference into height. These standard relations were parameterized using data from an existing SRC plantation.

The default parameters in ORCHIDEE were compared to measurements from an existing SRC plantation. LAI_{max}, $v_{c,max}$, J_{max} and the exponential decay factor of the root profile were changed based on this comparison (Chapter 1, Table 2). Parameters that were in the range of the measured data were left unchanged.

3.1.6 Model evaluation

The performance of the modified model was evaluated using data from two SRC stands in Belgium: the Boom site and the POPFULL site (Chapter 1). The Boom site was a poplar-based SRC plantation operated from April 1996 until November 2011 in Boom, near Antwerp. From this site mainly dendrometric measurements were available.

The operationally managed POPFULL site was established in April 2010 in Lochristi, near Ghent. At this site, an eddy covariance tower was erected. From this tower, CO_2 and H_2O fluxes were measured. The measured NEE flux was partitioned into GPP and R_{eco} using an online eddy-covariance gap-filling and flux-partitioning tool (Max Planck Institute for Biochemistry, 2005), which is based on the standardized methods described in Reichstein et al. (2005). Furthermore, dendrometric measurements were available.

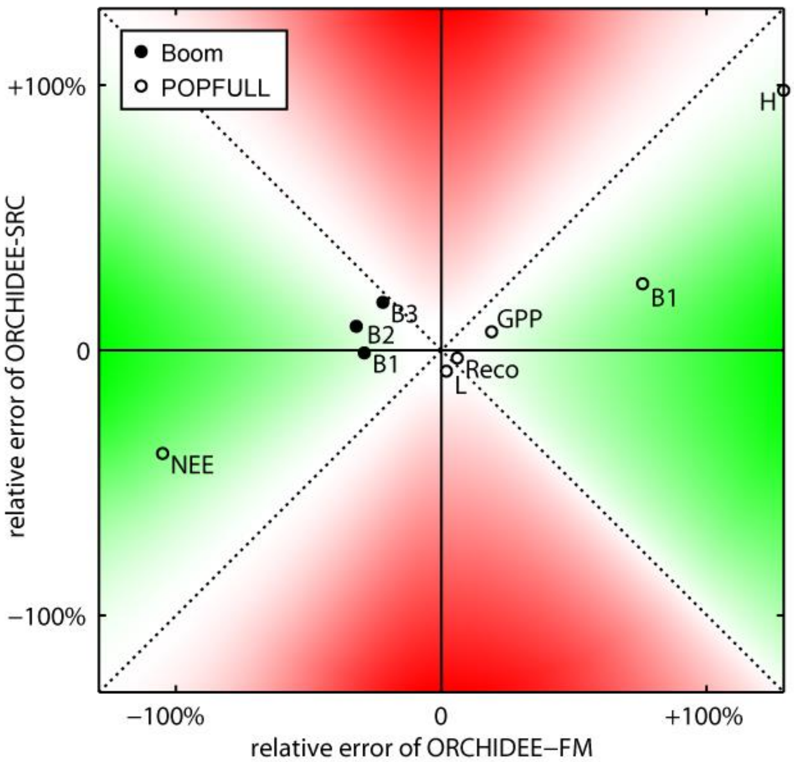

Figure 8: Comparison between the performance of ORCHIDEE-SRC and ORCHIDEE-FM. The relative error was calculated as the relative difference between the field measurements and the model simulations. The green background indicates an improvement by the extended model relative to ORCHIDEE-FM, the red background indicates a performance decline of the extended model results. A darker colour indicates a more pronounced difference. The letters next to the symbol are cumulated per rotation, whereby: GPP = gross primary productivity; Reco = ecosystem respiration; NEE = net ecosystem exchange; L = latent heat; H = sensible heat; Bx = aboveground woody biomass production

of rotation x. The Boom site simulations are shown as filled circles and the POPFULL site simulations are shown as open circles.

The calculated and observed GPP values matched well (Figure 8). The main difference could either be explained by photosynthesis of weeds during the winter, which are not represented in the model, or by errors in the flux partitioning.

The modeled R_{eco} fitted the measurements very well (Figure 8). The only point of divergence was the dry spell in the summer of the second year. Here, R_{eco} was underestimated, probably because the model is too sensitive to drought, although the simulated soil water content was within the measured range.

When comparing NEE, the fit is less good than for GPP and R_{eco} (Figure 8), because the small errors in GPP and R_{eco} were cumulated in NEE.

The simulated LE flux fitted reasonably well with the measurements (Figure 8). The main point of divergence was during a drier period.

We compared the yearly aboveground biomass production measured at these sites, with our model output. The model predictions were well within the range of measured values for both the Boom site, the POPFULL site (Figure 8) and 23 other European sites (Chapter 1).

3.1.7 ORCHIDEE-SRC

Overall, the modified model provided good values for biomass production, GPP, R_{eco}. Due to the simplicity of the soil moisture module, some discrepancies were found in the simulations of the LE flux during a dry spell. For the rest of the year, however, LE was simulated adequately. Therefore we adopted this version of the model for our further simulations, and called it ORCHIDEE-SRC.

3.2. Finding an optimized SRC management in Europe

3.2.1 The Data

3.2.1.1 Site data

To elucidate optimal management in Europe, we simulated site locations spread across the geographical range of Europe, with a variety of soil types and climates (Chapters 3 and 4). We therefore selected 22 sites from the European Fluxes Database Cluster (Europe Fluxdata, 2014), with a public data access policy and an open data use policy, and at least 5 years of data.

These sites were spread from Spain and Portugal in the south to Finland and Western-Russia in the north along a south-west to north-east axis (Figure 9). Soil texture differed, but clay-loam and loam textures were most common. The site annual minimum temperatures range from -13.0 °C to 2.9 °C (summer: 4.9 °C to 14.8 °C), the site annual maximum temperatures range from 19.4 °C to 37.0 °C (summer: 19.4 °C to 37.0 °C) and the site annual total precipitation ranges from 524 mm to 1263 mm (summer: 26 mm to 496 mm) (Figure 10).

Figure 9: Geographical distribution of the test sites across Europe.

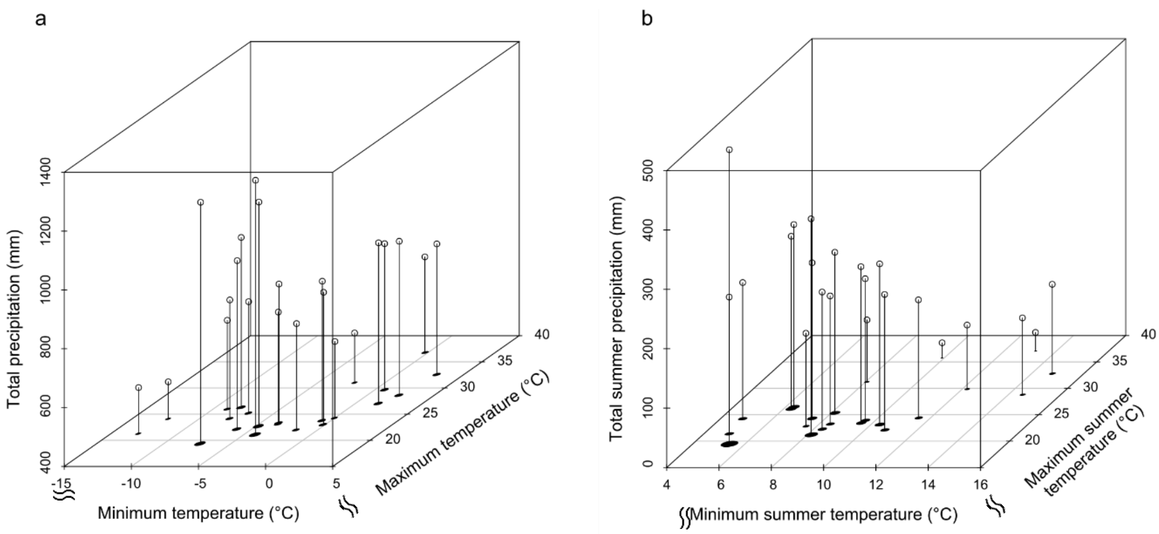

Figure 10: The variation in (a) annual and (b) summer values for precipitation, minimum and maximum temperature between the sites across Europe. Note that not all axes contain zero.

3.2.1.2 Future climate data

Using the Royal Dutch Meteorological Institute’s Climate Change Atlas (KNMI, 2013), monthly data was exported from the CMIP5 dataset (IPCC, 2013a) for absolute temperature difference and relative precipitation difference for the future period 2081-2100 compared to the reference period 1986-2005 for RCP 2.6, 4.5, 6.0 and 8.5 across Europe. Using this data, four additional average weather input files were created for each site, one for each RCP scenario.

For all sites, the temperatures increased over the entire year in all RCP scenarios, with a stronger increase in the more extreme scenarios. For all sites except the Russian and the Finish site, the temperature increase was strongest during the summer months. The precipitation change didn’t show a seasonal pattern for RCP 2.6, but for the higher RCPs, it evolved into a pattern with wet winters and dry summers. The most northern sites have a net increase in precipitation, while the southern sites have a net decrease in precipitation.

3.2.1.3 Management costs

In order to optimize the management of SRC throughout Europe, we wanted to include the CO_2 cost and energy cost of the management activities involved. We therefore gathered data from the Ecoinvent 2.1 (Frischknecht et al., 2007) database. The management activities are implemented in the following configuration. Before planting, cuttings of 10 g each are transported to the plantation from a supply station over a distance of 150 km. The soil is prepared by mechanical weeding, ploughing and a chemical herbicide application. After soil preparation, the cuttings are planted using a standard leek planter. The cuttings then grow into trees, while irrigation is applied in accordance with the management scenario. At the end of each rotation, the plantation is harvested with a modified combine harvester and the cuttings are transported to a power station 50 km from the plantation. After the harvest, chemical herbicide is reapplied to prevent weed growth during the sprouting of the new stems and a 20-6-6 NPK fertilizer is applied to replace exactly the amount of nitrogen lost through the harvest. The fertilizer is added because farmers typically fertilize their soils and because there is no nutrient limitation in our model. It therefore implies a fertilized soil. This cycle continues until the plantation is twenty years old. After twenty years the stumps are removed from the soil. The values can be found in Figure 5.

3.2.1.4 Simulations

In a smaller scale simulation for two Belgian SRC sites (Paper 2), we found no effect of planting density on the biomass yield, energy balance or CO_2 balance, within the range of 5,000 to 15,000 trees per hectare. We therefore didn't include variation in planting density in our simulations across Europe. This finding suggests that the increase in density is counteracted by the increased competition, cancelling out each other. In this range of planting densities, Djomo et al. (2015) and Bergante et al. (2010) found similar results.

For the simulations across Europe, we varied the rotation length from two up to five years, and we varied the irrigation volume from 0 up to 200 mm with increments of 50 mm. Irrigation was applied weekly from April until September, and the volume was evenly distributed to cumulate to the set volume over the entire year. The twenty different combinations of rotation length and irrigation volume were simulated for each of the 22 European sites, for each RCP, and for a total duration of twenty years. The current climate simulations were run for the years 2000 to 2020, the RCP simulations were run for the years 2081 to 2100.

For each of the management scenarios individually, the energy cost and the CO_2 cost was calculated. Based on the biomass yield, the emissions from the bioelectricity production by gasification were calculated, as well as the prevented CO_2 emissions from substituting grid mix electricity with this bioelectricity. A net energy balance was then calculated from photosynthesis, respiration, the gasification emissions and the energy substitution. A net energy balance was calculated from the management energy cost and the produced bioelectricity.

3.2.2 Finding an optimized management

We found general trends in the effects of the different climate scenarios on biomass yield, net CO_2 uptake from the atmosphere, actual evapotranspiration and the energy balance (Figure 11, Figure 12). Both biomass yield, net CO_2 uptake and the energy balance showed a positive correlation with the atmospheric CO_2 concentrations of each RCP. This demonstrated that in a projected future climate, even for the extreme scenarios, SRC becomes an even more viable option for energy production. Even for the Mediterranean sites, as drought becomes worse, the positive impact of increasing CO_2 concentrations on the water use efficiency (WUE) of the poplar trees had a stronger effect.

The inter-site variation in biomass yield (Figure 11, row 1) showed a pattern, going from south to north, of increasing yield, reaching a plateau and then decreasing again for the most other sites. The same pattern could be observed for the energy balance (Figure 11, row 4). Optimizing the management resulted in larger yield increases for the southern sites than for the other sites. This resulted in smaller net energy losses for the irrigated southern sites compared to the irrigated other sites. The energy gain from increased biomass yield was not large enough to offset the energy cost of irrigation (Figure 12, rows 1 and 4). The increase in biomass yield from shorter rotation was large enough to compensate for the extra energy from harvesting (Figure 12, rows 1 and 4).

The net CO_2 uptake from the atmosphere was positive for all sites and all scenarios except for a number of management scenarios in the most southern sites in the current climate and in RCP 2.6 (Figure 11, row 2). Shorter rotations showed a higher net CO_2 uptake (Figure 12, row 2), because increase in yield was large enough to counteract the increase in the management emissions. The effect of irrigation clearly differentiates between the southern sites and the other sites (Figure 12, row 2; Figure 10, row 2).

Changes in management caused large changes in actual evapotranspiration for the southern sites only (Figure 11, row 3). For these southern sites, almost all irrigated water was used and transpired by the trees, while in the other sites, the trees hardly used any of the irrigation water and most of it was lost through runoff and drainage. This clearly showed that for sites with a dry Mediterranean climate, water is a limiting factor, while it is not for the other sites. Variations in rotation length did not have an effect on the actual evapotranspiration rate (Figure 12, row 3).

A principal component analysis, performed on these data, showed that 40% of the variation in biomass yield, net CO_2 uptake and energy balance was explained by the climatic descriptors of the sites, i.e. minimum, average and maximum summer temperature, total summer precipitation, and total summer incoming radiation. 17% of the variation was explained by soil texture. 11% of the variation was explained by the RCP scenarios and a further 10% by both irrigation volume and rotation length. This showed that a good site selection is more critical in the implementation of SRC plantations than the management. The southern sites which showed overall deviating results from the other sites, have a Mediterranean climate, whereas the other sites have a temperate climate, with the most northern sites bordering boreal climates.

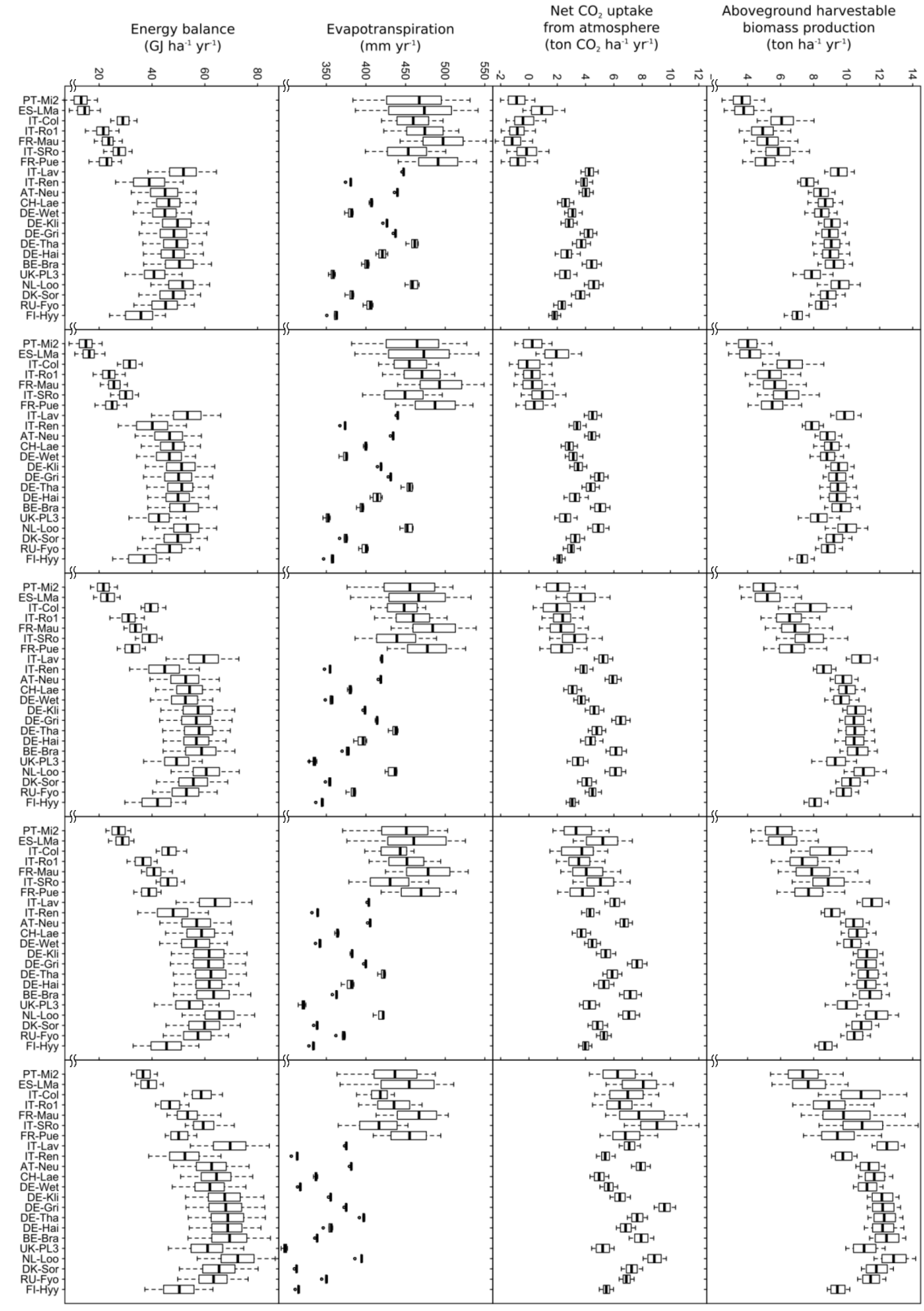

Figure 11: Boxplots showing the variation in aboveground harvestable biomass production, net CO_2 uptake from the atmosphere, evapotranspiration and energy balance per site. The columns are different RCP scenarios. Sites are arranged from lowest latitude to highest latitude. Note that not all axes contain zero.

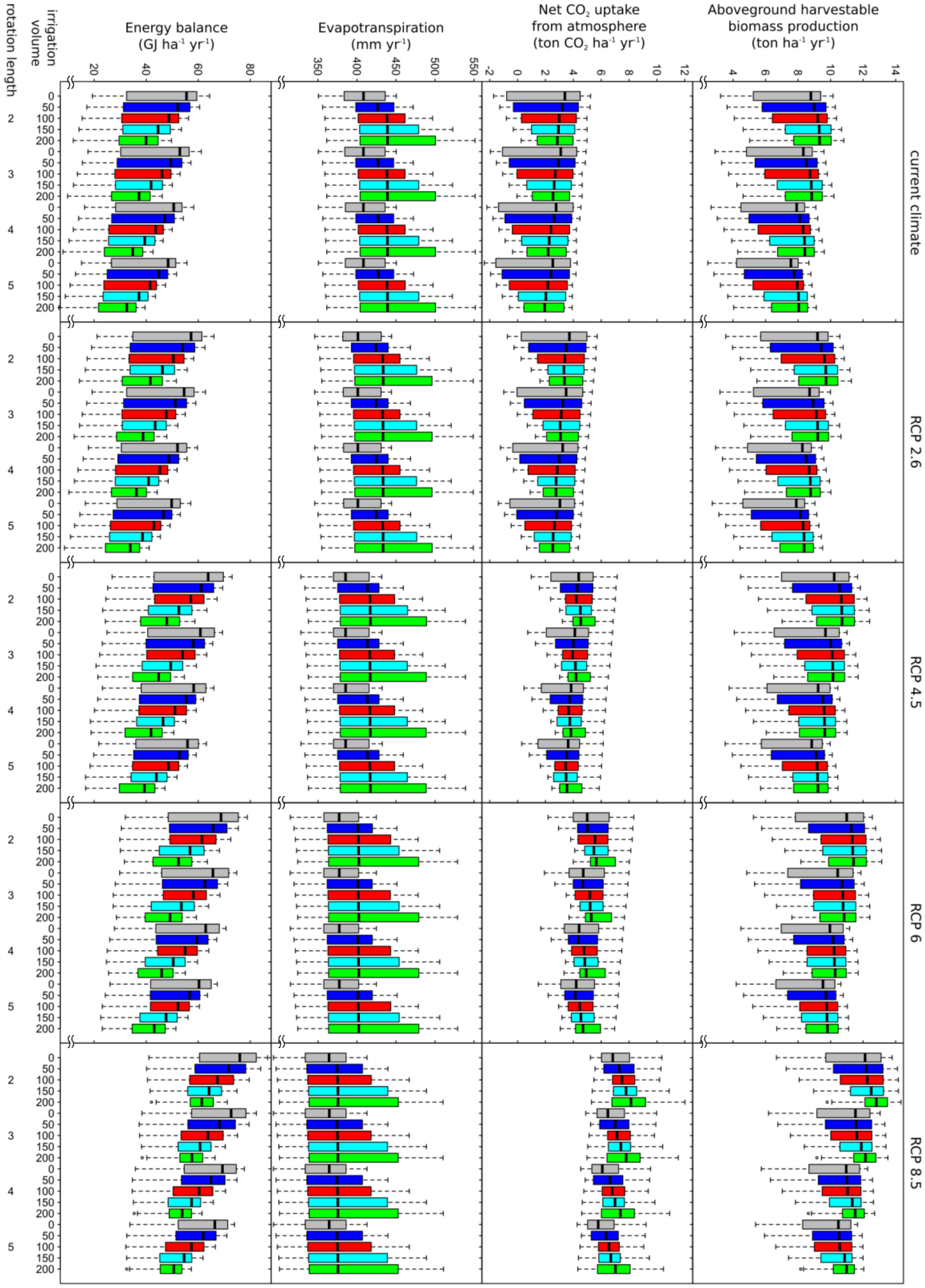

Figure 12: Boxplots showing the variation in aboveground harvestable biomass production, net CO_2 uptake from the atmosphere, evapotranspiration and energy balance per management scenario. The columns are different RCP scenarios. The different colours denote different irrigation volumes: grey = 0 mm yr^{-1}, blue = 50 mm yr^{-1}, red = 100 mm yr^{-1}, cyan = 150 mm yr^{-1}, green= 200 mm yr^{-1}. Note that not all axes contain zero.

3.3. General Discussion

3.3.1 Calibration vs evaluation

Calibration and evaluation data were kept separate in this study. We used some measurements from the Lochristi and Boom site for the calibration of the model, but these were not the same data that the model was evaluated on. We did not use data from a single site for the calibration of the model, but involved data from both sites. The evaluation of the model performance was subsequently carried out on both sites separately, and additional data from European sites along a north-south and east-west transect were used for evaluation.

More specifically, we used data from the Boom site to parameterize the equations for converting different tree size measurements into each other (Chapter 1, section 2.2.2). These parameters were mainly used to divide the biomass of the trees into tree size classes, and were included in the model's forest management module, where trees of different ages grow amongst each other. When simulating SRC, all trees are the same age and there is less variation in size. These parameters have no direct influence on the fluxes used for evaluation and therefore should be universal across poplar hybrids.

The photosynthetic parameters used from the Lochristi site are important for the simulation of GPP, and therefore also for the simulation of biomass production. The values from the Lochristi site were consistent with previously reported data for several poplar species and hybrids (Broeckx et al., 2014).

3.3.2 Implications of our life cycle choices

3.3.2.1 Fertilization

When calculating the amount of fertilizer to be applied to the site to replace the nitrogen lost through biomass removal, we assumed a nitrogen concentration of the wood of 0.2% of the dry mass. Reported values vary between 0.03% and 0.53% of dry mass for poplar wood (Euring et al., 2014; Kostecki et al., 2015; Overend et al., 1985). Assuming a 0.2% nitrogen concentration resulted in a fertilization rate of up to 29 kg N ha^{-1} yr^{-1}, which is close to the reported value of 34 kg N ha^{-1} yr^{-1} by Adler (Adler et al., 2007).

Fertilization requirements are much lower than in traditional agriculture, as the woody biomass has a low fertilization need. It is important that fertilizer application rates in SRC plantations are not too high, since excess nutrients will percolate into the groundwater or runoff into rivers causing eutrophication. Eutrophication can cause algal bloom, which in turn is harmful for the river ecosystem. The algal mat reduces the light penetration into the water, diminishes water oxygen levels and can produce toxins.

Moreover, fertilizer application results in N_2O emissions from the site. During denitrification of the fertilizer, N_2O can be produced and emitted into the atmosphere (Brentrup & Pallière, 2014). The amount of emitted N_2O is assumed to be about 1% of the applied amount of nitrogen, depending on the type of fertilizer used (Bouwman et al., 2002). This might seem small, but N_2O has a global warming potential of 298 over a 100 year timeframe (IPCC, 2013a), which means that every molecule is about 300 times more potent than CO_2 as a GHG.

3.3.2.2 Irrigation

We wanted to capture the range of conventional irrigation volumes used across Europe, and study their impact on both yield and environmental effects. We therefore varied the irrigation volume between 0 and 200 mm yr^{-1}. Irrigation for SRC is most typical and often required in the Mediterranean region. Bergante et al. (2010) reported irrigation volumes for 11 sites in Northern and central Italy. The irrigation volumes ranged from 0 mm yr^{-1} to 150 mm yr^{-1}, except for one year on one site with a divergent value of 366 mm. But, irrigation is not exclusive to this region and is sometimes also applied in the temperate zone. Schweier et al. (2016) reported an irrigation application of 51 mm yr^{-1} for a German site. Some other temperate sites reported not to use any irrigation (Broeckx et al., 2012; Dillen et al., 2007). When the poplar plantation is used for waste water treatment, the irrigation volume can be higher (Jerbi et al., 2015, 800 mm yr-1), but not necessarily (Holm & Heinsoo, 2013, 160 mm yr-1). In the waste water scenario, however, sustainable biomass production is not the main objective.

In the studied scenarios, irrigation represented the largest management cost, mainly for energy, but also in the non-biogenic GHG emissions (Figure 12). Adding more than 200 mm yr^{-1} of irrigation might be advantageous for biomass production, especially for the Mediterranean sites, but already at 200 mm yr^{-1} the energy use of irrigation largely exceeds the energy use of other management operations.

For a more efficient application of the irrigation, the soil moisture could be monitored, and irrigation applied when the soil moisture drops below a threshold. Contrary to our scenario with evenly spread irrigation, less water would be wasted by applying it when there is no soil moisture deficit. We opted to use the evenly spread irrigation scenario for comparability between sites.

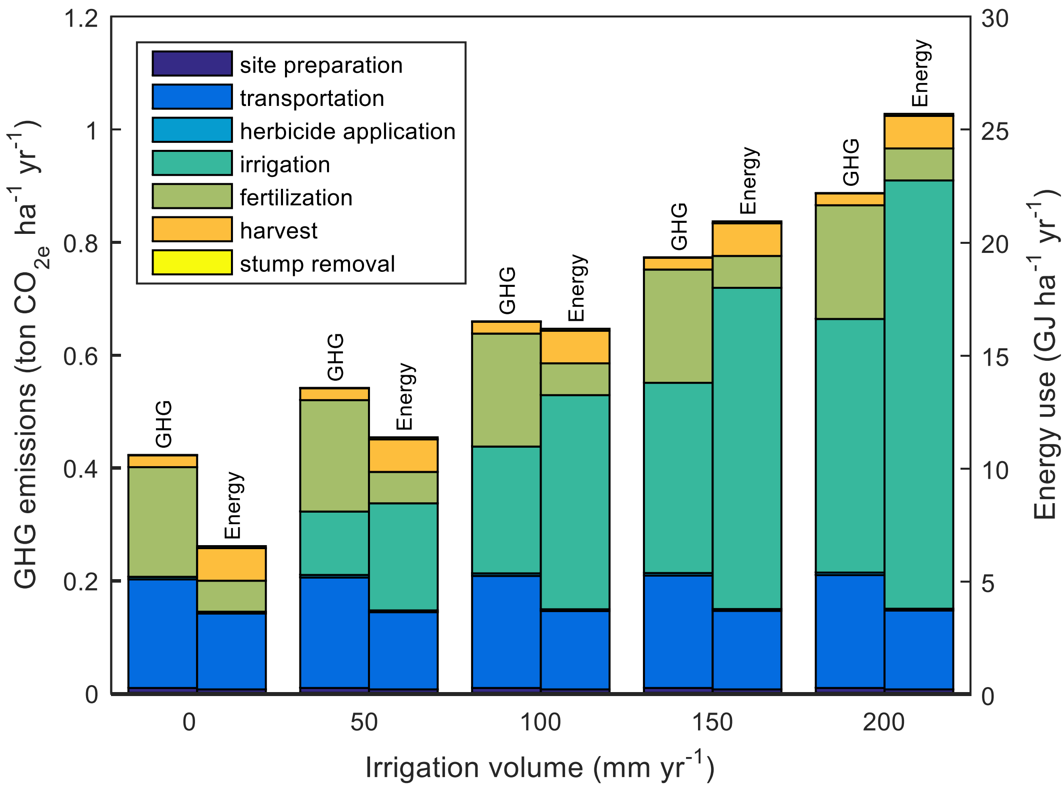

Figure 12: The impact of different management practices on the non-biogenic GHG emissions and management energy use with varying irrigation volume. For site AT-Neu with a rotation length of 2 years under current climate.

3.3.2.3 Transportation

At the establishment phase of the plantation, we assumed a 150 km distance for the transportation of the cuttings to the site. This is the same value as used by Djomo et al. (2013). The exact value of this distance is of lesser importance, as this operation only happens once over the entire life cycle. Moreover, this distance will never be very large, as it is important to choose plants adapter to the local climate.

The distance between plantation and power plant is more important. Biomass as an energy source is more sustainable if it can be locally sourced. We opted to use 50 km as a plausible distance for local sourcing. Schweier et al. (2016) also used this distance in their analysis.

Together with irrigation and fertilization, transportation is one of the largest sources of management related GHG emissions in our studied scenarios (Figure 12). It is the second most important of the management energy uses. When considering more transportation scenarios, i.e. very local (20 km), average local (50 km), neighbouring countries (500 km; e.g.: from France to Belgium) and across Europe (1000 km; e.g.: from Poland to Belgium), we can see that the energy use and GHG emissions of long distance biomass transportation dwarf even the energy use and CO_2 emissions of irrigation (Figure 13).

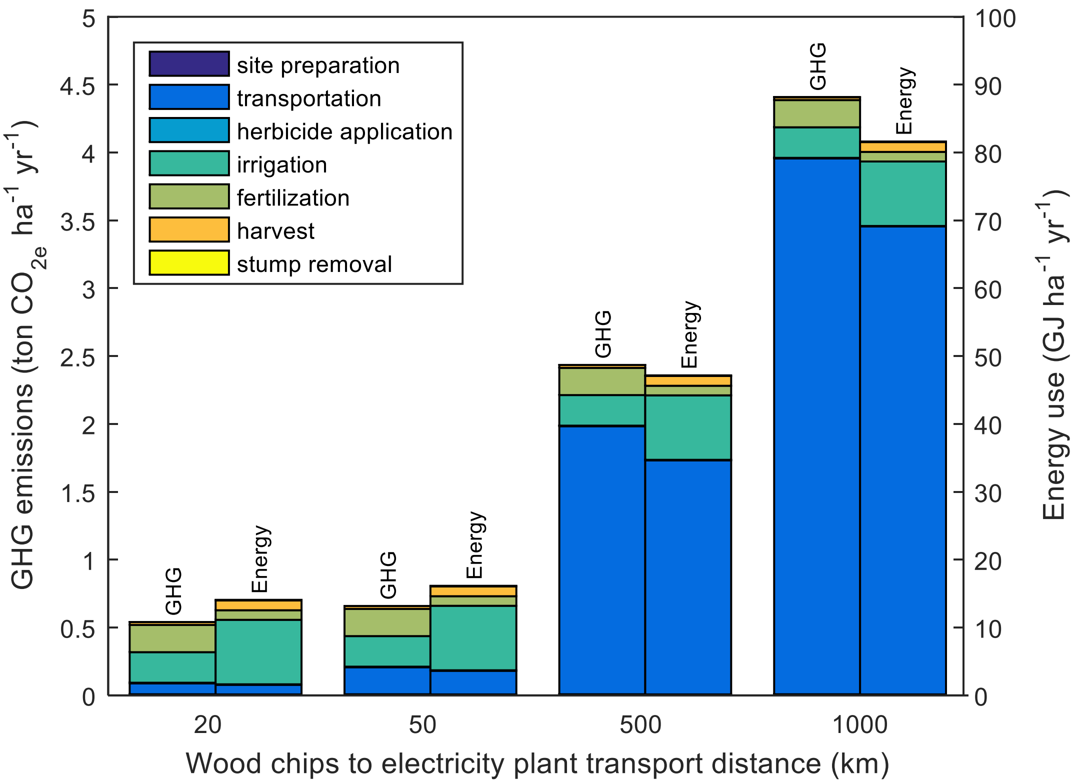

Figure 13: The impact of different management practices on the non-biogenic GHG emissions and management energy use with varying transportation distance of wood chips from the farm to the electricity plant. For site AT-Neu with a rotation length of 2 years and 100 mm yr^{-1} irrigation under current climate.

3.3.2.4 Harvest

We assumed that all harvested aboveground biomass could be used for the bioenergy production. Berhongaray et al. (2013), however, show that, depending on the type of harvester used, up to 20% of the harvested biomass can be lost during the harvesting and chipping of the wood. For a whole stem harvester, the losses were only 3%, while using a combined cut and chip harvester could result in losses of up to 20%. Using a whole stem harvester requires an extra management operation. It takes longer, it has higher CO_2 emissions and uses more energy (Figure 14). However, the extra energy use is much smaller than the energy that would be lost by losing 20% of the harvest. More careful operation of the harvesting machinery could also limit the harvest losses for the combined cut and chip harvester (personal observations).

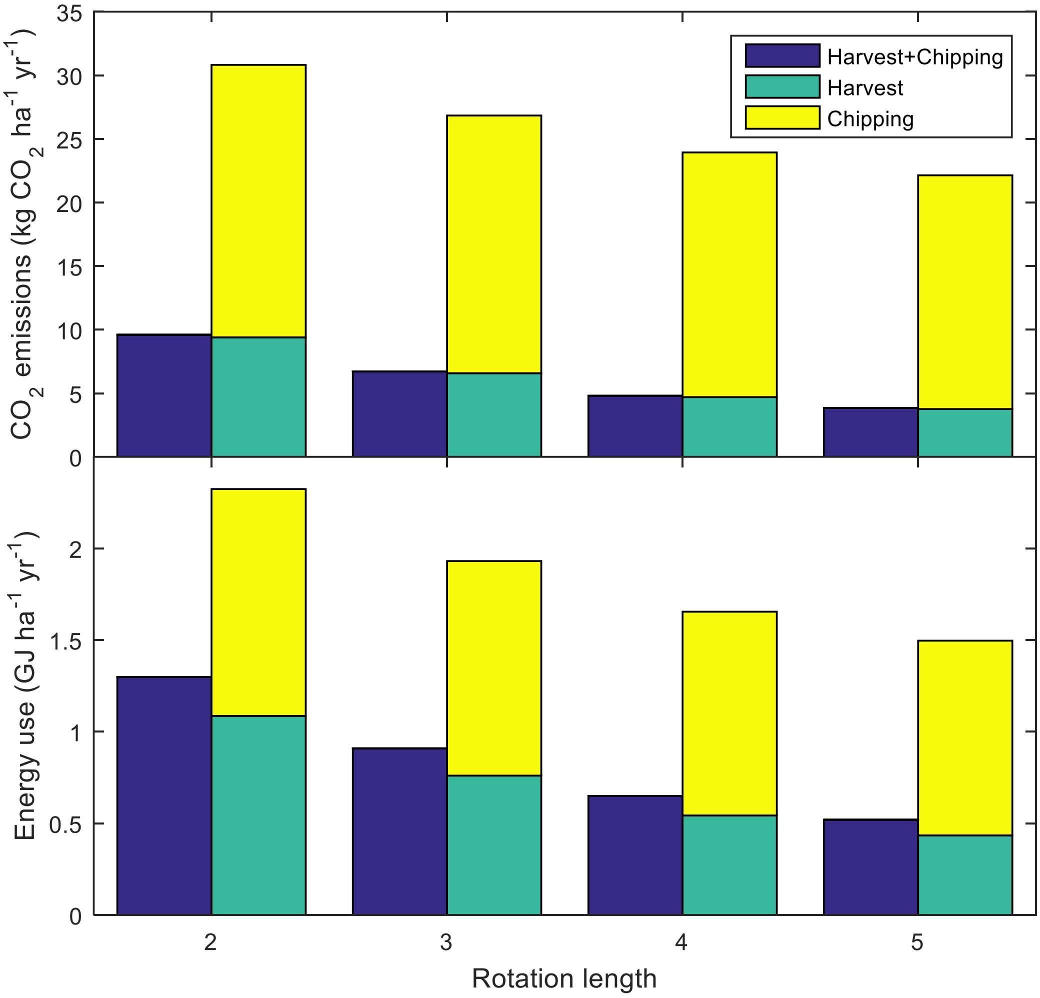

Figure 14: The CO_2 emission and energy use of harvesting with a combined harvester that harvests and chips at the same time, and a whole stem harvester with separate chipping, for rotation lengths of 2 to 5 years. For site AT-Neu with a rotation length of 2 years and 100 mm yr^{-1} irrigation under current climate.

3.3.2.5 Biomass conversion

For the conversion of biomass into electricity, we used a heating value for poplar wood of 18.5 MJ kg^{-1} reflecting the total calorific content of the wood. A value that is reported consistently in literature (Di Nasso et al., 2010; Overend et al., 1985; Vanbeveren et al., 2016).

However, not all this energy can be converted into usable energy. For conversion into electricity using combustion or gasification, the efficiency is typically between 25 and 37% (Adler et al., 2007; Djomo et al., 2013; EC, 2010b; IEA, 2007b; Mann & Spath, 1997), of which we used the upper bound. Also co-firing the biomass with coal gives a comparable efficiency (McKinsey, 2010). If the biomass is used not only for electricity production, but also for heat production, the efficiency can go up to 74 – 84% (EC, 2010b; Graham & Huffman, 1981; IEA, 2007b; Overend et al., 1985). Using this heat, however, requires the necessary infrastructure for its distribution, which is usually not present and is an expensive initial cost.

The energy content and conversion efficiency are important for the calculation of the amount of grid mix electricity that can be substituted with the bioenergy from the harvested biomass.

3.3.2.6 Genotypic variation

Our model simulated an average plantation, so that genotypic variations were averaged out. In real plantations, using a good site design should include a genotypic diversity of species and/or hybrids, to obviate the risk of pest damage and insure good yields. Therefore, the total biomass production, and fluxes of the plantation should also be averages of the larger variation between different genotypes.

3.3.3 Barriers for farmers

A barrier for farmers to grow SRC is the loss of flexibility. The farmer has to dedicate one or more land parcels to SRC for a number of years. During these years, he is uncertain of the financial returns he will get. During the years without harvest, he has no income for these parcels (McKinsey, 2010). This might be obviated by starting plantations in successive years, ensuring annual harvest incomes. But this also increases the total establishment and harvest costs. In traditional agriculture, when one crop fails, the farmer can replant his field with another crop during the same year, ensuring some revenue for that field during that year, but when SRC fails, an investment of several years is lost. During the time between establishment and harvest, market wood prices may also fluctuate, giving the farmer uncertainty of the revenue for this long term investment (McKinsey, 2010).

3.3.4 Regulation

The production of biomass as a sustainable energy source should follow the principles of sustainable intensification, where the CO_2 and energy balance are maximized and the yield optimized. Our results show that inappropriate management choices might increase the yield, but reduce the sustainability of the biomass production in terms of GHG emissions and energy use. Furthermore, LUC effects can negate any emission savings (UK Environment Agency, 2009). Planting energy crops on pristine old forest, permanent grassland or peatland can create carbon debts from carbon sequestered in the vegetation and soil, taking several hundreds of years to repay (McKinsey, 2010; Valin et al., 2015). Creating biomass sustainability criteria only on a national level doesn't establish sufficient environmental protection (Pelkmans et al., 2012). Therefore, international criteria should be applied through a combination of legally binding regulations and other schemes or standards (McKinsey, 2010). Unfortunately, the establishment of global frameworks through international negotiations may take years (McKinsey, 2010).

Actual actions that can be taken for the environmental protection regarding biomass production are limiting the use of biomass to that of countries with sustainability plans and regulations, like the Reducing Emissions from Deforestation and forest Degradation (REDD) plan (EC, 2016), that cover changes in grassland, forests and peatlands (McKinsey, 2010; Valin et al., 2015). An international GHG accounting framework, like Land Use, Land-Use Change and Forestry (LULUCF) (EC, 2016), can also be implemented to monitor GHG costs and retributions (McKinsey, 2010). This framework might not only inventory the GHG emissions, but may also put a monetary value on them (Valin et al., 2015). Putting a monetary value on GHG emissions will reduce emissions from unnecessary management practices and, if included in the framework, also reduce LUC emissions.

The use of biomass in combined heat and power plants, instead of electricity only should be encouraged, as the conversion efficiency of combined heat and power is much higher than that of electricity only (UK Environment Agency, 2009).

3.3.5 Average weather

The averaging of the meteorological data in our study had an impact on the weather patterns (Figure 15, 16). For both the temperate and the Mediterranean sites, the typical year has a high share of days without precipitation. When the meteorological data was averaged over 15 years, this number is drastically reduced. For the temperate site from almost 60% to almost 0%, and for the Mediterranean site from over 60% to just under 20%. Sites where the precipitation is averaged over only 5 years show a similar pattern, but less extreme. In the averaged years, days with high precipitation are completely lacking and the amount of days with an average amount of precipitation is increased.

This can have implications for the irrigation in our scenarios. The large reduction in rainless days causes a more gradual and constant water availability for the plantation. During the typical year, with more sporadic, higher intensity rainfall, a higher percentage of the precipitation can be lost through interception and runoff. Therefore, the effect of irrigation might be underestimated by our model.

However, when looking in more detail to the annual pattern of precipitation, we can see that for the Mediterranean climate, the summer is characterized by a dry period (Figure 17). This dry period is retained quiet well in the averaged year. This also explains why the Mediterranean site had more dry days left after averaging (Figure 16). Since the dry period coincides with tree growth, the model underestimation is probably smaller than might be expected at first. In the temperate climate precipitation is evenly distributed over the year, without a seasonal cycle.

The averaging of the meteorological data also has an effect on the temperature patterns (Figure 15, 16). Both high and low temperatures become rarer and average temperatures become more common. In general, the impact of this change was rather small, as the general pattern of temperature throughout the year was preserved (Figure 18). It can have an impact on the phenology of the trees, as averaging the temperatures might have an effect on the growing degree days, and therefore influence the leaf onset.

In our model set-up for scenario analysis we wanted to avoid the influence of extreme weather events which in part justified the methods applied. In addition, precipitation is intercepted by the canopy first, with our setup up to 0.25 mm (de Rosnay & Polcher, 1998). This precipitation is considered non-effective, i.e. not contributing to the SRC soil water balance, as it doesn’t reach the soil.

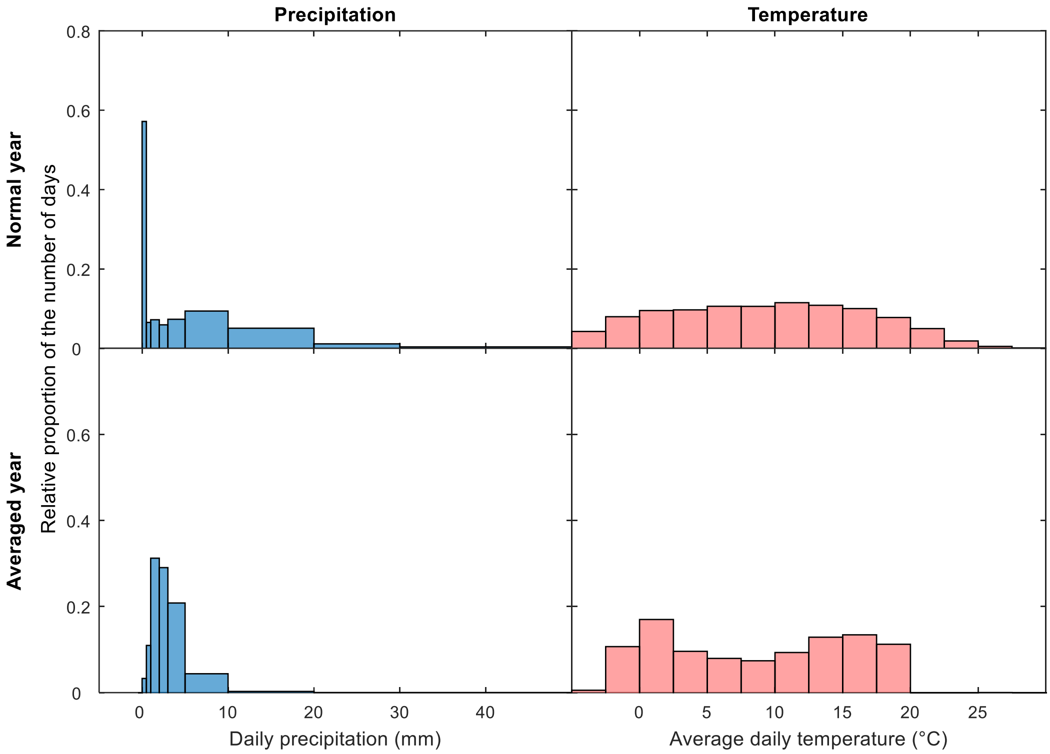

Figure 15: Precipitation and temperature patterns of a temperate site, for a typical year, and for an averaged year. The site DE-Tha was averaged over 15 years.

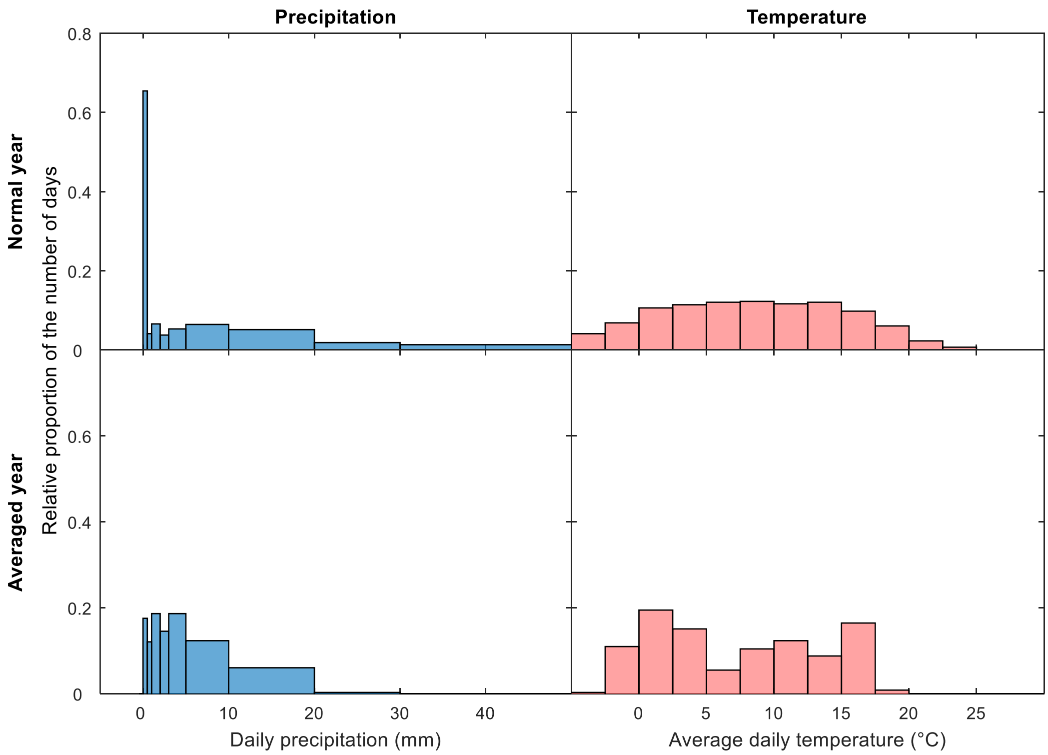

Figure 16: Precipitation and temperature patterns of a Mediterranean site, for a typical year, and for an averaged year. The site IT-Col was averaged over 15 years.

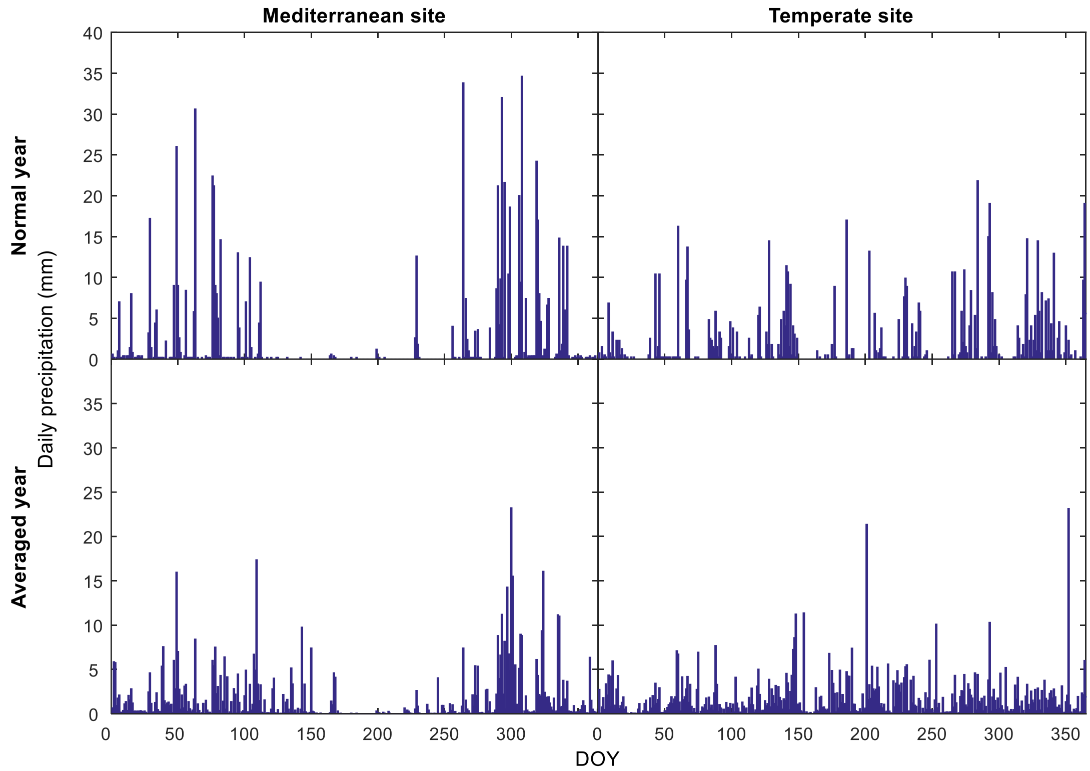

Figure 17: The pattern of precipitation throughout the year for a typical year and the averaged year in a Mediterranean site (PT-Mi2) and a temperate site (UK-Pl3).

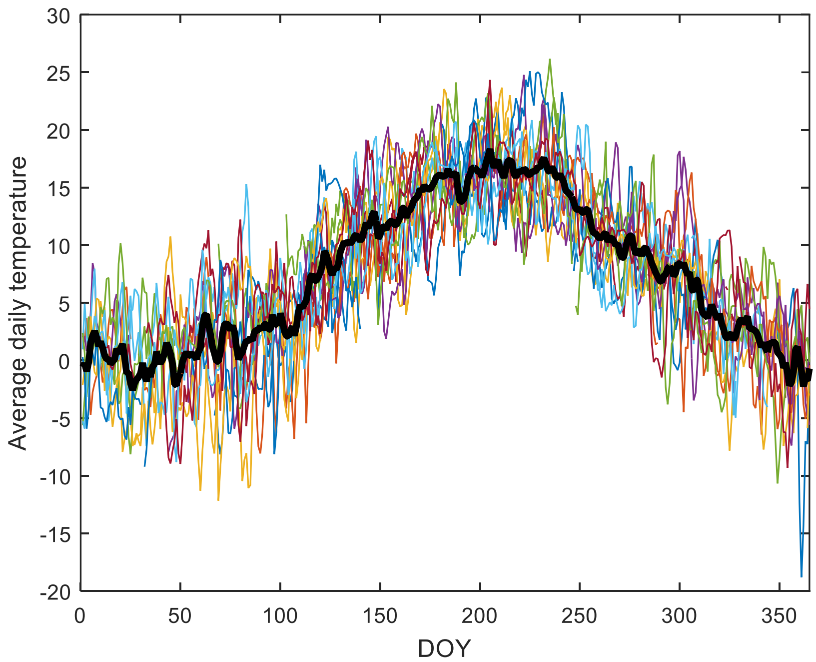

Figure 18: The pattern of temperature throughout the year for site IT-Col. The thin coloured lines are the actual measured daily values. The thick black line is the averaged meteorological year.

3.4. Strengths and possibilities for future improvement

Frequent cutting induces a large stress on the trees, possibly exhausting the trees and killing them. This effect, however, is not well studied yet, and possibly genotype specific. Dillen et al. (2011), showed a mortality ranging from 9% to 92% for different genotypes after 15 years. This effect may be irrelevant as the opened space in the canopy can be filled by extra shoots from neighbouring stools. Further research into the effects of frequent cutting will allow this effect to be incorporated in vegetation models.

Our use of open data and a well-documented model, allows for the reproducibility of our research. Furthermore, the use of a well-tested model is a cost-effective approach, as it allow a large number of scenarios to be tested without the need to set up field experiments.

The simulated biomass yields in the southern European sites are lower than the average reported yields for this region. This is possibly related to the fixed LAI_{max} which is used by ORCHIDEE. Poplar trees in the Mediterranean region can reach higher LAI values than those on more northern sites (personal communications with R. Ceulemans, 2014), to make more efficient use of the abundant sunlight. As our model limits this LAI, the Mediterranean trees in our model cannot exploit this advantage.

The current climate meteorological files were linearly perturbed to the RCP scenario meteorological files. This only changed the scale of the temperature and precipitation, whereas weather patterns and extremes are also projected to change. Precipitation will probably become more concentrated in high intensity rainfalls, alternated with longer dry periods (IPCC, 2007a). A more complex weather generator, that accounts for these changing patterns, could produce more representative meteorological input files for simulating future climate scenarios.

Differences between our model simulations and plantations relate to the large amount of natural variability. Our model was calibrated to simulate an average SRC poplar plantation, but a good clone selection, adapted to the local growing conditions, can result in high yields. In addition, a good variation in clone selection is the best cost-effective protection against pests and diseases. The occurrence of pests, such as rust or beetle infections, can impact the yield of a plantation.

Working with a model allows the use of unified average clones and average weather. Working with these averages should give a more generally representative result.

Direct or indirect LUC were outside the scope of this research. A review of land use changes for biofuel production has demonstrated a very large variation in reported changes because of inconsistent approaches (Djomo, 2012). Direct LUC ranged from −52 to 34 g CO_2 MJ^{-1}, whereas the indirect LUC ranged from 0 to 327 g CO_2 MJ^{-1}. The total LUC carbon intensity of bioethanol was found to be −29% to 384% of that of gasoline.

Our analysis assumed the use of an average European grid mix electricity and liquid fossil fuels for the management. Some countries, e.g. France and Belgium, produce a large amount of their electricity using nuclear energy (Eurostat, 2015), and therefore have much lower grid mix CO_2 emissions and little room to decrease their CO_2 emissions from electricity production. Contrary to this could be Poland, where much of the electricity comes from coal plants, so biomass could make a difference in the short term. The net CO_2 uptake from the atmosphere could therefore be reanalysed for each country.

Furthermore, in the future, renewable energy sources might become more widespread, also for agricultural vehicles. Therefore, our analysis could be extended to different levels of renewable fuel used for SRC management activities, and their effect on the CO_2 balance.

A number of practical recommendations for sustainable production can be made using our analysis. These recommendations will be presented in the next section.

4 Conclusion and practical recommendations

Stakeholders throughout the supply chain cover a broad spectrum ranging from biomass suppliers such as farmers and land owners, to energy producers and providers. Closely linked to this, decision making levels range from the field scale supply to regional scale demand and regulating governments.

We succesfully modified an existing mechanistic land-surface model (Chapter 1), to simulate the biomass yield and CO_2 fluxes of SRC plantations, although improvements to solve specific requirements are possible (section 3.3). Soil temperature and soil moisture were simulated adequately, but the effects of dry spells on the latent heat flux were not simulated well. The annual latent heat flux, however, was simulated reasonably well. Overall the ORCHIDEE-SRC version of the ORCHIDEE model was very well suited to simulate biomass production of SRC plantations.

Biomass yield, net CO_2 uptake and energy balance increased with higher atmospheric CO_2 concentrations of future climate scenarios. Even for the extreme scenarios, SRC remains a viable option for energy production, and becomes even more viable (Chapter 4). Under high atmospheric CO_2 concentrations the increased net CO_2 uptake of SRC might provide a negative feedback to climate change. However, drawing such conclusions from single rotations is dangerous (Holtsmark, 2013).

According to our results, site selection is the most important decision to be made in establishing a SRC plantation (Chapters 3 and 4), since inter-site differences are larger than intra-site differences. The main determinant in the inter-site differences was climate. Sites with a temperate climate were much more successful (double the yield under current climate) than sites with a Mediterranean climate (Figure 11).

Planting densities between 5,000 and 15,000 trees per hectare did not show any effects on biomass yield, net CO_2 uptake, net energy balance or actual evapotranspiration (Chapter 2). The reduction in competition by lowering planting density improves yields enough to compensate for the lower starting biomass in this range of densities. Because of financial considerations, the site manager might aim for the lower side of this range. This might, however, cause a greater risk in case of tree mortality, as in sparser plantations less trees are available to fill the gaps with their shoots.

The choice of the optimal management for SRC (Chapters 3 and 4) depends on the optimization aim. A site manager, whose income is dependent on the biomass yield, would prefer to use irrigation and two year rotations. Irrigation and harvesting, however, cost extra money, so a financial analysis should be made by the site manager, to compare the income of the increased yield with the management cost. El Kasmioui (2013) provides a detailed analysis of the financial aspects of SRC plantations. Irrigation, however, does also have a large energy cost.

Management should also be optimized for a maximized net energy production. The energy consumed by the irrigation pumps greatly reduces the net energy balance. Therefore, from an energetic point of view, two year rotations without irrigation are favoured. On Mediterranean sites, however, the absence of irrigation can cause the net CO_2 balance to switch to a net CO_2 source. Other studies also found that irrigation is necessary in Mediterranean SRC plantations to ensure tree survival (Bergante et al., 2010). One of the reasons might be that the sensitivity of certain poplar species and hybrids to drought induces cavitation and tree mortality (Fichot et al., 2015).

Care should be taken with subsidizing SRC biomass production for bio-electricity. Incautious implementation of subsidies, such as subsidizing based on biomass production will encourage the site manager to maximize his yield, without regard for the energetic or GHG cost of his management practices. We demonstrated that the benefits of bio-energy production from SRC biomass are counteracted by a focus on production only, counteracting the original aim of the subsidy. The principles of sustainable intensification should be followed.

We found that the most environmentally costly management practices are irrigation, fertilization and transportation. Schweier et al. (2016) also found these practices to have the highest global warming potential in SRC management. Transporting fuels over long distances and excessive use of nitrogen fertilisers can reduce the emissions savings made by the same fuel by between 15 and 50 per cent compared to best practice (UK Environment Agency, 2009). Management optimization will be most effective if targeting these management practices. Only irrigate when absolutely necessary. Apply carefully selected amounts of fertilization. And produce the biomass regionally.

Biomass could be used more efficiently when used for combined heating and power generation. Since heating is the most energy consuming activity for the majority of European households, the use of biomass as a combustible would mean an important reduction in emissions (Lapillonne et al., 2015), either directly in their homes, or indirectly through district heating from combined heat and power plants. Furthermore, heat conversion of biomass (74 – 84%) is much more effective than electrical conversion (25 – 37%). Derived heat is already widely implemented in a number of European countries, mainly in North, Central and Eastern Europe (Eurostat, 2016a). Deployment of new district heating networks, however, require substantial infrastructural adaptations and decentralization of energy production.

Chapter 1 ORCHIDEE-SRC v1.0: an extension of the land surface model ORCHIDEE for simulating short rotation coppice poplar plantations

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Modelling biomass production and the environmental impact of short rotation coppice (SRC) plantations is necessary for planning their deployment, as they are becoming increasingly important for global energy production. This paper describes the modification of the widely used land surface model ORCHIDEE for stand scale simulations of SRC plantations.

The model uses weather data, soil texture and species-specific parameters to predict the aboveground (harvestable) biomass production, as well as carbon and energy fluxes of an SRC plantation. Modification to the model were made to the management, growth, and allocation modules of ORCHIDEE.

The modifications presented in this paper were evaluated using data from two Belgian, poplar based SRC sites, for which multiple measurements and meteorological data was available. Biomass yield data was collected from 23 other sites across Europe and compared to 22 simulations across a comparable geographic range. The simulations show that the model performs very well to predict aboveground (harvestable) biomass production (within measured ranges), ecosystem photosynthesis (R2 = 0.78, NRMSE = 0.064, PCC = 0.89) and ecosystem respiration (R2 = 0.95, NRMSE = 0.078 PCC = 0.91). Also soil temperature and soil moisture are simulated adequately, but due to the simplicity of the soil moisture simulation, there are some discrepancies, which also influence the simulation of the latent heat flux.

Overall, the extended model, ORCHIDEE-SRC, proved to be a tool suitable for predicting biomass production of SRC plantations.

1 Introduction

In recent years, a great deal of research has gone into the development of renewable energy as a way to sustain energy production without contributing to climate change. The Europe 2020 headline targets of the European Commission state that by 2020, greenhouse gas emissions should be 20% lower than in 1990 and 20% of the European energy has to be renewable (EC, 2010a). The National Renewable Energy Action Plan (NREAP) predicts that in Europe 34.3% of the electricity production and 21.3% of the heating and cooling energy requirement will come from renewable energy production by 2020 (Zervos et al., 2011). An important share of this renewable energy production will come from biomass. Both annual and perennial energy crops and biomass residues from agriculture, forestry and processing industries can be used.

SRC plantations are perennial energy crops with fast growing tree species, mostly poplar (*Populus spp.*) or willow (*Salix spp.*), that are intensively managed in a coppice system (Aylott et al., 2008; Herve et al., 1996). The rotation duration typically ranges from 2 to 5 years. At the end of the rotation the shoots are cut back to the ground in winter and the stumps resprout the next spring. The harvested wood is then dried and used for energy production. Management intensity of a SRC plantation is thus higher than in traditional forests, but less than in food crops (Hansen, 1991).

Because of the growing societal demand for energy from biomass, SRC plantations are likely to become more widespread, although the full consequences on the carbon (C), water and energy budgets are not yet fully understood. For this reason models are needed that can simulate the larger-scale effects of wide-spread SRC use, which are sufficiently general to allow application at larger scales, while being specific in the essential details.

The objective of this study is to further develop an existing land surface model called ORCHIDEE, to have the model simulate the C and water fluxes of SRC plantations over a range of site conditions. In the future we want to use this model to test a number of management scenarios across Europe to study the variation in the management effects on biomass production and CO_2 uptake. To this aim we made changes to the management, growth and allocation modules of ORCHIDEE, adjusted the parameterization and evaluated the performance of the adapted model against site-level information from two operationally managed SRC stands in Belgium.

2 Materials and methods

2.1. Model description

ORCHIDEE is a mechanistic land surface model that was designed to operate from regional to global scales. The model is composed of two components: (i) SECHIBA, which computes the energy and hydrology budget on a half-hourly basis, and (ii) STOMATE, which simulates the carbon cycle on a daily time scale. The equations used by ORCHIDEE are given in Ducoudre et al. (1993), Krinner et al. (2005) and in the online documentation (http://forge.ipsl.jussieu.fr/orchidee). The source code can be accessed at http://forge.ipsl.jussieu.fr/orchidee/browser/tags/ORCHIDEE_1_9_5.

For these simulations, ORCHIDEE needs seven meteorological variables at a 30 min interval, i.e.: wind speed, air pressure, short-wave radiation, long-wave radiation, air temperature, precipitation and specific air humidity. Atmospheric CO_2 concentrations are required on a yearly time scale and a representative soil texture for the site is sufficient.

We evaluated the modifications to ORCHIDEE using output variables that are related to the carbon and energy balance, i.e.: Gross Primary Production (GPP), Net Ecosystem Exchange (NEE), Net Primary Production (NPP), respiration (R), sensible heat (H) and latent heat (LE).

In version r512, the C in ORCHIDEE is distributed over three main pools: (i) biomass, (ii) litter and (iii) soil carbon. These pools are divided into 8, 2 and 3 sub-pools, respectively. The biomass pool consists of leaves, roots, above- and belowground sapwood, above- and belowground heartwood, fruits (i.e. both flowers and fruits) and a carbohydrate reserve. The litter pool is composed of a structural and a metabolic litter pool. The former contains high-lignin litter, with a slow decay rate, while the latter contains low-lignin litter, which decays faster. The soil carbon consists of a fast, a slow and a passive pool, corresponding to the time it takes for the C in these pools to become biologically available again.

The soil water in r512 is simulated using two layers following the Choisnel scheme (Choisnel, 1977). The bottom layer is always present. The top layer is a dynamic layer that is absent in drier periods, and is created when it starts raining. When the top layer fills with rain, the layer expands as the soil profile becomes wetter and ultimately merges with the bottom layer.

The vegetation is classified into 12 plant functional types (Krinner et al., 2005) plus bare soil. In these plant functional types, plants with a similar physiology are grouped together. The

SRC simulations in this paper further develop the “temperate deciduous broadleaf forest” functional type.

As an extension to the standard version of ORCHIDEE, ORCHIDEE-FM was developed to include a number of adaptations for forest management (Bellassen et al., 2010). These adaptations include an age-related limitation of leaf area index (LAI) in young stands, an age-related decline in NPP, self-thinning in unmanaged stands and anthropogenic thinning in managed stands. The source code for this extended version can be found at http://forge.ipsl.jussieu.fr/orchidee/browser/perso/toon.degroote/orchidee_FM.

2.2. Model modifications to SRC

2.2.1 Management modifications

A first and essential modification was the ability to simulate multiple rotations, incl. the coppicing of the trees (Appendix A, teal sections, http://www.geosci-model-dev.net/8/1461/2015/gmd-8-1461-2015-supplement.pdf). Under SRC, the trees are not entirely harvested. A stump of approximately 10 cm is left, from which the trees can resprout (DEFRA, 2004). To account for this, the biomass of 10-cm long stumps is calculated using Equation 1, and remains in the aboveground woody biomass pool, instead of contributing to the exported biomass pool. Contrary to the thinning in ORCHIDEE-FM, only aboveground biomass is removed during the coppicing of a short rotation coppice.

$$f_{bm\_vol}\left(\sum \frac{L \cdot circ^2}{4\pi}\right) \quad \textbf{Equation 1}$$

where L is the length of the remaining stump (0.1 m), circ is the circumference of the individual shoot, which is a variable in ORCHIDEE-FM and f_{bm_vol} is an allometric function to calculate biomass from volume, as further described in section 2.2.2 and in Table 1.

A second modification was made for the cultivation regime at the site. In ORCHIDEE, trees start their lives as saplings. Contrary to forest tree plantations, SRC plantations are established using cuttings, i.e. 20-cm long hardwood sticks without any roots or leaves. The average carbon content of a cutting was estimated from the average volume and wood density to be 2.5 g of C. ORCHIDEE was modified to grow SRC from these cuttings (Appendix A, turquoise sections, http://www.geosci-model-dev.net/8/1461/2015/gmd-8-1461-2015-supplement.pdf). Half of this C is located in the aboveground sapwood pool of the cutting and the other half in the carbohydrate reserve. The number of cuttings per hectare can be defined in the configuration file when running the model.

Table 1: Conversion equations used for the SRC simulation in the ORCHIDEE-FM model and their parameter values. SRC = short rotation coppice culture.

Formula	Parameter	Value	Unit
$f_{vol\_bm} \rightarrow volume = \frac{biomass}{density}$	density	1.25e5	g C m^{-3}
$f_{bm\_vol} \rightarrow biomass = volume \cdot density$			
$f_{vol\_circ} \rightarrow volume = \sum \frac{a \cdot \left(\frac{circumference}{\pi}\right)^b}{density}$	density	1.25e5	g C m^{-3}
	a	0.033	
	b	2.6	
$f_{circ\_vol} \rightarrow circumference = \pi \cdot \left(\frac{volume \cdot density}{a}\right)^{1/b}$			
$f_{height\_circ} \rightarrow height = a \cdot circumference^b$	a	17.2684	
	b	0.6791	

2.2.2 Growth modifications

Because ORCHIDEE is a big leaf model and does not simulate individual trees, ORCHIDEE-FM uses allometric relations to convert and partition biomass. There are five conversion equations to convert stem biomass into stem volume, stem volume into stem biomass, circumference into stem volume, stem volume into circumference and circumference into height (Table 1; Appendix A, blue sections, http://www.geosci-model-dev.net/8/1461/2015/gmd-8-1461-2015-supplement.pdfThe functions f_{vol_bm}, f_{bm_vol}, f_{vol_circ}, and f_{circ_vol} are used to partition the biomass into circumference categories and to calculate the biomass of the initial hardwood cuttings from which the plantation is started. The function f_{height_circ} calculates the height from the circumference. This height is used to calculate LAI and roughness height. The roughness height is important in calculating the aerodynamic resistance. These standard relations were parameterized using data from the Boom site, one of the two SRC sites that we used for parameterization and evaluation (see 2.3.1).

After coppicing an SRC-tree resprouts as a multi-stemmed tree. This was incorporated into to the model as a second growth modification (Appendix A, violet sections, http://www.geosci-model-dev.net/8/1461/2015/gmd-8-1461-2015-supplement.pdf). The number of shoots with which the tree resprouts depends on the genotype. The variation in the number of stems resprouting after coppicing is very large, ranging from 1 to 25 (Dillen et al., 2013; Pontailler et al., 1999). Here, we adopted an average across the many genotypes of two stems after the first coppicing and four stems after the subsequent coppicing.

A final growth adaptation was made to the fine root growth. In ORCHIDEE, the senescence of the leaves and fine roots occurs simultaneously by the same phenological trigger. For SRC simulations, we decoupled the root mortality from the leaf senescence and included a turn-over time (Appendix A, yellow sections, http://www.geosci-model-dev.net/8/1461/2015/gmd-8-1461-2015-supplement.pdf). The poplar fine roots now stay alive for six months after their formation, an average lifetime observed in the field (Block et al., 2006; Coleman et al., 2000). The onset of fine root growth remains coupled with the phenological trigger for leaf growth.

2.2.3 Allocation modifications

A poplar tree can become sexually mature from the age of five onwards, depending on the genotype (Dickmann et al., 1983; Muhle Larsen, 1963). Because the duration of most SRC rotations is under five years, SRC-grown poplars will never produce flowers or seeds. The same holds for the sapwood to heartwood conversion. To account for this in the model, no carbon is allocated to the reproduction-pool (Appendix A, red sections, http://www.geosci-model-dev.net/8/1461/2015/gmd-8-1461-2015-supplement.pdf), and no aboveground sapwood is converted into heartwood (Appendix A, brown sections, http://www.geosci-model-dev.net/8/1461/2015/gmd-8-1461-2015-supplement.pdf) when the last coppicing was less than 5 years ago.

The tree species used in SRC plantations are fast-growing tree species that reach a large leaf area as fast as they can. The standard allocation to leaves in ORCHIDEE-FM is strictly constrained by the maximum leaf area index (LAI_{max}) for that year. This LAI_{max} evolves slowly, as the stand grows and the canopy closes. The high planting density and the different phenology of poplars in SRC plantations do not fit this scheme. Data show that for SRC plantations, this limitation is only present in the first one to two years. Therefore, we adapted LAI_{max} in the model such that it is only limited in the first year, and allowed to reach the plant functional type-specific LAI_{max} from year 2 onwards (Appendix A, green sections, http://www.geosci-model-dev.net/8/1461/2015/gmd-8-1461-2015-supplement.pdf).

After coppicing, poplar trees allocate almost no carbon to the growth of coarse roots. To simulate this effect, the trees in the extended ORCHIDEE model try to maintain a prescribed, structurally logical, root-shoot ratio. When the root-shoot ratio deviates from this prescribed ratio by more than 10%, such as after removal of the entire shoot biomass, 95% of the C allocated to wood production is allocated to the aboveground part (Appendix A, lime sections, http://www.geosci-model-dev.net/8/1461/2015/gmd-8-1461-2015-supplement.pdf).

2.2.4 Parameterization

The default parameters in ORCHIDEE were compared to measurements from the POPFULL site (see Sect. 2.3.2). A number of parameters (Table 2) were changed based on this comparison (Appendix A, pink sections, http://www.geosci-model-dev.net/8/1461/2015/gmd-8-1461-2015-supplement.pdf). Parameters that were in the range of the measured data were left unchanged. A first parameter is LAI_{max}. This is the maximal LAI that the trees can reach. The next two parameters $V_{c,max}$ (maximum carboxylation rate) and J_{max} (maximum electron transport rate) are photosynthetic parameters. When these parameters are higher, photosynthesis will be higher. Next, H_{root} is the exponential decay factor of the root profile. This parameter describes the distribution of the roots in the soil and therefore influences the water availability to the plant. Finally, $\rho_{leaf,SW}$ and , $\rho_{leaf,LW}$ are the short wave and long wave leaf albedo. These parameters determine how much of the incoming radiation is absorbed by the leafs and thus influence the energy uptake of the trees.

Table 2: Parameter values that where changed between the standard version of ORCHIDEE-FM and the adapted version for SRC simulation. LAI_{max} = maximal leaf area index, $V_{c,max}$ = maximum rate of carboxylation, J_{max} = maximum electron transport rate, H_{root} = exponential decay factor of the root profile, $\rho_{leaf,SW}$ = short wave leaf albedo, $\rho_{leaf,LW}$ = long wave leaf albedo.

Parameter	Unit	ORCHIDEE PFT 6	ORCHIDEE-SRC
LAI_{max}	$m^2\ m^{-2}$	4.5	2.5
$V_{c,max}$	$\mu mol\ m^{-2}\ s^{-1}$	55	130
J_{max}	$\mu mol\ m^{-2}\ s^{-1}$	70	180
H_{root}		0.8	1.5
$\rho_{leaf,SW}$		0.06	0.20
$\rho_{leaf,LW}$		0.22	0.30

2.3. Data description

2.3.1 Boom site

The Boom site was poplar-based SRC plantation operating from April 1996 until November 2011 in Boom, near Antwerp, Belgium (51°05’N, 4°22’E; 5 m above sea level). The plantation was established on a 0.56-ha former land fill, which was covered with a 2-m thick soil layer. Seventeen different poplar (*Populus spp.*) genotypes, belonging to six parentage lines, where planted in April 1996 in a double-row design with inter-row distances of 0.75 m and 1.50 m and a spacing of 0.90 m within the rows, resulting in a planting density of 10,000 cuttings ha^{-1}. The plantation was harvested in December 1996, January 2001, February 2004, February 2008 and November 2011, i.e. one establishment year and four subsequent rotations of each 4 years, 3 years, 4 years and 4 years, respectively.

At this site dendrometric measurements included aboveground biomass, tree height and circumference at 22 cm above ground level. A more complete description of the site and the plant materials has been provided by Laureysens et al. (2003) and Casella and Ceulemans (2002). The evolution of growth, biomass production and yield has been described in detail by Dillen et al. (2011) and Dillen et al. (2013).

2.3.2 POPFULL site

The operationally managed POPFULL site was established in April 2010 in Lochristi, near Ghent, Belgium (51°07’N, 3°51’E; 6 m above sea level), on 18.4 ha of former pasture and cropland. Twelve different poplar (*Populus spp.*) genotypes and 3 willow (*Salix spp.*) genotypes were planted in a double-row design with inter-row distances of 0.75 m and 1.50 m and a spacing of 1.10 m within the rows, resulting in a planting density of 8,000 cuttings ha^{-1}. The plantation was harvested for the first time in February 2012.

At this site, an eddy covariance tower was erected (Zona et al., 2014; Zona et al., 2013a; Zona et al., 2013b). The height of the tower varied between 3 m and 6 m, depending on canopy height. From this tower, CO_2 and H_2O fluxes were measured. Furthermore, leaf phenology was monitored and LAI was regularly measured. Soil temperature and soil moisture were also monitored during 2011. At the end of each growing season, the biomass production was estimated from stem circumference measurements and site-specific allometric relations.

A complete description of this site is given in Broeckx et al. (2012), while the eddy covariance flux measurements have been described in detail by Zona *et al.* 2014); 2013a); 2013b) and the carbon budget was calculated by Verlinden et al. (2013b).

2.3.3 European biomass sites

For the evaluation of aboveground standing woody biomass production across Europe, we used biomass measurements found in Djomo et al. (2015). From their list of sites, we selected the 23 sites that were not irrigated and had poplar trees (Table 3).

Because meteorological data of sufficient resolution and a detailed site description for these sites were not available, we could not perform a site-by-site comparison. Therefore, we collected meteorological data from 22 different European sites in a similar geographical range on the European Fluxes Database Cluster (http://gaia.agraria.unitus.it/, 1 September 2014) to run our simulations. This way we could compare the range and trend of aboveground woody biomass production along the latitudinal gradient, as well as along the annual precipitation gradient and the average annual temperature gradient.

We selected sites with a public data access and open data use policy, for which data was available for a minimum of five years (Table 3). Using this meteorological data, we ran the model for 20 years, to calculate the mean annual aboveground standing woody biomass production. For these simulations we chose a planting density of 10,000 trees ha^{-1} and a rotation cycle of 2 years.

2.4. Simulation setup

Before running the actual simulations, a spinup was run to initialize the soil carbon pool for every site. For this spinup the model was used without SRC modifications, with the standard “temperate deciduous broadleaf forest” plant functional type. This spinup is performed by running the model with the available input data repeatedly, until a soil carbon equilibrium is reached. Because this takes a very long time, a part of this spinup is executed with simplified versions of the model, i.e. teststomate and forcesoil. Teststomate deactivates sechiba, thus only running the daily processes, instead of half-hourly processes, hereby accelerating the model 48 times, reaching a steady state for the non-soil carbon pools. Forcesoil only uses the ORCHIDEE's soil carbon module, reaching a steady state for the soil carbon pools.

For this spinup, the model was first run for 20 years, followed by 50 years with teststomate. This was repeated three times. Thereafter, the model was run for 40 years, followed by 1000 years with forcesoil and finally another 260 years of the full model. This accumulates to a

Table 3: Biomass evaluation site info for the simulated sites, acquired from the European Fluxes Database Cluster (http://gaia.agraria.unitus.it/, 1 September 2014) and the measured sites, acquired from (Djomo et al., 2015).

Simulations						Measurements					
Country	Site name	Latitude	Longitude	Annual temp °C	Annual precip mm	Country	Site name	Latitude	Longitude	Annual temp °C	Annual precip mm
PT	Mitra IV (Tojal)	38.48 N	8.02 W	14.2	588	IT	Caramagna piemonte	44.47 N	7.44 E	12.5	700
ES	Las Majadas del Tietar	39.94 N	5.77 W	16.1	721	IT	Lombriasco	44.51 N	7.38 E	13.0	650
IT	Collelongo	41.85 N	13.59 E	7.3	1160	CZ	Nová Olešná	49.17 N	15.16 E	7.2	730
IT	Roccarespampani 1	42.41 N	11.93 E	15.6	840	CZ	Bystřice	49.21 N	12.48 E	5.7	800
FR	Mauzac	43.39 N	1.29 E	12.7	566	CZ	Smilkov	49.36 N	14.36 E	6.8	650
IT	San Rossore	43.73 N	10.28 E	15.2	921	CZ	Rosice	50.03 N	15.42 E	8.5	500
FR	Puechabon	43.74 N	3.6 E	13.6	894	DE	Arnsfeld	50.34 N	13.06 E	7.0	625
IT	Lavarone	45.96 N	11.28 E	6.9	1263	DE	Großschirma	50.57 N	13.17 E	7.2	820
IT	Renon	46.59 N	11.43 E	4.5	1219	DE	Krummenhennersdorf	50.98 N	13.36 E	7.2	820
AT	Neustift	47.12 N	11.32 E	6.8	700	BE	Zwijnaarde	51.02 N	3.43 E	9.8	821
CZ	Laegern	47.48 N	8.37 E	7.7	777	BE	Boom	51.05 N	4.22 E	11.1	824
DE	Wetzstein	50.45 N	11.46 E	6.5	971	BE	Lochristi	51.06 N	3.51 E	9.5	726
DE	Klingenberg	50.89 N	13.52 E	7.6	801	DE	Commichau	51.08 N	12.50 E	8.5	680
DE	Grillenburg	50.95 N	13.51 E	8.5	975	DE	Skäßchen	51.20 N	13.35 E	8.5	575
DE	Tharandt	50.96 N	13.57 E	8.6	871	DE	Großthiemig	51.22 N	13.4 E	8.5	575
DE	Hainich	51.08 N	10.45 E	8.3	779	DE	Thammenhain	51.25 N	12.51 E	8.5	575
BE	Brasschaat	51.31 N	4.52 E	10.6	848	DE	Nochten	51.25 N	14.36 E	8.5	650
UK	Pang/Lambourne forest	51.45 N	1.27 W	12.3	658	DE	Vetschau	51.46 N	14.04 E	8.5	550
NL	Loobos	52.17 N	5.74 E	10.0	872	DE	Methau I	51.50 N	12.51 E	8.1	690
DK	Soroe	55.49 N	11.64 E	8.4	760	DE	Methau II	51.50 N	12.51 E	8.1	690
RU	Fyodorovskoye	56.46 N	32.92 E	5.1	524	DE	Kuhstorf	53.23 N	11.15 E	8.2	616
FI	Hyytiälä	61.85 N	24.3 E	4.1	555	DE	Laage	53.55 N	12.20 E	8.0	630

total of 1510 years, of which 360 were run with the full model. The end state of the spinups is then used as initial state for the actual simulations.

For the simulation of the POPFULL site, the soil fractions where set to the average of the measured data (86% sand, 3% silt, 11% clay). For the Boom site, no texture data were available. Being a former land fill, the soil description for this site was very imprecise, mentioning only the broader texture classes, loam, sandy loam and silt loam. Therefore, the standard texture values (49% sand, 29% silt, 22% clay), which correspond to loam, were used for the Boom site. The number of cuttings was set to 8000 ha^{-1} for the POPFULL site and 10 000 ha^{-1} for the Boom site. The soil depth was set to 1 m for both sites.

2.5. Data processing

On the POPFULL site, meteo data for 2010 and 2011 were collected together with the eddy covariance flux data. Since the measurements did not start until June 2010, this gap was filled using data from a nearby station (Melle) from the Royal Meteorological Institute (RMI). For the Boom site, meteo data were used from a nearby field site (Brasschaat).

For the POPFULL site, measured eddy covariance fluxes (GPP, R_{eco}, NEE, H and LE) were used to evaluate the model outputs. These data were not related to the data that were used to calibrate the model. NEE, H and LE were measured directly by the eddy covariance technique, but for GPP and R_{eco} an approximation had to be calculated using flux-partitioning. Here, GPP and R_{eco} were calculated using the online eddy-covariance gap-filling and flux-partitioning tool of the Max Planck Institute for Biogeochemistry (Max Planck Institute for Biochemistry, 2005), which is based on the standardized methods described in Reichstein et al. (2005).

To quantify the model fit of the modelled fluxes with the measured data, three statistical criteria for model efficiency were evaluated using the half hourly data. The coefficient of determination (R^2), the normalised root mean square error (NRMSE) and a Pearson correlation coefficient (PCC) were calculated. The root mean square error was normalised by dividing it by the range of values of the measured variable.

R^2 explains the variance in model performance by comparing it to the data variation. The NRMSE gives a measure for the accumulated model error. The PCC shows how well the data is correlated. While R^2 and PCC give a measure for how well the trends in the data are simulated, NRMSE gives a measure for the total cumulated model error.

To visualise the model fit, the modelled fluxes were plotted against the measured weekly averages.

To compare the total fluxes, the half hourly data were cumulated. Since there were no flux measurements before June 2010, this gap was filled with the modelled data.

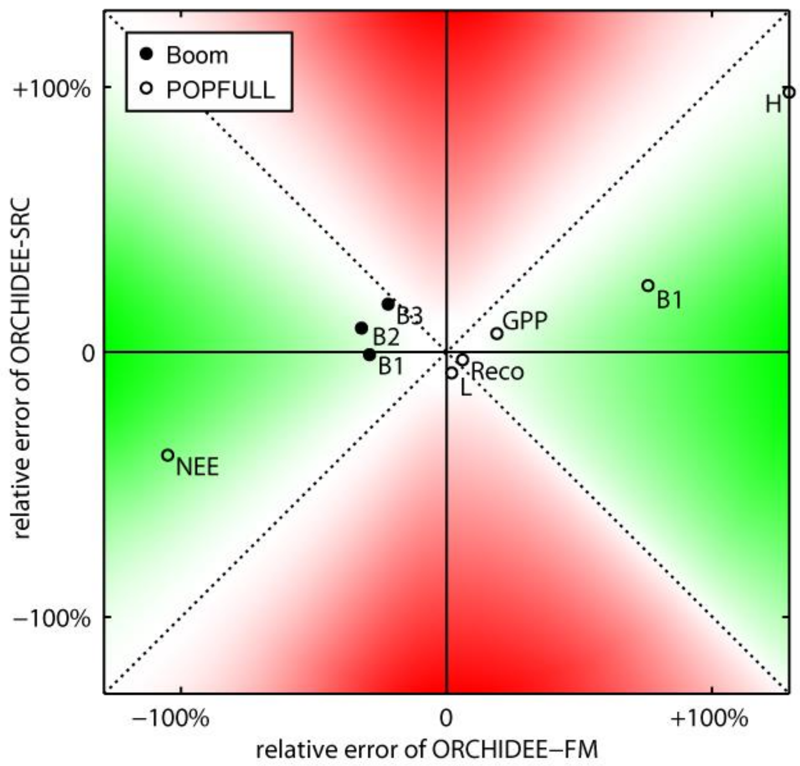

Figure 1: Comparison between the performance of the ORCHIDEE-SRC and ORCHIDEE-FM. The relative error was calculated as the relative difference between the field measurements and the model simulations. The green background indicates an improvement by the extended model relative to ORCHIDEE-FM, the red background indicates a deterioration of the model results from the extended model. A darker colour indicates a more pronounced difference. The Boom site simulations are shown as filled circles and the POPFULL site simulations are shown as open circles. The letters next to the symbol are: GPP = gross primary productivity cumulated over the two measurement years; Reco = ecosystem respiration cumulated over the two measurement years; NEE = net ecosystem exchange cumulated over the two measurement years; L = latent heat cumulated over the two measurement years; H = sensible heat cumulated over the two measurement years; Bx = aboveground woody biomass production of rotation x.

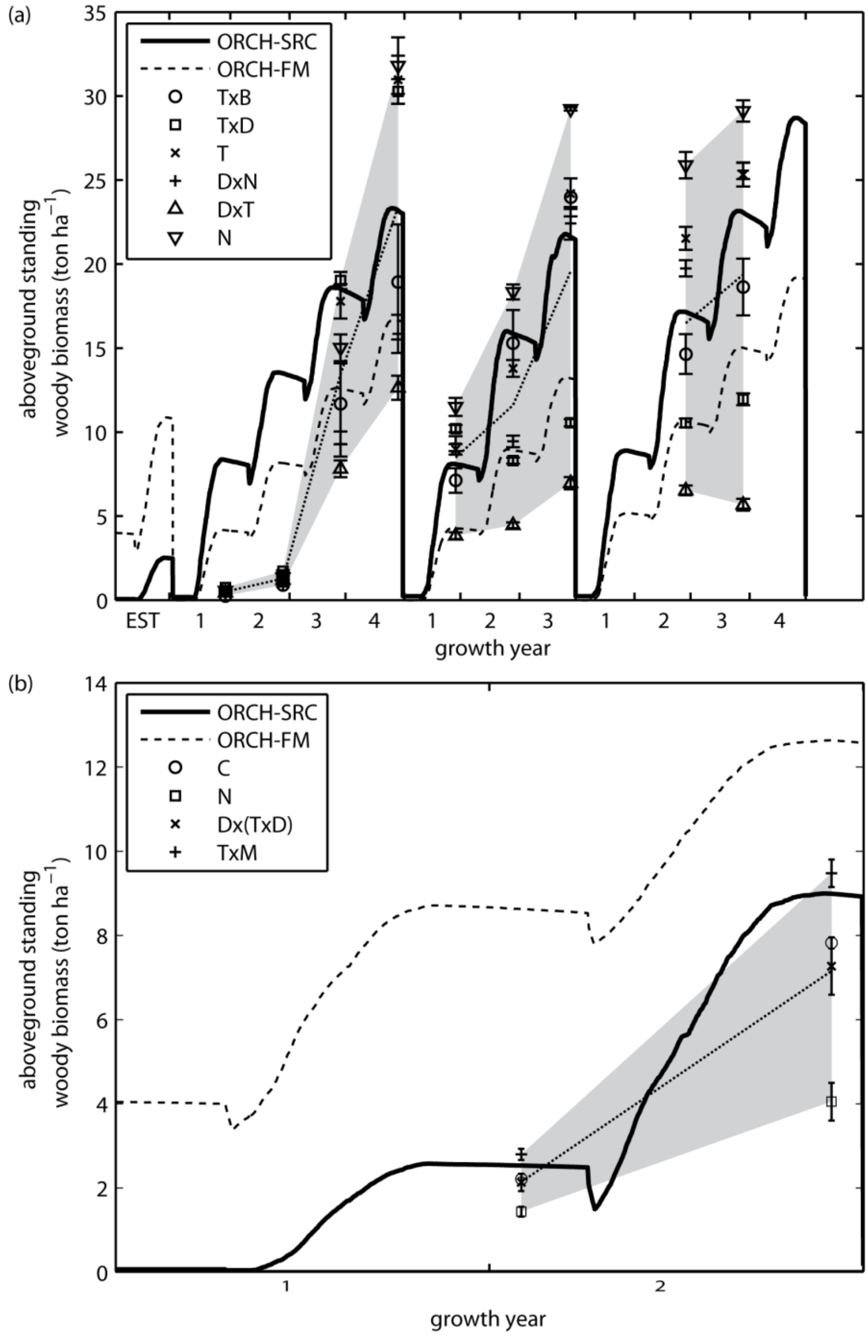

Figure 2: The simulated standing aboveground woody biomass (a) for the Boom site and (b) for the POPFULL site. The solid black line is the biomass simulated by the extended model, ORCHIDEE-SRC. The dashed line is the biomass simulated by the standard version of ORCHIDEE-FM, with only coppicing implemented. The symbols are the different parentages of the poplars at that site and the grey area is the range of measured biomasses. The parentages are *Populus trichocarpa* × *P. balsamifera* (T×B), *P. trichocarpa* × *P. deltoides* (T×D), *P. trichocarpa* (T), *P. deltoides* × *P. nigra* (D×N), *P. deltoides* × *P. trichocarpa* (D×T), *P. nigra* (N), *P. canadensis* (C), *P. deltoides* × (*P. trichocarpa* × *P. deltoides*) (D×(T×D)), *P. trichocarpa* × *P. maximowiczii* (T×M).

3 Results & Discussion

The relative impact of the model modifications on the accuracy of the model simulations by the extended model, ORCHIDEE-SRC, relative to ORCHIDEE-FM is presented in Figure 1. Biomass production and all fluxes were simulated better or equally well by the extended model. Figure 2 also shows the improvement in the simulation of biomass production compared to ORCHIDEE-FM. Detailed analysis of the model simulations of biomass production, carbon fluxes, energy fluxes and soil parameters are given in the sections below.

3.1. Biomass evaluation

3.1.1 Site level

For the Boom site, the yearly aboveground biomass measurements were compared to the model output (Figure 2a). From the third year of the first rotation onwards, the model predictions were well within the range of measured values and approximate the average aboveground woody biomass production. Measurements were available for 17 genotypes, hence the wide range in observations. The low measured values in the first two years might be explained by strong competition from weeds, which was observed in the starting years of this plantation (personal communications with R. Ceulemans, 2013). The low values for the year 1998 – a cold wet year – are explained by a severe rust infection at the site (Al Afas et al., 2008).

The modelled aboveground biomass for the POPFULL site was also well within the measured ranges (Figure 2b), although the prediction for the first year was in the lower limits of the range.

3.1.2 Europe

Since we couldn’t simulate the same sites as we collected measurements for, we compared the average annual aboveground standing woody biomass for the sites across Europe based on their latitude, average annual temperature and average annual precipitation (Figure 3).

The simulations were within the range of the measured values and followed their general trends. When comparing with latitude, increasing latitudes increase biomass production up to around 55°N. The biomass production of simulations for latitudes above 55°N start declining again, but can’t be compared to measurements, because of lacking data (Figure 3a). Increasing temperatures have a negative effect on aboveground woody biomass production for both the measurements and the simulations (Figure 3b). This is probably caused by the negative relation between temperature and precipitation. The simulated aboveground biomass production increases slightly with increasing precipitation (Figure 3c). This trend is also shown by the measured data, except for two high producing sites in the low precipitation range.

Generally, the measured data had a higher spread, which could be explained by variable factors we could not account for in the general modelling approach. Such factors could include genotype selection, weed competition, rotation length, planting density, etc.

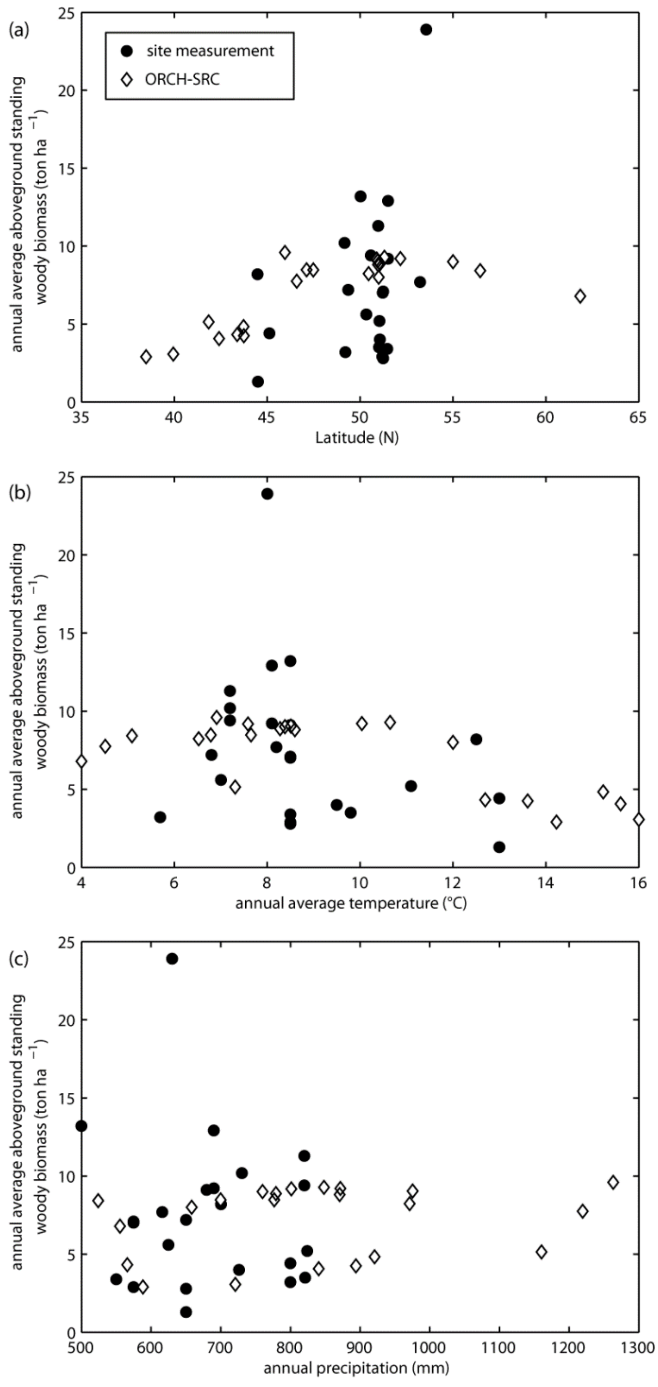

Figure 3: Comparison of aboveground standing woody biomass for ORCHIDEE-SRC simulations (open diamonds) across Europe with site measurements (black circles) across Europe. The biomass is plotted against (A) latitude, (B) annual average temperature and (C) annual precipitation.

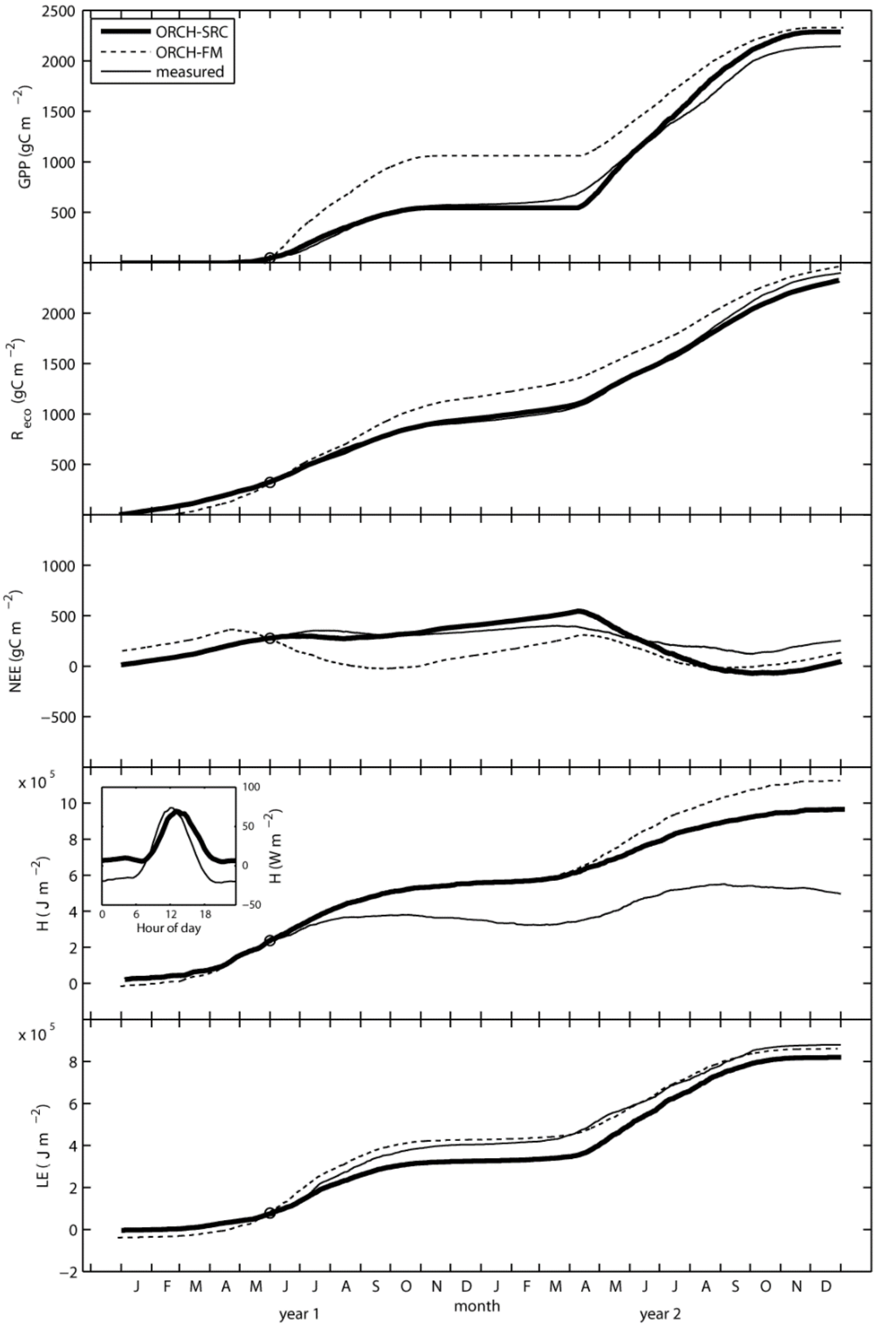

Figure 4: Cumulative fluxes of gross primary production (GPP), ecosystem respiration (R_{eco}), net ecosystem exchange (NEE), sensible heat (H) and latent heat (LE) for the POPFULL site. The insert in the graph for sensible heat flux shows the average diurnal cycle of the sensible heat flux. The thin solid lines are the measured values from the eddy-covariance measurements or recalculated from these measurements using the flux-partitioning tool of the Max Planck Institute for Biogeochemistry (Max Planck Institute for Biochemistry, 2005). The dashed line are the model outputs using the standard model ORCHIDEE-FM. The solid thick lines are the model outputs using the modified model

ORCHIDEE-SRC. Since there were no flux measurements before June 2010, both simulated and measured values coincide before that date.

3.2. CO_2 flux evaluation

The measured C and energy fluxes at the POPFULL site were compared to the model outputs. Figure 4 depicts both the simulated and observed cumulative GPP, NEE, H, LE and R_{eco}.

During the first year, the calculated and observed GPP values matched well (R^2 = 0.78, NRMSE = 0.064, PCC = 0.89; Figure 4). In winter, measured values established a slight increasing trend, while GPP remained constant in the model outputs. This could either be explained by photosynthesis of weeds, which are not represented in the model, or by errors in the flux partitioning. During the second year, the modelled GPP started rising about one month later than the measured values, but thereafter caught up with the measurements (Figure 4). Again, this difference might have been caused by the presence of weeds in the field, which were not accounted for in the model. Another reason for these differences could be the use of different genotypes at the field site, while the model only simulates an average genotype. In 2011, the spring bud flushing date of the different genotypes ranged from day 72 until day 107, which is about a one month difference. The modelled bud flush started on day 97, which is well within this observed range, but logically results in a lag of 25 days between observed and simulated date of onset of GPP. After two years, the cumulated GPP values were 23.0 Mg C ha^{-1} and 21.4 Mg C ha^{-1} for the model and the measurements, respectively. This difference of 1.6 Mg C ha^{-1}, represents an overestimation by the model of only 7%, well within the uncertainty of eddy covariance-based GPP estimates (Desai et al., 2008; Richardson et al., 2006).

The modelled R_{eco} fitted the measurements very well (R^2 = 0.95, NRMSE = 0.078 PCC = 0.91). The only point of divergence was the dry spell in the summer of the second year. Here, R_{eco} was underestimated, probably because the model is too sensitive to drought. The accumulated R_{eco} for the first rotation based on observations was 24.0 Mg C ha^{-1}, while the model predicted 23.3 Mg C ha^{-1}; an underestimation of only 3%.

C is taken up by photosynthesis (GPP) and emitted through respiration (R_{eco}). The resulting net flux is NEE. Small errors in GPP and R_{eco} might therefore accumulate in NEE giving it a worse fit. When comparing NEE, the fit is less good than for GPP and R_{eco} (R^2 = 0.51, NRMSE = 0.069, PCC = 0.84. In the model results, the plantation switched from emitting C to taking up C in July of the first year. In the measured data, this switch occurred only during August, possibly because of the increased C loss due to the land use change after the plantation establishment (Zona et al., 2013a). During the winter and spring of the second growing season, both the simulated and the measured fluxes indicated a net loss of CO_2, but the simulation suggested a stronger source. This difference could probably be explained by the presence of weeds on the site, which were not present in the model simulation. The photosynthesis of these weeds partly counteracted the C losses from soil respiration. From August until October, both the model and the measurements indicated a C uptake. The model, however, presented a stronger C sink than the measurements. From October onwards, both modelled and measured data showed a C source. At the end of the second year, the end of the first rotation, the measurements showed a cumulated net C loss of 5.4 Mg ha^{-1}, while the model only predicted a C loss of 3.3 Mg ha^{-1}. The model underestimated the C loss to the atmosphere by 39%.

A good fit for GPP and R_{eco} is, however, more important than an accurate simulation of NEE, because they are the real (and large) physical fluxes that occur in the field, and are simulated by the model. Also the soil C loss was simulated adequately. The measured soil C loss was 700 g m^{-2} for the top 15 cm (Verlinden et al., 2013a), while the model predicted a soil C loss of 740 g m^{-2} over the first rotation.

3.3. Water and energy flux evaluation

For H, the cumulative plot (Figure 4) shows diverging lines and an overestimation of 120% of the cumulative energy loss from H at the end of the rotation (R^2 = 0.36, NRMSE = 0.057, PCC = 0.71). The error is probably caused by a stable stratification that often develops in dense plantations at night. Because of this stratification the measured sensible heat flux at night is lower than the simulated flux. The averaged diurnal pattern shown in the insert of Figure 4 clearly shows this discrepancy. The stratification cannot be represented correctly by the calculation of surface drag, in the way it is implemented in ORCHIDEE. This problem did already exist in the model, as described by Krinner et al. (2005). Because H has no impact on the C or water cycle in the model algorithms, this problem was not considered an issue in this study.

During the first growing season, LE increased slower in the model than can be observed in the measured data (R^2 = 0.68, NRMSE = 0.055, PCC = 0.78; Figure 4). This might be explained by the LAI. The modelled LAI (LAI_{max} 0.75) for the first year was on the lower end of the measured LAI ranges (LAI_{max} 0.6 – 1.8). This lower leaf area consequently resulted in a lower leaf surface to evaporate water from. From November of the first year onward, the cumulative LE curves of the simulations and the measurements keep running in parallel, except for a small period during the second year. This was caused by a dry spell during August. The model slightly underestimated the effect of the drought, allowing the trees to transpire more water. This can be observed in Figure 5, as the six highlighted dots that represent the six dry weeks that are marked in Figure 6b. At the end of the rotation, this resulted in a cumulative LE of 880 kW m^{-2} for the measurements and 806 kW m^{-2} for the model, which is an underestimation of 8% by the model.

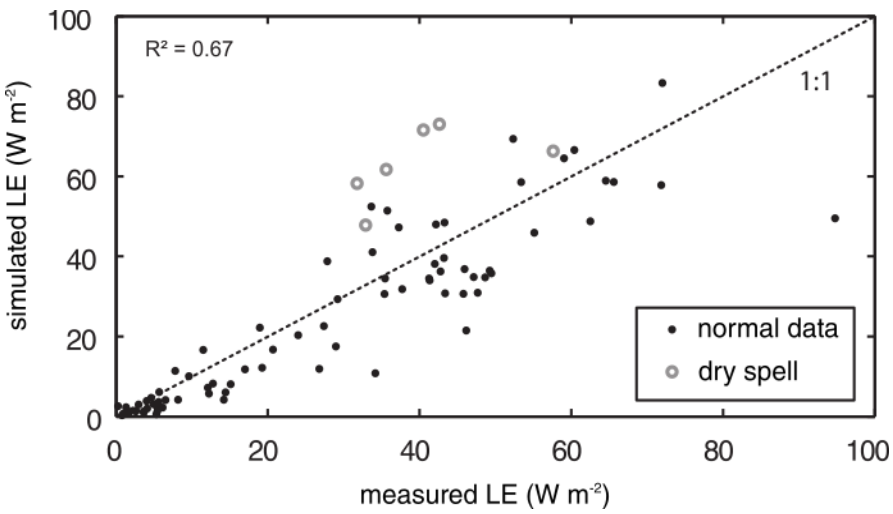

Figure 5: A 1-to-1 comparison of weekly averages of latent heat (LE) for the POPFULL site, between the model outputs and the measured values. The dotted line is the 1:1 line. Weeks 18-23 which represent the dry spell are highlighted as grey circles.

3.4. Evaluation of soil variables

Figure 6a shows the measured and modeled soil temperature during 2011 for the POPFULL site. This is the only data we had available on soil temperature. This data shows that the soil temperature was simulated very well by our model (R^2 = 0.955, NRMSE = 0.098, PCC = 0.907).

For soil moisture, ORCHIDEE only has two soil compartments, of which one is only present after rainfall (Figure 6b). We compared the total simulated soil water content to the average measured soil water content of the top 50 cm of soil, which had a reasonable fit (R^2 = 0.976, NRMSE = 0.152, PCC = 0.828). Due to the simplicity of the implementation of soil moisture in ORCHIDEE, the model cannot simulate the level of detail that is shown by the measurements. The model does, however, very clearly show the decline of soil water content during the dry spell, and the replenishment of the top layer with the precipitation after the dry spell.

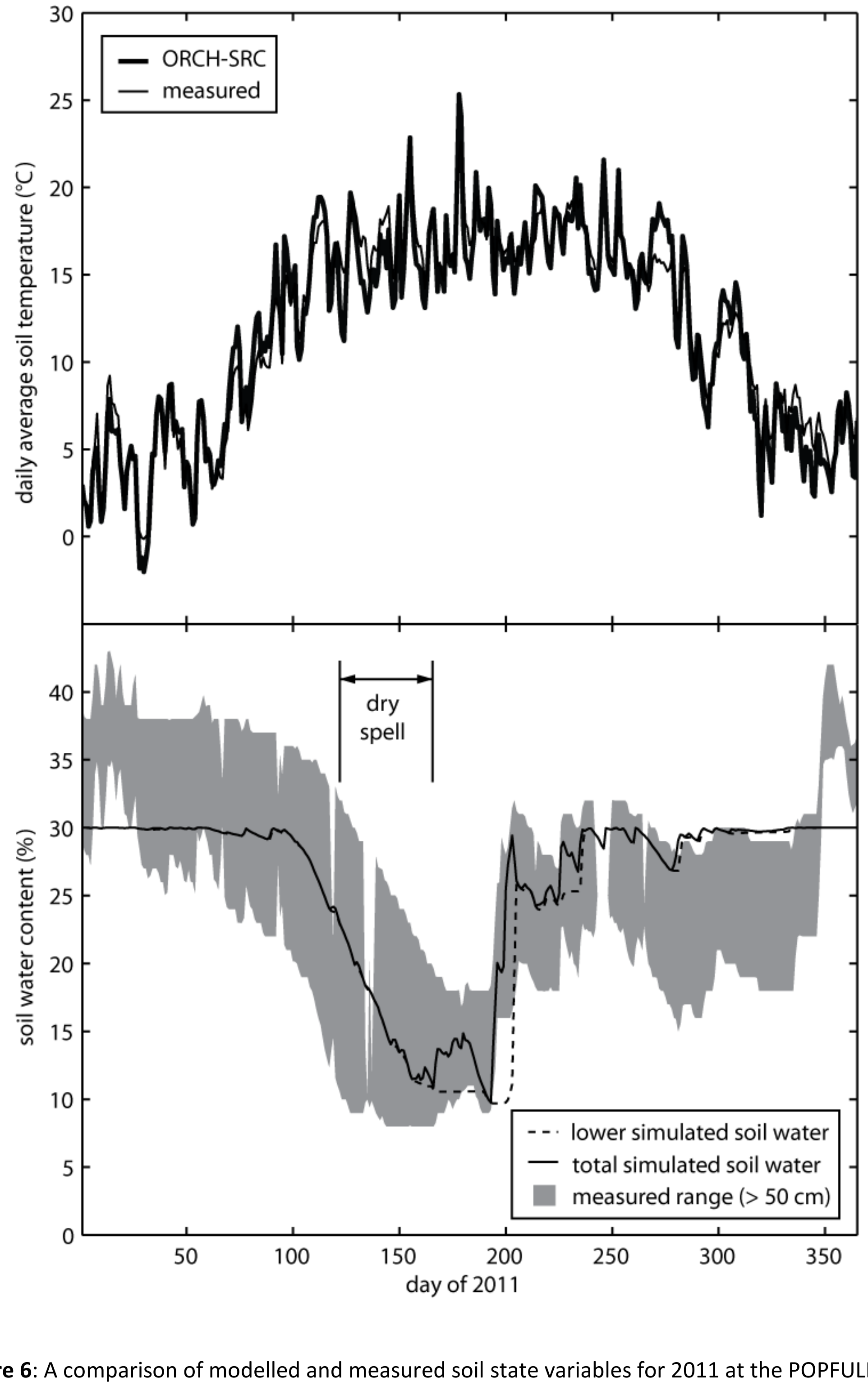

Figure 6: A comparison of modelled and measured soil state variables for 2011 at the POPFULL site. (A) shows the daily average soil temperature simulated (fat) and measured (thin). (B) shows the soil water content. The grey area represents the measured range of soil water content values for the top 50 cm of the soil. The dotted line is the soil water content of the lower soil water compartment of the model and the solid line is the total soil water content of the upper and lower soil water compartments.

4 Conclusion

Our model evaluation shows that the modifications to the model ORCHIDEE presented in this paper perform well to predict aboveground harvestable woody biomass. Also gross primary production (R^2 = 0.78, NRMSE = 0.064, PCC = 0.89) and ecosystem respiration (R^2 = 0.95, NRMSE = 0.078 PCC = 0.91) were simulated very well. Also soil temperature and soil moisture are simulated adequately, but due to the simplicity of the soil moisture simulation, there are some discrepancies, which also influence the simulation of the latent heat flux. The annual latent heat flux was, however, simulated reasonably well. Overall the ORCHIDEE-SRC version of the ORCHIDEE model is very well suited to simulate biomass production in SRC plantations.

The research leading to these results has received funding from the European Research Council under the European Commission's Seventh Framework Programme (FP7/2007-2013) as ERC grant agreement n°. 233366 (POPFULL), the Flemish Hercules Foundation as Infrastructure contract ZW09-06, the Flemish Methusalem Programme, the Research Council of the University of Antwerp, and the Research Foundation – Flanders (FWO; DOFOCO project). We gratefully acknowledge the excellent technical support of Joris Cools and the logistic support of Kristof Mouton at the field site. T. De Groote is a Ph. D. fellow of the Research Foundation – Flanders (FWO) and the Flemish Institute for Technological Research (VITO).

Chapter 2 Combining carbon modeling and LCA for optimizing the management of short rotation coppice in Belgium

To be submitted to Biomass & Bioenergy

Short rotation coppice (SRC) systems are a promising renewable energy candidate. Site managers typically optimize biomass production at their sites. However, maximal biomass production does not necessarily equal optimal CO_2 balance, nor optimized energy yield. This is because many operational actions produce CO2 and consume energy, either on site or off site. Coupling a land surface model (ORCHIDEE-SRC) to a life cycle analysis enabled us to determine the optimal management for SRC. We simulated 120 different management scenarios for each of two Belgian SRC sites (in Boom and Lochristi). Our results show that in Belgium, optimal management of SRC has short rotations of two years and no irrigation. Planting density turned out to be not important. Proper site selection, however, showed to be more important than proper management selection, as inter-site differences were larger than the effects of management.

1 Introduction

Short rotation coppice (SRC) is a promising addition to the suite of renewable energies (Aylott et al., 2008; Berndes et al., 2003; IEA, 2007a; Rowe et al., 2009). It does, however, need to be implemented properly and thoughtfully. The use of SRC wood for energy production is portrayed as a CO_2 neutral process (Righelato et al., 2007), because CO_2 emitted into the atmosphere by biomass burning was first sequestered from the atmosphere through tree growth. There are, however, a number of factors that influence this carbon balance. SRC plantations are established, managed and harvested using agricultural and forestry machines. The establishment includes ploughing, weeding and the planting of cuttings. These cuttings have to be transported from a nursery to the plantation and the harvested biomass has to be transported from the plantation to the energy plant. The machinery involved in all these steps uses fossil fuels and therefore emits CO_2 when operating, adding to the non-biogenic carbon costs of SRC. Thus, SRC-derived bioenergy is not entirely CO_2 neutral, and the selection of the most suitable management for a given SRC is very important because it will determine both the CO_2 balance and the biomass production.

Not only the CO_2 balance and biomass production is of importance when considering the management of SRCs. Also the water use and net energy balance of the SRC plantation are key in determining the optimal management. In water-limited regions irrigation might be necessary to achieve high yields in SRC plantations, which has consequences for the region’s water availability and the environment (Hughes et al., 2007). Moreover, irrigation requires energy. From an energetic point of view, it is important not to invest more energy than the energy contained in the produced woody biomass, as this would reduce the energy efficiency of the SRC system (Djomo et al., 2015).

In Europe, many SRC systems are based on the Swedish double-row configuration, which facilitates the use of agricultural equipment with a density of 10,000-20,000 cuttings per hectare (Abrahamson et al., 2002). Factors such as rotation length, soil type, climate conditions and desired dimensions of the end products affect the initial planting density (Keoleian & Volk, 2005). Consequently, failure to match the SRC varieties and planting site characteristics, with the planting densities, irrigation volumes, and rotation cycles could reduce the sustainability of the system (i.e. reduce the net energy yield or increase carbon emissions). Based on two well-documented SRC plantations in Belgium, the aim of this study is to identify the optimal management scenario for SRC production in Belgium, taking into account all on-site and off-site energy, CO_2 costs and assuming the wood will be used for bioelectricity production.

2 Materials & Methods

2.1. Site descriptions

Two well-studied and well-documented SRC plantations are used here as case studies to identify optimal management.

2.1.1 Boom site

The Boom site was an operational SRC plantation from April 1996 until November 2011 in Boom, Belgium (51°05′N, 4°22′E; 5 m above sea level). Seventeen different poplar (*Populus spp.*) genotypes, belonging to six parentage lines, were planted on a 0.56-ha former landfill (Dillen et al., 2013). The trees were planted as cuttings in a double row design with inter-row distances of 0.75 m and 1.50 m and intra-row spacing of 0.90 m, resulting in a planting density of 10,000 cuttings ha^{-1}. The climograph of the measured years on the Boom site (Figure 1a) shows that the average annual temperature on the site was 11.1 °C and the average annual precipitation was 799 mm. The former landfill was covered with a loam soil. There was no irrigation or fertilization applied on this site. A more complete description of the site and the plant materials has been provided elsewhere (Casella et al., 2002; Laureysens et al., 2003). The evolution of growth, of biomass production and of yield has been described in detail by Dillen et al. (2013; 2011).

2.1.2 Lochristi site

The Lochristi site is an operational SRC plantation since April 2010 in Lochristi, Belgium (51°07′N, 3°51′E; 6 m above sea level). Twelve different poplar (*Populus* spp.) genotypes and three willow (Salix spp.) genotypes were planted on 18.4 ha of former pasture and cropland. The trees were planted as cuttings in a double row design with inter-row distances of 0.75 m and 1.50 m and intra-row spacing of 1.10 m, resulting in a planting density of 8000 cuttings ha^{-1}. The climograph of the measured years on the Lochristi site (Figure 1b) shows that the average annual temperature at the site was 10.6 °C and the average annual precipitation was 796 mm. The soil consists of loamy sand. There was no irrigation or fertilization applied on this site. A complete description of this site has been previously published (Broeckx et al., 2012). Eddy covariance flux measurements of all greenhouse gases have been described in detail by Zona et al. (2014; 2013a; 2013b) and the plantation's carbon budget was calculated by Verlinden et al. (2013b).

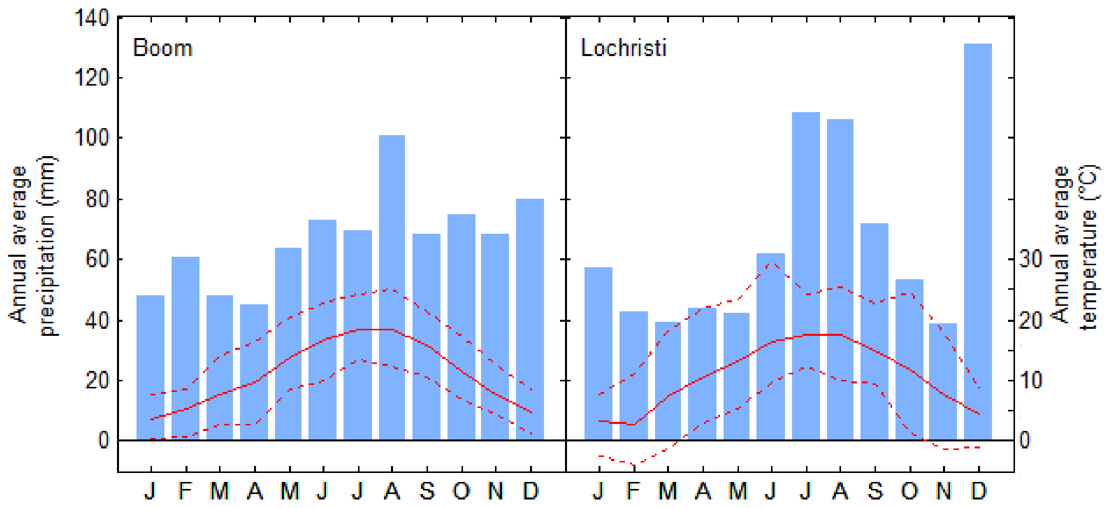

Figure 1: Climograph of the Boom site and the Lochristi site. The blue bars give the average monthly precipitation during the measured years (Boom: 1996-2007, Lochristi: 2010-2012). The solid red line gives the average temperature for these years and the dashed lines give the maximum and minimum monthly temperatures.

2.2. Management scenarios

For both sites, a number of different management scenarios were simulated using the ORCHIDEE-SRC model (see 2.5 and 2.6). In these management scenarios, four management options were varied. (i) Planting density varied from 5,000 trees ha^{-1} in steps of 5,000 up to 15,000 trees ha^{-1}. (ii) Rotation length varied from two years up to five years in steps of one year, and (iii) optionally the first cutback was performed at the end of the establishment year, instead of the year specified by the rotation cycle. After this optional establishment year cut the normal rotation cycle was started. (iv) Irrigation was added from 0 up to 200 mm year^{-1}, in steps of 50 mm year^{-1}. The total irrigation volume was divided by the number of applications. This volume was applied weekly from April until September, independent of rainfall, assuming sprinkler irrigation. This results in a total of 120 different management scenarios. For each site, each of these 120 management scenarios was simulated for 20 years.

2.3. Operational energy and CO_2 costs

Operating an SRC plantation is more intensive than traditional forestry. All these management actions consume energy and thus emit CO_2. For this study, the following actions were accounted for: First the cuttings are transported to the plantation from a supply station over a distance of 150 km. This transport cost is dependent on the transported weight. One cutting weighs 10 g. The soil is prepared by ploughing, mechanical weeding, and a chemical herbicide application. After the soil preparation, the cuttings are planted using a leek planter. Although the cuttings were planted manually in Boom, for fair comparison, it is assumed that both sites are planted using a leek planter. During the growing seasons, irrigation is applied according to the chosen management scenario. At the end of the designated years, the plantation is harvested with a modified corn harvester and the cuttings are transported to a power station 50 km from the plantation. Chemical herbicide is applied again to prevent weed growth during the sprouting of the new stems.

Costs were quantified both as CO_2 emissions and as non-renewable energy required for biomass production. The costs were quantified from the Ecoinvent 2.1 (Frischknecht et al., 2007) database using Simapro 7.1 (PRé, 2007) and are visualised in Figure 2.

2.4. Energy substitution

The carbon emission saving from substituting grid mix electricity with the energy from the SRC wood was quantified by comparing the produced bio-electricity with an equal amount of electricity from grid mix. For this calculation, an energy density of 18.5 MJ kg^{-1} (higher heating value of poplar wood) (Di Nasso et al., 2010) was used. The wood was converted into electricity in a biomass gasification plant with an electrical conversion efficiency of 37.2% (Mann et al., 1997). The estimated greenhouse gas (GHG) emissions of the European non-renewable grid mix electricity are 564 g CO_{2e} kWh^{-1} (Djomo et al., 2013). This estimate was obtained by calculating the emission factors of the different energy producing systems in Europe multiplied by their relative fractions in the European grid mix. If we assume that the carbon content of dry biomass is 50%, then the energy production per emitted g CO_2 becomes 3.75 kJ gCO_2^{-1} for the SRC wood and 6.38 kJ gCO_2^{-1} for the European grid mix electricity. For the grid mix electricity, a full LCA is included in this number (Djomo et al., 2013). For biomass burning, the LCA part was calculated for each management scenario and for each site separately.

Energy produced from the biomass was combined with the energy input to calculate an energy ratio (the energy production divided by the energy input) and an energy balance (the energy production minus the energy input). The energy ratio gives a relative efficiency of the energy production, while the energy balance gives the net energy production.

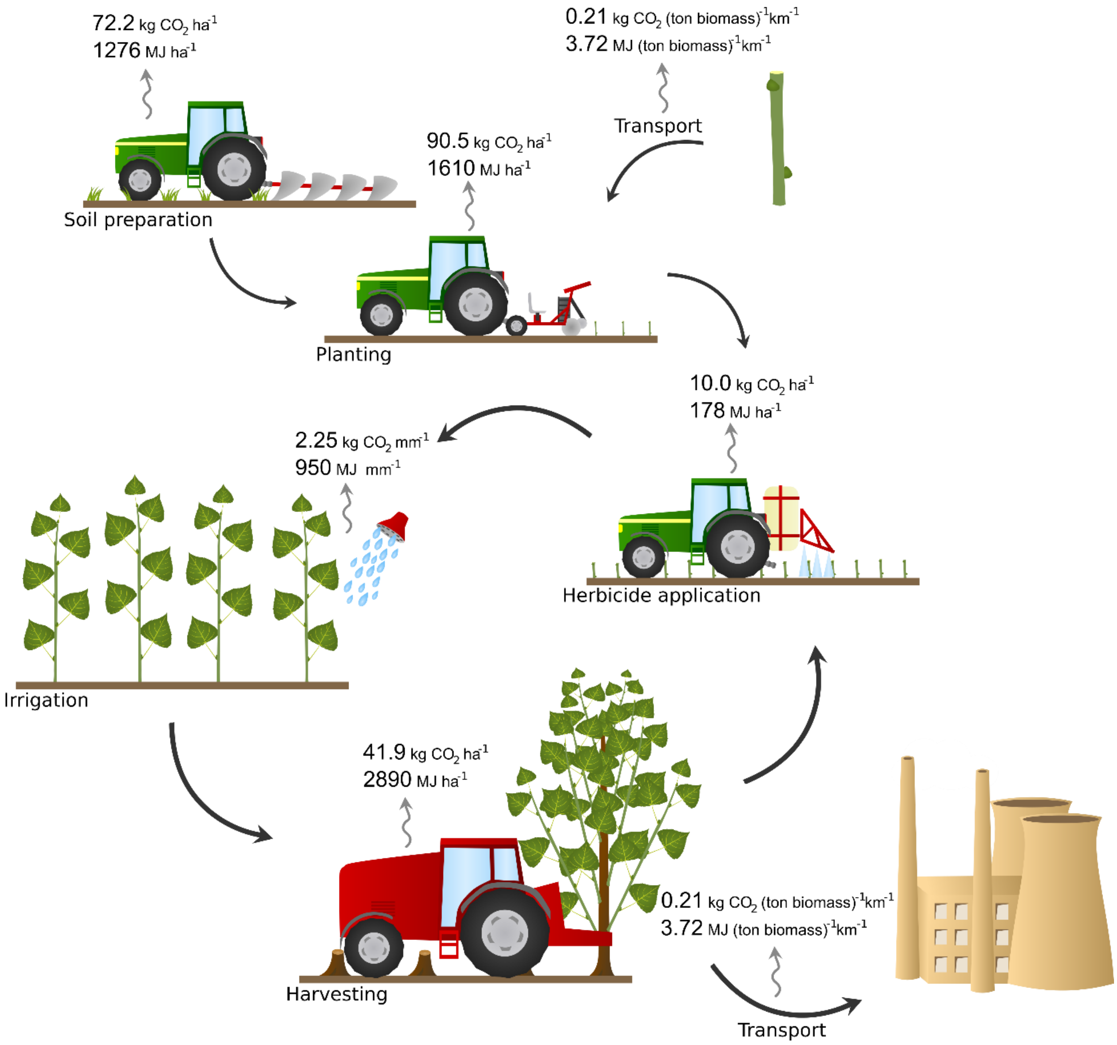

Figure 2: Visualization of the management actions and associated CO_2 and energy costs that were taken into account to select the optimal management scenario.

2.5. Model description

For the simulations, we used the model ORCHIDEE-SRC (De Groote et al., 2015) (Chapter 1), which is a modification of the ORCHIDEE model, aimed at simulating SRC plantations. A more detailed description of the ORCHIDEE model is provided in (Bellassen et al., 2010; Ducoudre et al., 1993; Krinner et al., 2005). ORCHIDEE is a mechanistic land surface model. As input, the model needs meteorological data and site-specific parameters. The meteorological data are short- and long-wave incoming radiation, air temperature, specific humidity, wind speed, precipitation and atmospheric pressure. Site-specific parameters include site longitude and latitude, soil textural fractions, meteorological instrument height, plantation rotation cycle and initial planting density. The model then simulates the carbon, water and energy fluxes.

The modifications to the ORCHIDEE model we made resulted in the ORCHIDEE-SRC model (De Groote et al., 2015) and include modifications to (1) management, (2) growth, (3) allocation and (4) parameterization. Details can be found in De Groote et al. (2015), but for almost all outputs, ORCHIDEE-SRC yielded improved simulations relative to ORCHIDEE. In brief, at our two study sites, the ORCHIDEE-SRC model reproduced biomass production, gross primary production (GPP), ecosystem respiration (R_{eco}) and latent heat (LE) loss very well (within 25% of the rotational total for biomass and within 5% of the rotational total for GPP, R_{eco} and LE).

ORCHIDEE-SRC did slightly overestimate the belowground biomass production (De Groote et al., 2015). Because of this, root production can stop earlier with carbon allocation shifting to aboveground woody tissues, making shorter rotations preferable. Moreover, in real life shorter rotations are more demanding for the trees and might promote earlier mortality or a decreased long term yield. Literature on this effect is limited and shows a large clonal variability (Dillen et al., 2011). This interactive effect of rotation time on mortality is not simulated in our model.

2.6. Model setup

The meteorological data, i.e. short-wave incoming radiation, long-wave incoming radiation, rainfall, snowfall, specific humidity, surface pressure, air temperature and wind speed, of all available years were collected on site with half-hourly time steps. Per site, all matching half hours were averaged over the years for all the available years into one average year. This average meteorological year was used for the simulations, so that the output of the modelling is not dependent on coincidental extreme weather. For the Boom site, the data of 1996 to 2007 were averaged, for the Lochristi site, the data of 2010 to 2012 were averaged.

Before the actual simulations, the model was optimised to achieve a soil carbon equilibrium using a spinup. This spinup was performed by running the standard ORCHIDEE model, alternated with a simplified version, for 1510 years (De Groote et al., 2015).

Because of the heterogeneity of the Boom site soil (former landfill), the soil textural measurements varied strongly and only the general soil texture classes of loam and sandy loam were reported. We used the average of these classes 49% sand, 29% silt and 22% clay as model inputs. For the Lochristi site the fractions varied less and the measured average values of 86% sand, 3% silt and 11% clay were used for the simulations.

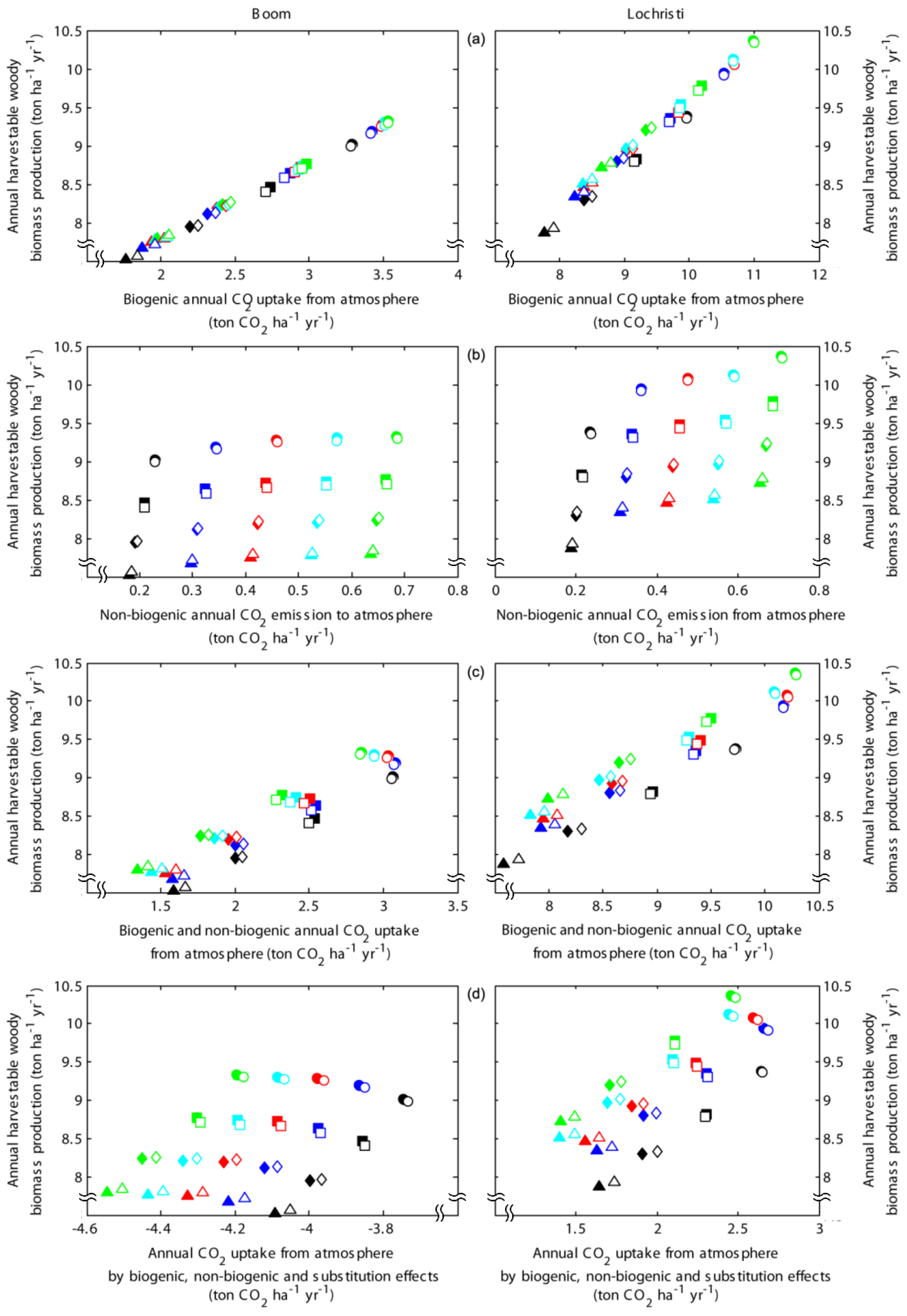

Figure 3: The CO_2 emissions and uptake by the plantation. This graph compares the average annual harvestable woody biomass production to (a) the modelled biogenic annual CO_2 uptake from the atmosphere (= NEP), (b) the calculated non-biogenic annual CO_2 emissions to the atmosphere from the management activities, (c) the combined on and non-biogenic CO_2 uptake from the atmosphere and (d) the combined on and non-biogenic CO_2 uptake with addition of the addition of the energy substitution effect. The different management scenarios are shown as different symbols.

Figure 3 (continuation): rotation length: ● = 2 yr, ■ = 3 yr, ◆ = 4 yr, ▲ = 5 yr
establishment year: open symbol = no establishment year cut, filled symbol = establishment year cut
irrigation: black = no irrigation, blue = 50 mm yr^{-1}, red = 100 mm yr^{-1}, cyan = 150 mm yr^{-1}, green = 200 mm yr^{-1}
plantation density: larger symbol = higher planting density.
Note that not all axes contain zero.

3 Results

3.1. CO_2 uptake

The biogenic CO_2 uptake from the atmosphere, i.e. the NEP (Net Ecosystem Production), was positively and linearly correlated with the harvestable woody biomass production (Figure 3a). Surprisingly, for both the Boom and Lochristi sites, the C contained in the woody biomass was higher than the C amount that was taken up from the atmosphere, which implies that soils lost organic matter during the conversion to SRC and its operation.

Among all management options, changes in rotation length elicited the largest differences in biomass yield (different symbols in Figure 3a), with shorter rotations yielding higher biomass. Changes in irrigation and the implementation of an establishment year cut had a smaller impact. Varying the initial plantation density did not change yields in the simulations.

In addition to plant and soil CO_2 fluxes, also management-related CO_2 emissions (both on-site and off-site) contributed to the SRC CO_2 balance, albeit to a lesser degree (Figure 3b; 5-30% for Boom; 2-8% for Lochristi). Irrigation was the management option with the highest CO_2 emissions (Figure 3b). Although these non-biogenic emissions were not very large, between 0.2 and 0.7 ton CO_2 ha^{-1} yr^{-1}, they caused a very noticeable difference in the net C emission - biomass production patterns of the different management scenarios (Figure 3a-c).

When the biogenic CO_2 uptake and the management-related CO_2 emissions were summed, rotation length remained the dominant control over the net CO_2 balance of the plantations, with shorter rotations being more favourable (Figure 3c). The effect of the establishment year coppice depended on the rotation length, but was generally negligible. The effect of irrigation differed between Boom and Lochristi. In Boom, irrigation reached an optimum at 100 mm. Up to this level, biomass production increased, while the net CO_2 emissions did not increase much. Above 100 mm the CO_2 emissions increased, while the increase in biomass production was much smaller. In contrast with the loamy-sandy Lochristi site, with a much lower water retention capacity, where more irrigation continued to increase the biomass production, as well as increasing the CO_2 uptake from the atmosphere. For the Lochristi site, the increase in CO_2 uptake was between three and four times larger between an irrigation of 50 mm and no irrigation than for Boom. Adding more irrigation still had a positive impact on biomass production and CO_2 emissions, but much smaller than the 50 mm application.

Accounting for the energy substitution of grid mix electricity by the produced biomass demonstrated a clear difference between the two study sites (Figure 3d). When using the bio-electricity produced from the biomass yield on the Boom site to substitute the same amount of grid mix electricity, the system turned into a net CO_2 source. These CO_2 emissions were, however, still only about 50% of the CO_2 amount that would be emitted if the same amount of energy had to be produced using grid mix electricity. For the Boom site, the optimal management scenario for the CO_2 balance had two year rotations and no irrigation. Adding irrigation increased the biomass production slightly, but made the CO_2 balance worse. Using biomass from the Lochristi site to substitute grid mix electricity reduced the site CO_2 balance to a net sink of 1.4 to 2.7 ton CO_2 ha^{-1} yr^{-1}. Therefore, using woody biomass from the Lochristi site to produce electricity was always a net CO_2 sink in addition to an energy source, while the SRC plantation at Boom offers an energy source with 50% reduced CO_2 emissions as compared to grid-mix electricity. For the Lochristi site, the shortest rotation, two years, gave the best CO_2 emission savings. Adding 50 mm of irrigation increased the biomass production by about 0.5 ton ha^{-1} yr^{-1}, compared to the no irrigation scenarios, while the net CO_2 emission stayed the same. Further increasing the irrigation had a less pronounced effect on the biomass production, while the CO_2 emissions to the atmosphere increased. For the best performing rotation lengths, the effect of the establishment year cut was negligible.

3.2. Water use

For all management scenarios, the mean annual evapotranspiration was plotted against the aboveground harvestable woody biomass (Figure 4). For both the Boom site and the Lochristi site, the main difference between the management scenarios was caused by the difference in irrigation volumes. The larger the amount of irrigation, the larger the evapotranspiration, although the difference remained small. At 200 mm annual irrigation, the increase in annual evapotranspiration was only about 10 mm for both the study sites. There was no noticeable effect of the planting density.

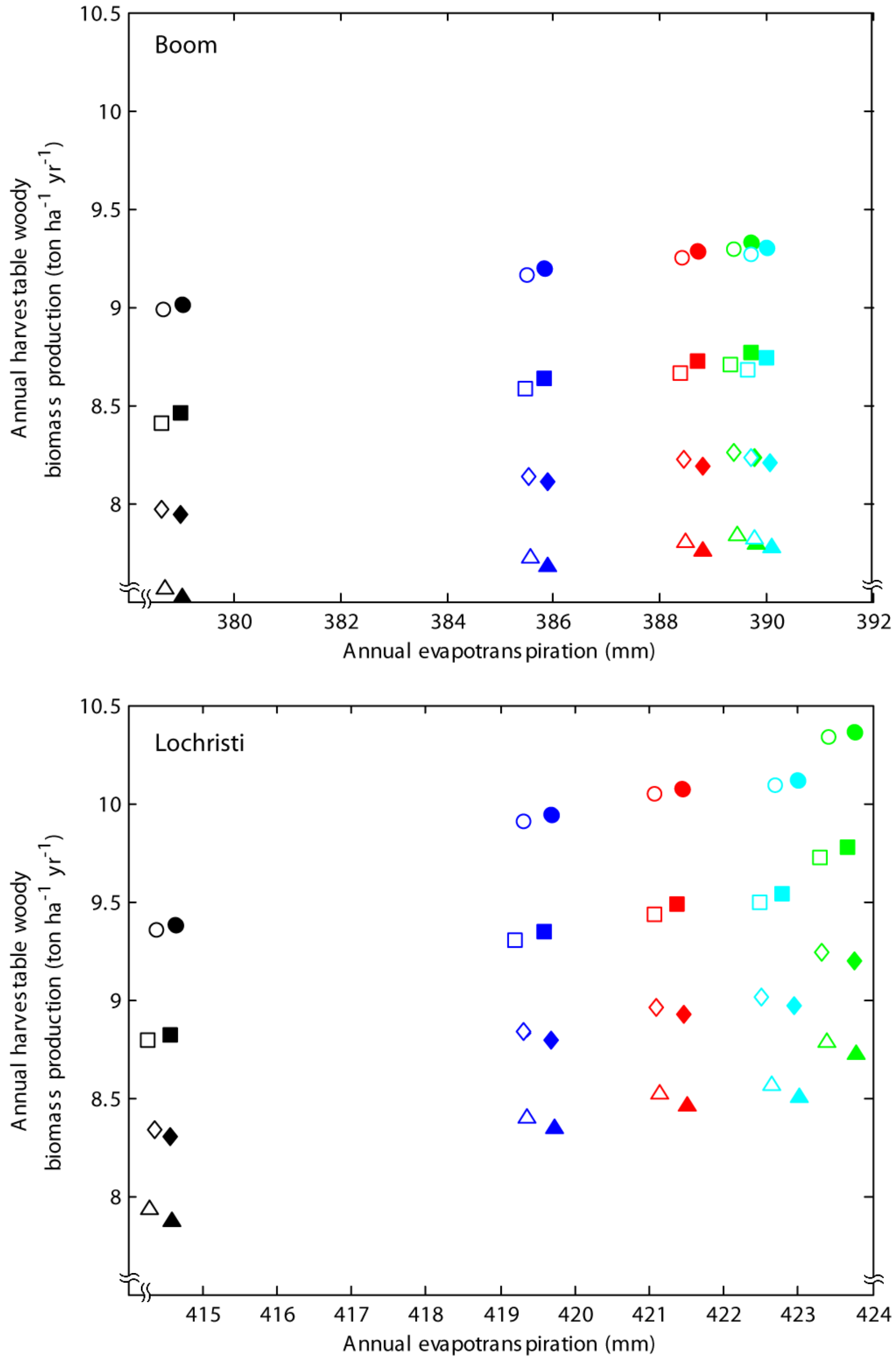

Figure 4: The annual evapotranspiration by the plantations. This graph compares the average annual harvestable woody biomass production to the annual evapotranspiration of the plantations. The different management scenarios are shown as different symbols.

rotation length: ● = 2 yr, ■ = 3 yr, ◆ = 4 yr, ▲= 5 yr

establishment year: open symbol = no establishment year cut, filled symbol = establishment year cut

irrigation: black = no irrigation, blue = 50 mm yr^{-1}, red = 100 mm yr^{-1}, cyan = 150 mm yr^{-1}, green = 200 mm yr^{-1}

plantation density: larger symbol = higher planting density.

Note that the axes do not contain zero.

The small increase in evapotranspiration for large volumes of irrigation, suggests that irrigation is not really necessary for these sites. Making the irrigation more frequent, i.e. daily instead of weekly, did not change the effect of the irrigation noticeably. Adding 200 mm of irrigation adds only around 10 mm of evapotranspiration for both sites, which is an efficiency of only 5%. Further analysis of the modelled water balance shows that another 5% is lost as runoff and the left over 90% is lost as drainage.

3.3. Energy use

Assuming an energy substitution of 6.882 kJ electricity (g biomass)$^{-1}$ (see section 2.4), all management scenarios for both test sites had an energy ratio higher than 1 (Figure 5), meaning that more energy was produced than was put into the system when producing the wood and converting it to electricity.

The main energy input into the plantation came from irrigation. Scenarios with an irrigation of 200 mm consumed five times more energy than scenarios without irrigation. The increase in biomass production resulting from the increased irrigation also resulted in an increased energy output. However, increased energy production only made up for about 10% of the increased energy consumption. The energy use of 50 mm of irrigation adds around 5 GJ ha^{-1} yr^{-1} to the energy input. The increase in energy output, due to the increased biomass production of the extra irrigated management scenarios, was always lower than 5 GJ ha^{-1} yr^{-1}. Shorter rotations required higher energy inputs, but also yielded a higher biomass production. The increase in biomass production had an energy content equal to the increased energy input, cancelling out the effect of rotation length, except for the scenarios without irrigation. The energy ratio for both study sites was comparable for similar management scenarios. The highest energy ratio was simulated for SRCs without irrigation, with energy ratio ranging between 11.9 and 14.6. The scenario with an irrigation of 200 mm year^{-1} and a rotation length of 5 years had the lowest energy ratio: 2.3 for Boom and 2.6 for Lochristi. The scenario without irrigation and 5 year rotations with an establishment year cut had the highest energy ratio, 14.4 and 14.5 for the Boom and Lochristi sites, respectively. The harvest after the establishment year and the planting density had no significant influence on the energy input.

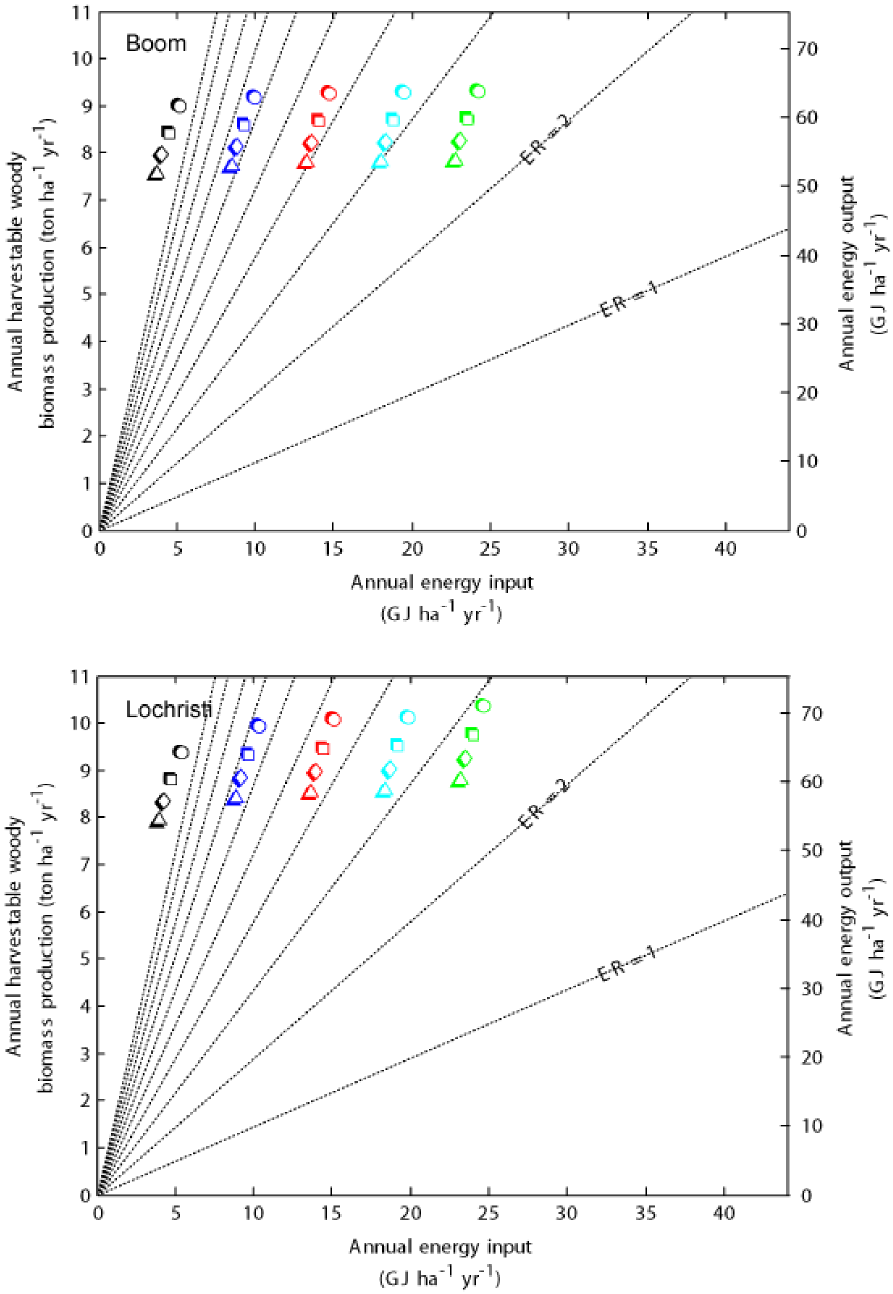

Figure 5: The annual energy input into the plantations. This graph compares the average annual harvestable woody biomass production to the average annual energy input into the plantations. The dotted lines represents the energy ratios (ER) of 1 to 10. For an energy ratio of 1, the energy input equals the energy output, for an energy ratio of 10, the energy output is ten times higher than the energy input. The different management scenarios are shown as different symbols.

rotation length: ● = 2 yr, ■ = 3 yr, ◆ = 4 yr, ▲ = 5 yr

establishment year: open symbol = no establishment year cut, filled symbol = establishment year cut

irrigation: black = no irrigation, blue = 50 mm yr^{-1}, red = 100 mm yr^{-1}, cyan = 150 mm yr^{-1}, green = 200 mm yr^{-1}

plantation density: larger symbol = higher planting density.

4 Discussion

Because biomass has a lower energy density than coal or gas (Frischknecht et al., 2007; McKendry, 2002), the grid mix substitution with biomass requires more biomass to be processed in order to break even. Therefore the CO_2 emission for an equal amount of produced energy is higher when using biomass than when using grid mix electricity. The advantage of using biomass is, however, that part of the emitted CO_2 is recycled. It was captured from the atmosphere during biomass production, and therefore not newly added to the atmosphere (Righelato et al., 2007).

While the biomass production in our simulations was correlated to the CO_2 uptake, as could be expected, the carbon ratio is lower than 1. This means that there is more carbon in the produced biomass than the amount of carbon that was taken from the atmosphere. This points to a loss of soil carbon. Loss of soil carbon, combined with the management-related C costs, imply that we do bring new C into the atmosphere when the wood is converted into energy. There is, however, still enough renewable C in the biomass to make electricity from biomass more favourable than grid mix electricity.

The total net CO_2 balance of SRC bio-energy, including biogenic emissions, non-biogenic emissions and energy substitution, made the Boom site a net CO_2 source. The net carbon balance, for this site did not have enough renewable C to make it a net sink. The Lochristi site was a net CO_2 sink for every management scenario. This inter-site difference thus showed that site selection was important when establishing an SRC plantation. A more elaborate study including more sites with a wider range of site conditions might identify which site characteristics are best for SRC plantations in terms of biomass production, net CO_2 balance, as well as net energy balance.

The difference between the sites might be explained by the soil properties, as the Lochristi site had a much sandier soil (86%) compared to the Boom site (49%). The water holding capacity of sandy soil is lower, hence the increased benefit of added irrigation. The benefit of added irrigation on the biomass production is, however, small, i.e. less than 0.5 ton ha^{-1} yr^{-1} for the Boom site and less than 1 ton ha^{-1} yr^{-1} for the Lochristi site. An efficiency of only 5% is low for a management activity with such high energy costs.

The energy ratio of scenarios with higher irrigation levels is lower than the energy ratio of scenarios with lower irrigation levels. This means that, looking only at the energy ratio or at the net energy balance, using energy for irrigation doesn't pay off and is detrimental for the net energy yield.

Changes in the other management options caused very minor changes to the energy ratio, except in the rainfed scenarios. This difference can be attributed to the very small energy input values for rainfed scenarios.

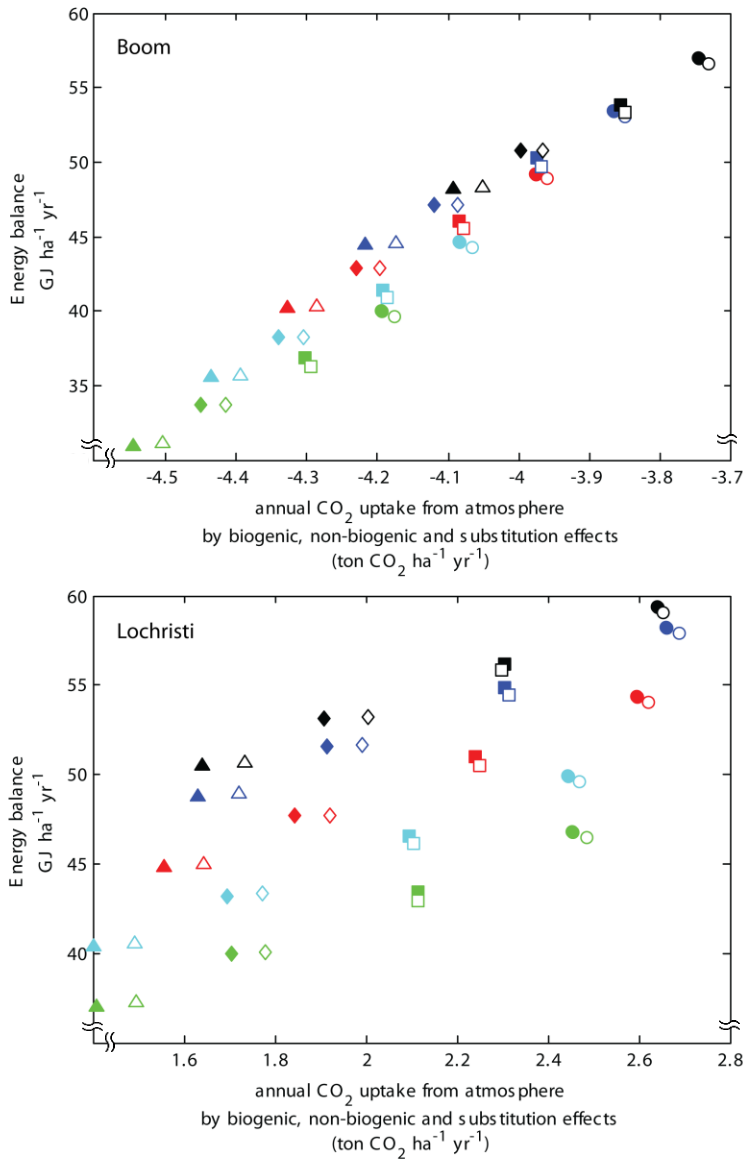

Figure 6: A comparison of the annual net energy balance and the annual CO_2 uptake from the atmosphere, including biogenic, non-biogenic and substitution effects. The net energy balance is difference between the energy input and the energy output. The different management scenarios are shown as different symbols.

rotation length: ● = 2 yr, ■ = 3 yr, ◆ = 4 yr, ▲= 5 yr

establishment year: open symbol = no establishment year cut, filled symbol = establishment year cut

irrigation: black = no irrigation, blue = 50 mm yr^{-1}, red = 100 mm yr^{-1}, cyan = 150 mm yr^{-1}, green = 200 mm yr^{-1}

plantation density: larger symbol = higher planting density.

Note that the axes do not contain zero.

Finding the optimal management

When deciding on a general optimal management scenario, the main focus should be on yield, because this is the income for the farmer. However, the energy and CO_2 balance should be included in a subsidy system. Otherwise, farmers might adopt wasteful energy practices that increase biomass production at the expense of high energy inputs or high greenhouse gas emissions.

In this study we did not find any effects of planting density on yield, CO_2 balance, energy balance or evapotranspiration. Similar results can be found in other datasets in literature (Bergante et al., 2010; Djomo et al., 2015). Kauter et al. (2003), states that planting density becomes more important for shorter rotation lengths. It is, however, possible that a density of 5000 trees ha^{-1} is sufficiently dense for biomass production. Adding more trees is not beneficial to yield, as increased intra-species competition hinders extra yield.

We aimed to find an optimal management, for which we attain the highest yield at the best possible CO_2 and energy balance. Using energy ratio instead of the net energy balance, a five year rotation, without irrigation would be preferable. However, we prefer to use the net energy balance instead of the energy ratio for finding an optimal management, as the energy ratio tends to get skewed for smaller energy values, whereas the net energy balance provides a net energy production value. The energy balance provides the amount of net energy produced using the specified scenarios. For both our study sites, the net energy balance was comparable, although somewhat lower for the Boom site, because of the lower biomass production. The optimal scenario for both sites based on net energy production has two year rotations without irrigation. Our finding that a two year rotation cycle is optimal is, however, contrary to prior studies, where five year rotations were found to be optimal (Hofmann-Schielle et al., 1999; Kauter et al., 2003; Willebrand et al., 1993). This might be caused by a flaw in the used model (see section 2.5).

For both sites, a scenario without irrigation and two year rotation cycles is thus optimal from the perspective of yield and energy balance (Figure 6). When taking the net C balance into account instead of the net energy balance, for Lochristi, a two year rotation but with 50 mm yr^{-1} irrigation would be optimal. However, the added energy of the irrigation outweighs the small net carbon gain realized by the irrigation. Based on our analysis, irrigation of SRC plantations is not justified in Belgium, where rainfall is sufficient to sustain close to maximal biomass production.

Care should be taken with the model results, because the model is a generalization of reality. It assumes that the plantations are established using an averaged poplar clone, whereas in real life there is a large variety in tree characteristics. Furthermore, the model doesn't include pests or diseases and uses a simple soil water model.

5 Conclusion

In conclusion, under Belgian conditions (moderate temperatures and sufficient rainfall during the growing season) the optimal management for SRC systems would be to not irrigate and apply two year rotation cycles. In this scenario the farmer has the highest yield, while maintaining the highest benefit for the environment, in terms of net energy and CO_2 balance.

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Chapter 3 Balancing yield, CO_2 emissions, water use and energy production for Short Rotation Coppice plantations across Europe

In this study, we look for an optimal management for short rotation coppice plantations across Europe, in which yield, CO_2 emissions, water use and energy production are balanced. We collected meteorological data from various European monitoring stations and used this data to simulate harvestable aboveground woody biomass production, CO_2 uptake and actual evapotranspiration of virtual short rotation coppice plantations across Europe for a number of management scenarios, using the model ORCHIDEE-SRC. We complemented this data with CO_2 emissions and energy use specific to the management, to calculate the net CO_2 emissions and net energy balance of the plantations for the different management scenarios. The management scenarios consist of 20 permutations of irrigation volume and rotation length. We found that climate has a much larger influence on the performance of the plantation than management. In temperate Europe, the most optimal management uses no irrigation and has rotation cycles of 2 years. For locations with dry summers, however, irrigation can switch the plantation from being a net carbon source to being a net carbon sink. And at these sites, irrigation will be necessary to ensure tree survival.

1 Introduction

Electricity production needs to become more sustainable (EC, 2010a). The current main methods for the production of electricity consume non-renewable fuels, like coal, natural gas, oil and enriched uranium and plutonium. Furthermore, fossil fuels emit CO_2 that was previously stored deep in the earth into the atmosphere, thus promoting climate change by increasing greenhouse gas concentrations (IPCC, 2007a). Although following construction, the operation of nuclear power stations is often presented as CO_2 neutral, nuclear power stations pose an intergenerational risk to the surrounding environment (Taebi, 2012).

One of the most interesting sustainable energy options in the EU is the production of electricity from biomass (EC, 2007). This biomass can be regrown and is therefore renewable. The CO_2 that is emitted during the combustion or gasification of biomass was first sequestered from the atmosphere during the biomass growth (Righelato et al., 2007). In practice, some CO_2 is emitted to the atmosphere by the handling and management involved in the production of biomass.

In this study, we perform a model study of short rotation coppice (SRC) plantations. This type of biomass plantation allows a fast production of woody biomass. Trees with a good regrowth potential, like poplar (*Populus spp.*) or willow (*Salix spp.*), are reproduced vegetatively by planting cuttings in a dense grid (Aylott et al., 2008; Herve et al., 1996). After two to five years, depending on the management scenario, the trees are cut back during winter to about 10 cm above the ground (Berhongaray et al., 2013) and the harvested biomass can be used for the production of energy, paper, etc. After cutting, the trees naturally regrow as multi-stemmed trees.

As plantations of this type might become more abundant in the quest for sustainable energy, it is important to optimize their management. In this study, we therefore aim to find the optimal SRC management for a range of locations across Europe, from the perspective of biomass production, net energy production and CO_2 balance. We use the mechanistic model ORCHIDEE-SRC (De Groote et al., 2015) (Chapter 1) to predict biomass production, carbon fluxes and water use, and combine these model results with CO_2 emissions and energy use data related to the management. In a previous, more limited study, we tested the management options rotation length (including and excluding an establishment year cut), amount of irrigation and plantation density at two Belgian SRC sites, but only showed significant effects for rotation length and irrigation (Chapter 2). Therefore, we only consider these two management factors in this study.

2 Materials and Methods

2.1. Synoptic model description

For the simulations, we used the model ORCHIDEE-SRC (De Groote et al., 2015) (Chapter 1), which is a modification of the ORCHIDEE model (Bellassen et al., 2010; Ducoudre et al., 1993; Krinner et al., 2005), aimed at simulating SRC plantations. The ORCHIDEE-SRC model was previously tested at two SRC sites (De Groote et al., 2015) (Chapter 1) and reproduced biomass production, gross primary production (GPP), ecosystem respiration (R_{eco}) and latent heat (LE) losses very well (within 25% of the rotational total for biomass production and within 5% of the rotational total for GPP, R_{eco} and LE). The modifications to the ORCHIDEE-SRC model are described in detail in De Groote et al. (2015) (Chapter 1). ORCHIDEE-SRC is a mechanistic land surface model. As input, the model requires meteorological data and site-specific parameters. The meteorological data are short and long wave incoming radiation, air temperature, specific humidity, wind speed, precipitation and atmospheric pressure. Site-specific parameters include site longitude and latitude, soil texture, meteorological instrument height, plantation rotation cycle and initial plantation density. The model consists of two big modules: sechiba and stomata. Sechiba calculates hydrology and energy on a half-hourly time-scale and stomata calculates carbon processes on a daily time-scale.

2.2. Site data

2.2.1 Data sources

Sites from the European Fluxes Database Cluster (Europe Fluxdata, 2014) were used as meteorological inputs in the model. We selected 22 sites with at least five years of data and with a public data access and open data use policy.

The L2 meteo data of the available years for these sites was used, this is half-hourly data, not gap-filled or filtered but quality checked. The half-hourly data was converted into the correct units for ORCHIDEE and per site an average year was calculated. This was achieved by averaging the half-hourly data over the available years. This gave us an average meteorological year per site. Hereby, we generate the same average year for all years of the simulations, to prevent the accidental coinciding of unfavourable years or extreme events at crucial growing stages from having a big impact on the plantation. For three sites, missing meteo data had to be gapfilled. Hyytiala (FI-Hyy) and Roccarespampani (It-Ro1) missed 1,350 out of 262,800 and 43 out of 175,200 data points respectively for long wave incoming radiation. Renon (IT-Ren) missed 4,753 out of 332,880 data points for precipitation. Missing meteo data was gapfilled using data from the ERA-interim 3-hour product (Berrisford et al., 2011), based on the sites coordinates. The data was collected for the same years as the L2 site data. The missing data was then replaced by the ERA-interim data.

Only 10 of the selected sites also reported data on soil texture in the database. For the twelve other sites, soil texture data was gathered from an interpolated grid (Luyssaert et al., 2007). They are not the observed soil fraction, but the most likely soil fraction.

2.2.2 Data range

The 22 test sites differed in meteorology, soil structure and location (Table 1). Figure 1 shows a map of Europe with the location of the selected sites. On the North-South axis, the sites span from Southern Scandinavia to the south of the Iberian Peninsula. On the East-West axis, the sites span from Western Russia to Portugal. The soil textures of the sites are shown in Figure 2. The textures span from the centre of the soil triangle to the three corners. Most of the sites, however, have a soil composition located around the centre of the triangle, i.e. Clay-Loam or Loam. The climatic range of the sites is shown in Figure 3. The site annual minimum temperatures range from -13.0 °C to 2.9 °C (summer: 4.9 °C to 14.8 °C), the site annual maximum temperatures range from 19.4 °C to 37.0 °C (summer: 19.4 °C to 37.0 °C) and the site annual total precipitation ranges from 524 mm to 1263 mm (summer: 26 mm to 496 mm).

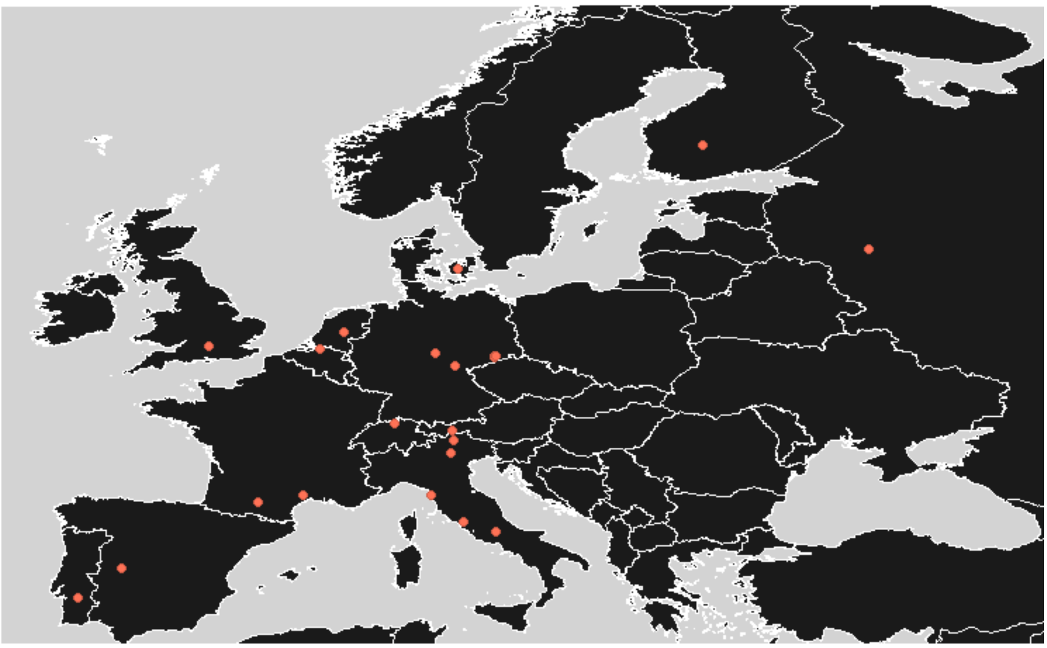


Figure 1: Distribution of the test sites across Europe.

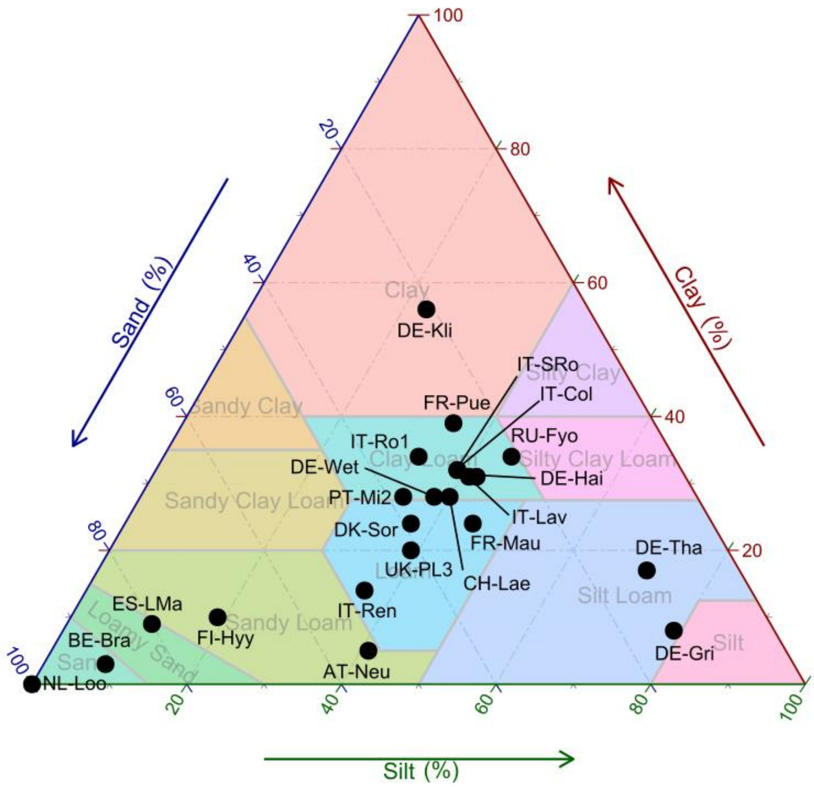


Figure 2: Distribution of the test sites in the soil texture triangle.

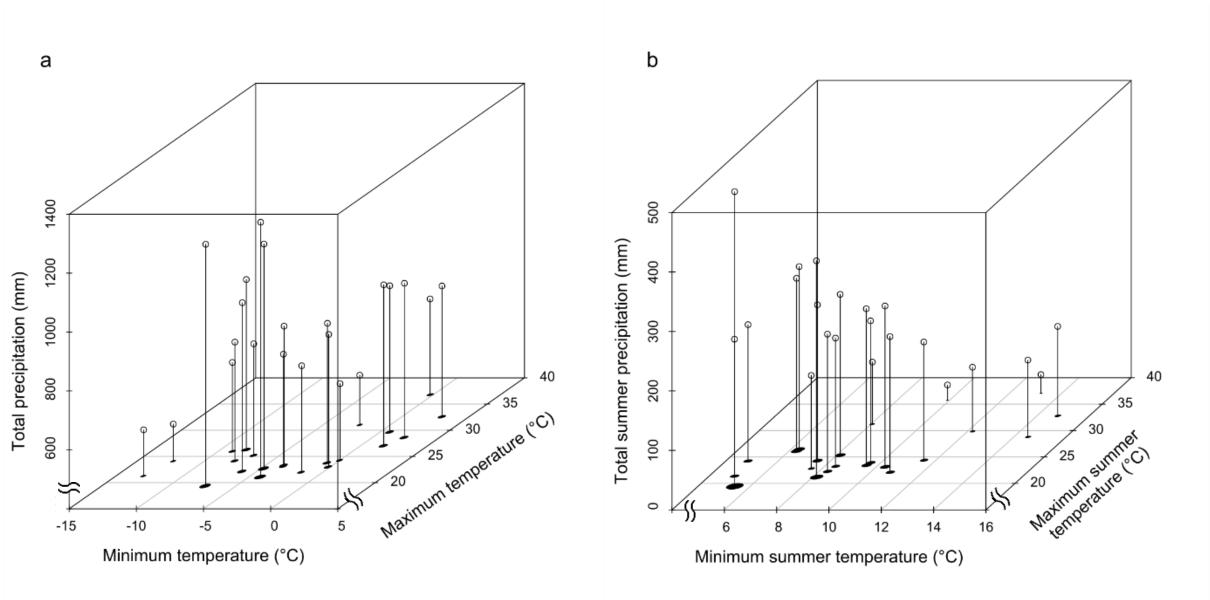


Figure 3: The climatic range of the different test sites. The minimum and maximum temperature and the total precipitation per site are shown (a) for the entire year and (b) for the summer period. The height of the stalks and the size of their shadow shows the total precipitation amount. Note that not all axes contain zero.

Table 1: The sites and their characteristics.

Country	Site name	Site code	N° of years	Location: Latitude	Location: Longitude	Location: Elevation (m)	Soil texture: Clay (%)	Soil texture: Silt (%)	Soil texture: Sand (%)	Meteo: Annual (summer) temperature (°C)	Meteo: Annual (summer) precipitation (mm)
Belgium	Brasschaat	BE-Bra	14	51° 18' 33"	4° 31' 14"	16	3	8	89	10.6 (16.9)	848 (271)
Italy	Collelongo	IT-Col	15	41° 50' 58"	13° 35' 17"	1560	32	39	29 †	7.3 (15.3)	1160 (157)
Russia	Fyodorovskoye	RU-Fyo	13	56° 27' 42"	32° 55' 19"	210*	34	45	21 †	5.1 (15.9)	524 (230)
Germany	Grillenburg	DE-Gri	7	50° 56' 58"	13° 30' 45"	385	8	79	13	8.5 (16.6)	975 (308)
Germany	Hainich	DE-Hai	11	51° 04' 45"	10° 27' 11"	421*	31	42	27 †	8.3 (16.2)	779 (216)
Finland	Hyytiälä	FI-Hyy	15	61° 50' 51"	24° 17' 42"	181	10	19	71	4.1 (14.4)	555 (231)
Germany	Klingenberg	DE-Kli	7	50° 53' 34"	13° 31' 21"	478	56	23	21	7.6 (15.7)	801 (262)
Czech Republic	Laegern	CH-Lae	7	47° 28' 41"	8° 21' 54"	846*	28	40	32 †	7.7 (15.8)	777 (271)
Spain	Las Majadas del Tietar	ES-LMa	7	39° 56' 29"	-5° 46' 24"	260	9	11	80	16.1 (25.8)	721 (32)
Italy	Lavarone	IT-Lav	11	45° 57' 22"	11° 16' 53"	1228*	31	41	28 †	6.9 (14.8)	1263 (364)
The Netherlands	Loobos	NL-Loo	15	52° 09' 60"	5° 44' 37"	25	0	0	100	10.0 (16.8)	872 (239)
France	Mauzac	FR-Mau	6	43° 23' 07"	1° 17' 32"	189	24	45	31	12.7 (20.4)	566 (105)
Portugal	Mitra IV (Tojal)	PT-Mi2	5	38° 28' 35"	-8° 01' 28"	200*	28	34	38 †	14.2 (21.6)	588 (26)
Austria	Neustift	AT-Neu	9	47° 07' 00"	11° 19' 03"	970	5	41	54	6.8 (15.4)	700 (291)
United Kingdom	Pang/Lambourne forest	UK-PL3	5	51° 27' 00"	-1° 16' 00"	119*	20	39	41 †	12.3 (17.9)	658 (199)
France	Puechabon	FR-Pue	11	43° 44' 29"	3° 35' 45"	270	39	35	26	13.6 (21.7)	894 (108)
Italy	Renon	IT-Ren	19	46° 35' 13"	11° 26' 01"	1730	14	36	50 †	4.5 (12.3)	1219 (496)
Italy	Roccarespampani 1	IT-Ro1	10	42° 24' 29"	11° 55' 48"	139*	34	33	33 †	15.6 (23.6)	840 (151)
Italy	San Rossore	IT-SRo	12	43° 43' 40"	10° 17' 04"	6	32	39	29 †	15.2 (23.1)	921 (130)
Denmark	Soroe	DK-Sor	15	55° 29' 09"	11° 38' 41"	40	24	37	39 †	8.4 (16.1)	760 (229)
Germany	Tharandt	DE-Tha	15	50° 57' 49"	13° 34' 01"	380	17	71	12	8.6 (16.7)	871 (263)
Germany	Wetzstein	DE-Wet	7	50° 27' 13"	11° 27' 27"	751*	28	38	34 †	6.5 (14.7)	971 (231)

* Elevation data from Google Maps: http://maps.google.com
† Soil texture data from Luyssaert, S., et al., CO_2 balance of boreal, temperate, and tropical forests derived from a global database. Global Change Biology, 2007. 13(12): p. 2509-2537

2.3. Management activities

The CO_2 emissions and energy use of management activities is not calculated by ORCHIDEE-SRC, but is calculated separately from the Ecoinvent 2.1 (Frischknecht et al., 2007) database using Simapro 7.1 (PRé, 2007). The management activities taken into account are ploughing, mechanical and chemical weeding, planting, irrigation, harvesting and transportation (Table 2). The activities are implemented in the following configuration. Before planting, cuttings of 10 g each, for a planting density of 10,000 trees ha^{-1} are transported to the plantation from a supply station over a distance of 150 km. The soil is prepared by mechanical weeding, ploughing and a chemical herbicide application. After this soil preparation, the cuttings are planted using a standard leek planter. The cuttings then grow into trees, while irrigation is applied in accordance with the selected management scenario. At the end of each rotation, the plantation is harvested with a modified combine harvester and the cuttings are transported to a power station 50 km from the plantation. After every harvest, chemical herbicide is reapplied to prevent weed growth during the sprouting of the new stems and this cycle continues until the plantation is twenty years old.

Twenty different management scenarios were created. As a first management factor, the rotation length was varied from two to five years in increments of one year. The irrigation was varied 0 to 200 mm per year in steps of 50 mm per year. Each scenario was run for each site, for twenty years. Each management scenario was one of the twenty possible combinations of these values of rotation length and irrigation volume.

Table 2: CO_2 emission and energy use of the management activities from the Ecoinvent 2.1 (Frischknecht et al., 2007) database.

Management activities	CO_2 emission kg CO_2 ha-1	Energy use MJ ha-1
Ploughing	57.7	981
Mechanical weeding	14.5	295
Chemical weeding	10.0	178
Planting	90.5	1 610
Irrigating (per mm)	2.25	950
Harvesting	41.9	2 890
Transport (per tkm)	0.213	3.72

2.4. Model setup and simulations

For each of these sites, a spinup was run to initialize the soil carbon pool. This spinup is performed by running the model with the input data repeatedly, until a soil carbon equilibrium is reached. Because this takes a very long time, a part of this spinup is executed with simplified versions of the model, i.e. teststomate and forcesoil. Teststomate deactivates sechiba, thus only running the daily processes, instead of half-hourly processes, hereby accelerating the model 48 times, reaching a steady state for the non-soil carbon pools. Forcesoil only uses the ORCHIDEE's soil carbon module, reaching a steady state for the soil carbon pools. The spinup scenario starts with three times 20 years of the full model, followed by 50 years of teststomate. Then 40 years of the full model, followed by 1000 years of forcesoil, and 260 more years of the full model. This gives a total of 1510 years, of which 360 are run with the full model. The end state of the spinups is then used as initial state for the actual simulations. The model was then used to simulate the 20 different management scenarios for all of the sites.

2.5. Data analysis

For each of the simulations, the harvestable aboveground woody biomass yield and the actual evapotranspiration were calculated directly from the model outputs. For the calculation of the net CO_2 balance and net energy balance, the model outputs were complemented with data from the Ecoinvent 2.1 database (Frischknecht et al., 2007).

The net CO_2 balance was calculated as the net balance of (i) photosynthesis, (ii) ecosystem respiration, (iii) management CO_2 emissions, (iv) emissions from converting the biomass into electricity and (v) the saved emissions from substituting grid mix electricity with the bioelectricity produced by the biomass.

The net energy balance was calculated as the energy generated as electricity from the gasification of the harvested wood minus the energy cost of the management operations. The harvested wood (higher heating value of poplar wood = 18.5 MJ kg^{-1} (Di Nasso et al., 2010)) was converted into electricity through gasification with an electrical conversion efficiency of 37.2% (Mann et al., 1997).

To study the effect of the management scenario’s, independent of the site, a linear mixed effects analysis was performed. As fixed effects, the rotation length and irrigation volume were added to the model. As random effect, site was chosen with random intercepts. P-values were obtained by ratio-likelihood tests of the full model with the management in question against the model without the management in question.

To explain the inter-site differences, a linear model was constructed using meteorological and management dependant factors. There was, however, some co-variation between a number of the factors. Therefore, the factors were first clustered using a Principal Component Analysis (PCA). A correlation matrix was used in the PCA, to account for the difference in magnitude of the different units of the factors. The tests were done using the annual meteo values, growing season meteo values (from 1 April to 31 September) and summer meteo values (from 21 June to 21 September). The test were most significant using the summer meteo values. Therefore only these values are reported here.

The CO_2 emissions and energy use data related to management activities were calculated using Simapro 7.1 (PRé, 2007). Input file creation for ORCHIDEE-SRC and general data processing was performed using Matlab R2013a (The MathWorks Inc, 2013). The statistical analyses were performed using R 3.1.0 (R Core Team, 2014). The linear mixed effects analysis was performed using the lme4 package for R (Bates et al., 2014).

3 Results

3.1. Inter-site variation

The inter-site variation of harvestable aboveground woody biomass yield (Figure 4a), net CO_2 uptake (Figure 4c) and net energy balance (Figure 4g) is larger than the intra-site variation caused by the effects of different management scenarios. For biomass production, the intra-site differences range from 0.6 to 1.6 ton DM ha^{-1} yr^{-1}, while the inter-site differences range from 2.5 to 3.0 ton DM ha^{-1} yr^{-1}. For CO_2 uptake, the intra-site differences range from 1.0 to 3.2 ton CO_2 ha^{-1} yr^{-1}, while the inter-site differences range from 4.6 to 7.2 ton CO_2 ha^{-1} yr^{-1}. For net energy balance, the intra-site differences range from 10 to 24 GJ ha^{-1} yr^{-1}, while the inter-site differences range from 34 to 44 ton ha^{-1} yr^{-1}. For actual evapotranspiration (Figure 4e), the same pattern holds true for fifteen of the sites, but for the seven Mediterranean sites, the difference in actual evapotranspiration caused by changing the management scenario, can be as large as the inter-site variation, up to 150 mm yr^{-1}.

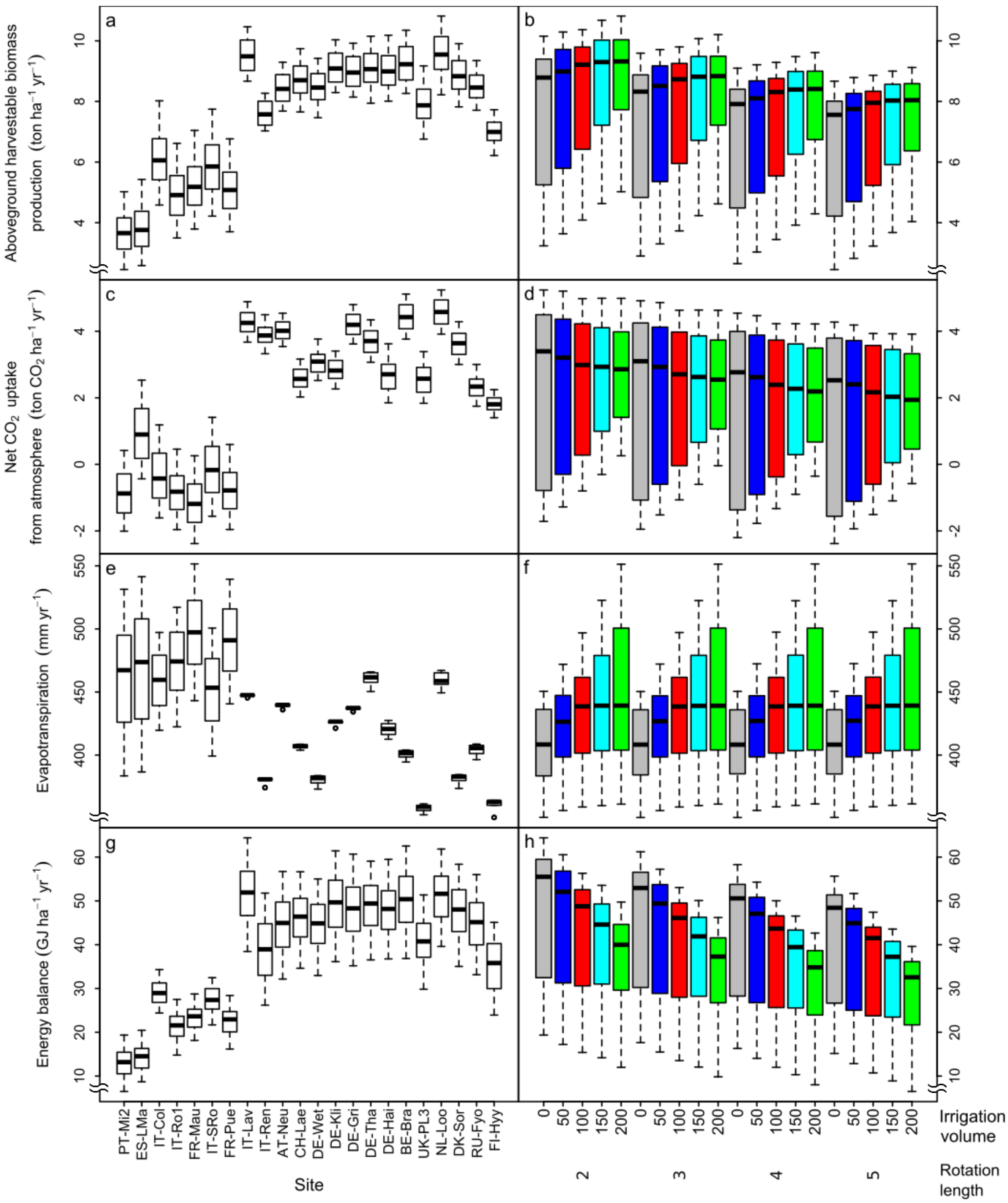


Figure 4: Boxplots showing the variation in (a,b) aboveground harvestable woody biomass production, (c,d) net CO_2 uptake from the atmosphere, (e,f) actual evapotranspiration and (g,h) energy balance. a, c, e and g show boxplots per site. The sites are ordered according to their latitude, from South (left) to North (right). b, d, f and h show boxplots per management scenario. For the management scenarios, different colours denote different irrigation volumes: grey = 0 mm yr^{-1}, blue = 50 mm yr^{-1}, red = 100 mm yr^{-1}, cyan = 150 mm yr^{-1}, green= 200 mm yr^{-1}. Note that not all axes contain zero.

3.2. Management scenario variation

Harvestable aboveground woody biomass production shows an effect of both irrigation and rotation length (Figure 4b). Increasing the irrigation causes an increase in median biomass yield until 150 mm yr^{-1} (~ 0.5 ton DM yr^{-1} for 0 to 200 mm). The highest biomass yields increase slightly (< 1 ton DM ha^{-1} yr^{-1} for 0 to 200 mm), while the lowest biomass yields increase more (~ 1.5 ton DM ha^{-1} yr^{-1} for 0 to 200 mm). Increasing the rotation length causes a slight decrease in biomass yield (~ 1 ton DM ha^{-1} yr-^{1} for the highest and median producers, and ~ 1.5 ton DM ha^{-1} yr^{-1} for the lowest producers, for 2 to 5 year rotations). The linear mixed effects analysis supports this finding. The ratio-likelihood tests show that both irrigation volume and rotation length have significant effects ($p<0.001$) on harvestable aboveground woody biomass production, but there is no interaction between them.

The net CO_2 uptake from the atmosphere also shows an effect of both irrigation and rotation length (Figure 4d). Increasing the irrigation decreases both the median and the highest CO_2 uptake by approximately 0.5 ton CO_2 ha^{-1} yr^{-1} for an increase of 0 to 200 mm per year. The least productive sites increase their CO_2 uptake by approximately 2 ton CO_2 ha^{-1} yr^{-1} for an increase of 0 to 200 mm yr^{-1}. Increasing the rotation length decreases the CO_2 uptake by approximately 0.5 ton CO_2 ha^{-1} yr^{-1} for an increase of 2 to 5 years. The linear mixed effects analysis supports this finding. The ratio-likelihood tests show that both irrigation volume and rotation length have significant effects ($p<0.001$) on net CO_2 uptake, but there is no interaction between them.

The actual evapotranspiration only shows an effect of irrigation (Figure 4f). The median actual evapotranspiration increases with about 25 mm yr^{-1} for the first 100 mm added irrigation, but doesn't increase further for more added irrigation. The same goes for the lowest actual evapotranspiration values, but with an increase of only approximately 10 mm yr^{-1}. The highest evapotranspiring sites show a continuing increase of 100 mm yr^{-1} for an irrigation increase of 0 to 200 mm yr^{-1}. The linear mixed effects analysis supports this finding. The ratio-likelihood tests show that only irrigation volume has a significant effect ($p<0.001$) on actual evapotranspiration, and there is no interaction between irrigation volume and rotation length.

The net energy balance decreases for an increase of both irrigation or rotation length (Figure 4h). Increasing the irrigation volume decreases both the highest and median energy balance by 15 GJ ha^{-1} yr^{-1} for an increase of 0 to 200 mm yr^{-1}. For the lowest energy balances, the decrease is only approximately 8 GJ ha^{-1} yr^{-1} for an increase of 0 to 200 mm yr^{-1}. Increasing the rotation length decreases the energy balance for approximately 10 GJ ha^{-1} yr^{-1} for the highest energy balances, 8 GJ ha^{-1} yr^{-1} for the median energy balances and 5 GJ ha^{-1} yr^{-1} for the low energy balances, for an increase of 2 to 5 year rotations. The linear mixed effects analysis supports this finding. The ratio-likelihood tests show that both irrigation volume and rotation length have significant effects ($p<0.001$) on energy balance, but there is no interaction between them.

3.2.1 Effects of irrigation

Sites that already have a high production don't gain much from increased irrigation, showing a clear saturation towards higher irrigation values (Figure 4b). The more prominent effect of irrigation on the low productive sites suggests that these sites were water limited while the highly productive sites were not. This can also be seen in Figure 4f, where adding 50 mm yr^{-1} or 200 mm yr^{-1} doesn't make a difference in actual evapotranspiration for some sites, while it increases actual evapotranspiration by 100 mm yr^{-1} for other sites.

The highly productive sites that were not water limited don't use the extra irrigation and the water is lost as runoff and drainage, while the water limited, low productive sites use the water to increase their biomass production. Because of this difference, there is a differentiation between these sites in Figure 4a,c,e,g. The difference in the maximum CO_2 uptake and minimum CO_2 uptake for different irrigation volumes in Figure 4d can be explained by this difference between high and low productive sites. In the low productive sites, the increased biomass production, which also implies an increased CO_2 uptake, outweighs the increased CO_2 emissions from the increased irrigation. For the highly productive sites, the minor increase in carbon storage from increased biomass production cannot outweigh the increased CO_2 cost of the irrigation, therefore reducing the net CO_2 uptake from the atmosphere.

From the energetic point of view (Figure 4h), the energy gained from the increased biomass production cannot outweigh the energetic cost of irrigation. Not even for the sites that gain the most from irrigation.

The low productive sites are the sites with a Mediterranean climate, while the highly productive sites are the sites with a temperate climate. For these temperate sites, no irrigation should be applied. For the Mediterranean sites, however, some irrigation is should be applied to attain viable yields, or even to assure the survival of the trees during droughts, as some studies found (Bergante et al., 2010; Fichot et al., 2015).

3.2.2 Effects of rotation length

Lengthening the rotations from two up to five years has the same effect on aboveground woody biomass production, net CO_2 uptake from the atmosphere and energy balance Figure 4b, d, h. They all decrease for increasing rotation lengths. The effect of rotation length is comparable for all sites. No different effect can be seen between high productive and low productive sites. There is neither an effect of irrigation on the effect of rotation length. This is supported by the lack of a significant interaction component of irrigation volume and rotation length in the ratio-likelihood test of the linear mixed effects analysis. Shorter rotations means more rotations and thus a higher management cost, i.e. higher CO_2 emission and higher energy use. However, according to our model, this cost is entirely compensated for by the increased aboveground biomass production, which is possible because the investment in belowground biomass can be lower. For longer rotations, the aboveground biomass has to become bigger than for shorter rotations, to have an equal annual yield. The belowground biomass does, however, have to increase accordingly, thus wasting biomass to a non-harvestable pool.

According to our analysis, two year rotations are optimal for all sites across Europe.

3.3. Attribution to drivers

The summer minimum temperature, summer mean temperature, summer maximum temperature, total summer precipitation, cumulated summer irradiation, rotation length, irrigation volume and sand fraction of the soil where used as factors in the PCA.

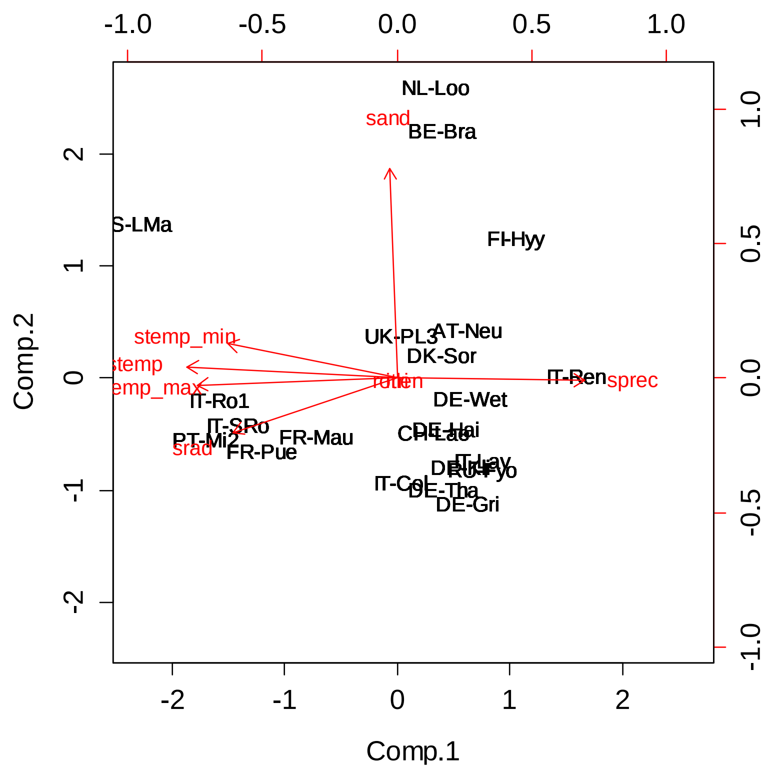
The first four components each predict more than 10% of the variance in the factors. Cumulated, they explain 85% of the total variance. Table 3 summarizes the loadings and the importance of the first four components of the PCA, while Figure 5 shows biplots of these components. The first component consists of the summer meteorological values and contains 47% of the variance. The second component consists mainly of the sand fraction of the soil and to a minor degree the summer irradiation and minimum summer temperature. It contains 13% of the variance. The third component contains only the rotation length and the fourth factor contains only the irrigation volume. They each contain 13% of variance.

The first component of our PCA (Figure 5, Table 3) combines all climatic factors. The summer precipitation influences the component positively, while summer minimum, mean and maximum temperature and summer irradiation influence the component negatively. Therefore, a high component 1 points to a more temperate oceanic climate, with temperate wet summers, while a low component 1 indicates a more Mediterranean climate, with warm, dry summers.

Four linear models were constructed, explaining harvestable aboveground woody biomass production, net CO_2 uptake from the atmosphere, actual evapotranspiration and net energy balance as a function of the first four components of the PCA and all their possible interactions. Each of the models was significant (Biomass yield: $F(15,424)=83.35$, $p<0.001$; Net CO_2 emission: $F(15,424)=95.34$, $p<0.001$; Actual evapotranspiration: $F(15,424)=37.64$, $p<0.001$; Net energy balance: $F(15,424)=90.67$, $p<0.001$). The coefficients and their significance codes from these linear models are shown in (Table 4). For harvestable woody biomass production, net CO_2 uptake from the atmosphere and net energy balance, all four of the components, and the interaction between the first and the second component, and the interaction between the first and the fourth component were significant to the model. For actual evapotranspiration, the third component and the interaction between the first and the second component were not significant to the model.

The linear models of our PCA components (Table 4) show that both climate and soil composition have a significant influence on the aboveground woody biomass production, net CO_2 emission to the atmosphere, actual evapotranspiration and net energy balance. With the exception of actual evapotranspiration, the simulated effects of climate and soil composition are the same. Sites with a less Mediterranean climate have a higher aboveground woody biomass production, net CO_2 uptake from the atmosphere and net energy balance. A possible explanation is the limited summer precipitation in the Mediterranean climate that causes a higher water stress in the trees (Chapter 4, Figure 6). Higher sand fractions also result in higher aboveground woody biomass production, net CO_2 uptake from the atmosphere and net energy balance.

This is contrary to what we expected, as sandy soils have a lower water holding capacity, thus limiting the water availability for tree growth. Our simulations do not include all combinations between climate and soil, which might result in this illogical trend, as we are not looking at the entire trend. The effect is, however, quiet small for aboveground woody biomass production and energy balance. The interaction coefficient between the climate and soil fraction components is negative, which means that in a less Mediterranean climate, a higher sand fraction reduces the increase in aboveground woody biomass production, net CO_2 uptake from the atmosphere and net energy balance. A similar effect is illustrated by the negative interaction coefficient between climate and irrigation. Irrigation is more effective in increasing aboveground woody biomass production, net CO_2 uptake from the atmosphere and the net energy balance in a Mediterranean climate. This was to be expected, as the summer precipitation is low in this climate, thus creating a water-limited system.



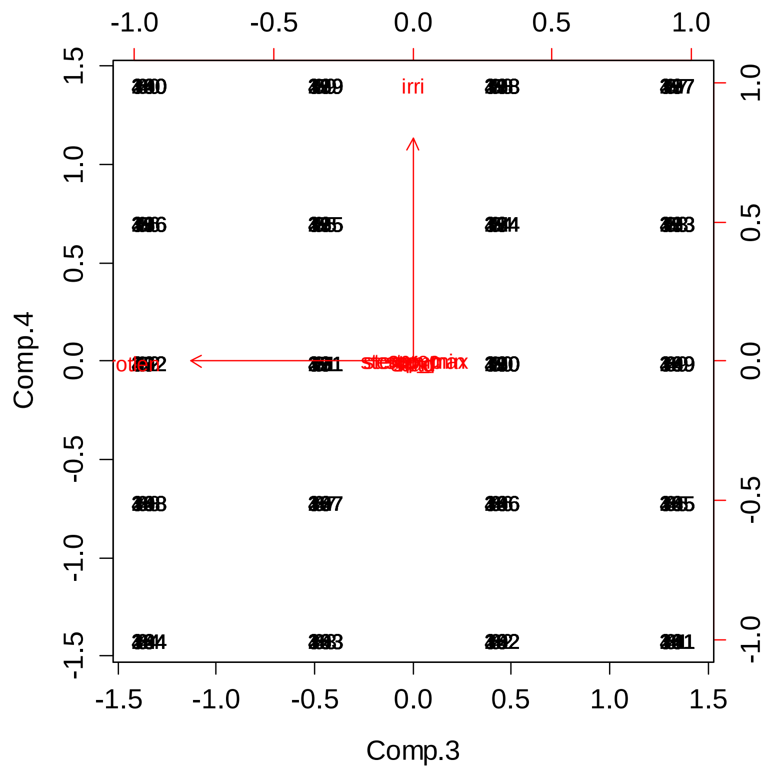


Figure 5: Biplots of the first four components of the PCA. stemp_min = summer minimum temperature, stemp = summer mean temperature, stemp_max = summer maximum temperature, srad = cumulated summer irradiation, sprec = total summer precipitation, sand = soil sand fraction, irri = irrigation volume, rotlen = rotation length.

Table 3: Loadings and importance of the first four components of the PCA.

	Comp.1	Comp.2	Comp.3	Comp.4
Summer minimum temperature	-0.406	0.156	-	-
Summer mean temperature	-0.502	-	-	-
Summer maximum temperature	-0.477	-	-	-
Total summer precipitation	0.448	-	-	-
Cumulated summer irradiation	-0.392	-0.246	-	-
Rotation length	-	-	-1.00	-
Irrigation volume	-	-	-	1.00
Soil sand fraction	-	0.955	-	-
Standard deviation	1.94	1.02	1.00	1.00
Proportion of Variance	0.471	0.131	0.125	0.125
Cumulative Proportion	0.471	0.602	0.727	0.852

Table 4: Significant coefficients of the linear models of the principal components.

Coefficients	Aboveground woody biomass production	Net CO_2 uptake from atmosphere	Actual evapotranspiration	Net energy balance
Intercept	(***) 7.51	(***) 2.15	(***) 430	(***) 38.2
Comp. 1	(***) 0.844	(***) 0.830	(***) -13.3	(***) 5.49
Comp. 2	(***) 0.183	(***) 0.657	(***) -8.60	(***) 1.19
Comp. 3	(***) 0.479	(***) 0.301	-	(***) 2.77
Comp. 4	(***) 0.365	(*) 0.116	(***) 14.7	(***) -4.34
Comp. 1 * comp. 2	(***) -0.128	(***) -0.344	-	(***) -0.830
Comp. 1 * comp. 4	(***) -0.116	(***) -0.176	(***) -8.39	(***) -0.755

Significance codes: 0 < *** ≤ 0.001 < ** ≤ 0.01 < * ≤ 0.05

4 Discussion

ORCHIDEE-SRC does not account for N or P availability. Therefore, the simulations assume perfect and free access to nutrients. It is well observed that this is not the case in intensive land uses such SRC (Schulze et al., 2012). Our simulations assume perfect and free access to nutrients. To achieve this, fertilization will probably be necessary, which is not included into our analysis. Fertilization will add an extra energetic and greenhouse gas cost from its production and application, as well as from on-site N_2O emissions (Bouwman et al., 2002). The levels of fertilizer required for maintaining SRC production, however, are not high (Adler et al., 2007), as only the nutrient low wood (Euring et al., 2014; Kostecki et al., 2015; Overend et al., 1985) is exported from the site while the nutrient rich leaves stay at the site . Therefore the impact of fertilizer on the management CO2 emissions and energy use should remain limited.

ORCHIDEE-SRC does also not include a survival cost for frequent cutting. Cutting the trees more frequently induces a larger stress to the trees, possibly exhausting the trees and killing them. This effect is however not well studied yet, and possibly genotype specific. Dillen et al. (2011), shows a mortality ranging from 9% to 92% for different genotypes after 15 years. The high mortalities are appointed to severe rust infections, competition by weeds or reduction in (re)growth vigour after multiple rotations. If there exists a survival cost that is linked to cutting frequency, than this will negatively influence the biomass yield from the shorter rotations over the entire life cycle of the plantation. This effect can possibly favour longer rotations, instead of the short rotations that are preferred in our analysis.

With the exception of weed control, pest control was not included in our analysis. Fungal and insect attacks on the trees are possible, but treatments are expensive and hard to apply on the tall trees (Hummel et al., 1988). As they do not generally kill the trees (Meridian Corporation, 1988), fungicide and insecticide applications are generally not applied to SRC plantations, except as a last resort in severe repeated infections. In case of infection, the biomass production will be lowered, but a good site design, with a mix of different genotypes should maximize the resistance against infections and therefore also minimize the yield losses (Hummel et al., 1988; Meridian Corporation, 1988).

The meteorological input files for our simulations are synthetic. Averaging of the meteorological years, can have unwanted side effects, such as spreading out precipitation. Short term, high intensity, meteorological events will be lost by our approach. We did, however, choose to use this approach to make the comparison of the management scenarios as objective as possible. By using the same average year for all simulations, there will be no hidden positive or negative influences of extreme weather conditions during a crucial stage in the development of the trees. Figure 18 (Chapter S), shows that there is no problem for temperature. But there is a significant effect on precipitation (Chapter S , Figure 15 – 17). The number of days without irrigation is drastically reduced, causing a more evenly spread irrigation. This effect is stronger for the temperate sites than for the Mediterranean sites, as the Mediterranean sites have a seasonal precipitation pattern, with low summer precipitation, that is retained in the averaged meteorological data. Using these averaged meteorological input files will possibly lead to an underestimation of the water stress levels, and therefore underestimate the irrigation requirements.

We found a two year rotation cycle to be optimal in all scenarios. This contradicts prior studies, where five year rotations were found to be optimal (Hofmann-Schielle et al., 1999; Kauter et al., 2003; Willebrand et al., 1993). This might be caused by a flaw in the vegetation model. ORCHIDEE-SRC did slightly overestimate the belowground biomass production (De Groote et al., 2015). Because of this, root production can stop earlier with carbon allocation shifting to aboveground woody tissues, making shorter rotations preferable. Moreover, in real life shorter rotations can be more demanding for the trees and might promote earlier mortality or a decreased long term yield. This effect is not well studied yet, and possibly genotype specific. Dillen et al. (2011), shows a mortality ranging from 9% to 92% for different genotypes after 15 years.

Our simulations show that a good site selection is more important than a good management selection. The climate is most important in site selection (Table 4), as it has the biggest coefficient. A temperate oceanic climate is preferable. If the site has to be established in a less favourable location, irrigation might be necessary to prevent the site from being a net CO_2 source, at the cost of decreasing the net energy output of the site. Even if irrigation is not applied in this scenario, the net CO_2 emission would still be lower than when that amount of electricity had to be produced using the current grid mix (564 g CO_{2e} kWh^{-1} (Djomo et al., 2013)).

The simulated biomass yields in the southern European sites are lower than the average reported yields for this region (Djomo et al., 2015). We found values of 2 up to 8 ton ha^{-1} yr^{-1}, while values for the 17 reported Mediterranean sites go up to 20 ton ha^{-1} yr^{-1} and average at 10 ton ha^{-1} yr^{-1}.This is possibly related to the fixed LAI_{max} which is used by ORCHIDEE. Poplar trees in the Mediterranean region can reach higher LAI values than those on more northern sites (personal communications with R. Ceulemans, 2014), to make more efficient use of the abundant sunlight. As our model limits this LAI, the Mediterranean trees in our model cannot exploit this advantage. For the temperate sites, our simulated biomass production is similar to the reported average of the 30 temperate sites of 8.5 ton ha^{-1} yr^{-1} (Djomo et al., 2015).

Adding irrigation increases aboveground woody biomass production. Looking only at this biomass production, our optimal management would be 2 year rotations with an irrigation of 200 mm yr^{-1}. The energetic cost of irrigation is however too high to be profitable (Figure 4h). The energy that is gained by increasing irrigation is lower than the energy required to irrigate the plantation, thus lowering the net energy balance. Therefore, for plantations with a temperate climate irrigation is not recommended. In plantations with a Mediterranean climate irrigation is probably necessary to assure tree survival.

Given that climate has a clear spatial location, as has energy production, it would be interesting to make this analysis at the national level. Despite the fact that France and Belgium have a temperate oceanic climate that is suitable for SRC, these countries get 50% to 70% of their energy from nuclear power and so there is little room to decrease their CO_2 emissions from electricity production. Contrary to this could be Poland, where much of the electricity comes from coal plants, so biomass could make a difference in the short term.

5 Conclusion

Our analysis shows that it is more important to select a good location for the installation of an SRC plantation, than it is to select the best management, as inter-site variation is generally larger than intra-site variation. Although, for poorly chosen locations, choosing the optimal management can mean the difference between a plantation that is a net carbon sink or one that is a net carbon source. The optimal SRC management scenario for plantations with a temperate climate in Europe has two-year rotations, without irrigation. Plantations with a drier Mediterranean climate will need irrigation to assure tree survival.

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Chapter 4 Growing short-rotation coppice in Europe in a future climate, a model study

We used the mechanistic model ORCHIDEE-SRC to simulate short rotation coppice (SRC) growth under current climate and under the IPCC RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 scenarios for the end of this century. We tested the model at various locations across Europe and varied management in terms of irrigation volume and rotation length. CO_2 emissions and energy use associated with the installation and management of the plantations was derived from the Ecoinvent 2.1 database, and taken into account when calculating the net energy balance and the net carbon balance of the plantations. Aboveground harvestable biomass, net CO_2 uptake from the atmosphere, evapotranspiration and the net energy balance were compared. In general, the future climate improved the potential of SRC plantations. From the perspective of renewable energy, the optimal management for all RCPs has two year rotations and no irrigation, except for the sites with a Mediterranean climate, for which irrigation is recommended.

1 Introduction

Anthropogenic CO_2 emissions have caused a dramatic rise in atmospheric CO_2 concentrations and already exceed pre-industrial levels by about 40% (IPCC, 2013a). About 26% of these emissions come from electricity production (IPCC, 2007b). Therefore, extensive research has gone into more renewable energy sources, ranging from wind, hydro and solar to biomass energy.

One promising source of biomass for energy is short rotation coppice (SRC) systems (EC, 2007), in which fast growing trees such as poplar (*Populus spp.*) or willow (*Salix spp.*) are grown in dense plantations and harvested frequently, allowing for fast production of woody biomass (Aylott et al., 2008; Herve et al., 1996). Carbon is taken up from the atmosphere during biomass growth and part of this carbon is emitted during the burning or gasification of the harvested biomass as CO_2. Theoretically, SRC plantations are therefore carbon neutral (Righelato et al., 2007). However, management is needed to assure fast growth of the trees, which also has a carbon and energy cost, implying that SRC is not entirely carbon neutral.

In a future climate, biomass production will most likely be influenced by the elevated CO_2, elevated temperatures and drier summers. Field experiments found that under elevated CO_2, the photosynthetic rate increases and the stomatal conductance decreases, resulting in an increase in water use efficiency (WUE) (Ainsworth & Long, 2005).

It is thus important to study SRC plantations also under these conditions. Representative concentration pathways (RCP) were created by the IPCC as a standard for scientist studying future climate. The four RCPs represent different possible futures for atmospheric CO_2 emissions. RCP 2.6 has a peak of atmospheric CO_2 concentration around mid-century and thereafter starts to decline again (van Vuuren et al., 2007). RCP 4.5 and RCP 6 are scenarios in which radiative forcing doesn't overshoot the long term target level. The atmospheric CO_2 concentration stabilizes shortly after 2100 (Clarke et al., 2007; Fujino et al., 2006; Hijioka et al., 2008; Smith et al., 2006; Wise et al., 2009). RCP 8.5 is a scenario in which CO_2 emissions keep rising, leading to very high atmospheric CO_2 concentrations (Riahi et al., 2007).

In this study we simulated the aboveground harvestable biomass, net CO_2 uptake from the atmosphere, evapotranspiration and the net energy balance of poplar SRC plantations under four RCP scenarios, at various sites across Europe, at the end of this century, and compared the results to current climate predictions.

2 Materials and Methods

2.1. Synoptic model description

We used the model ORCHIDEE-SRC (Chapter 1) for our simulations. This modification of the ORCHIDEE model (Bellassen et al., 2010; Ducoudre et al., 1993; Krinner et al., 2005), is aimed at simulating SRC plantations. ORCHIDEE-SRC includes modifications to (1) management, (2) growth, (3) allocation and (4) parameterization. The full details of the model modifications are provided in De Groote et al. (2015) (Chapter 1). The ORCHIDEE-SRC model reproduced biomass production, gross primary production (GPP), ecosystem respiration (R_{eco}) and latent heat (LE) loss very well (within 25% of the rotational total for biomass and within 5% of the rotational total for GPP, R_{eco} and LE).

ORCHIDEE is a mechanistic land surface model. The inputs for the model are, meteorological data: short and long wave incoming radiation, air temperature, specific humidity, wind speed, precipitation and atmospheric pressure; and site-specific parameters: site longitude and latitude, soil textural fractions, meteorological instrument height, plantation rotation cycle and initial planting density. The model simulates the carbon, water and energy fluxes at a half-hourly time step.

2.2. Meteorological data

We selected 22 sites (Table 1) from the European Fluxes Database Cluster (http://gaia.agraria.unitus.it, 1 September 2014) as meteorological inputs for ORCHIDEE-SRC. The selected sites had a public data access and open data use policy, and had at least five years of data.

The L2 (standardised) meteo data of the available years for these sites were used, because not all the selected years were available as L3 (quality assessed) or L4 (gap-filled) data. The half-hourly data were converted into the correct units for ORCHIDEE and per site an average meteorological year was calculated. Per site, the average years were calculated by taking the average value over all years for every half hour. For three sites, missing meteo data had to be gapfilled. Hyytiala (FI-Hyy) and Roccarespampani (It-Ro1) missed 1,350 out of 262,800 and 43 out of 175,200 data points respectively for long wave incoming radiation. Renon (IT-Ren) missed 4,753 out of 332,880 data points for precipitation. The gap-filling was done using data from the ERA-interim 3-hour product (Berrisford et al., 2011), based on the sites coordinates. The data were collected for the same years as the L2 site data. The missing data were subsequently replaced by the ERA-interim data.

Table 2: The sites and their characteristics.

				Location			Soil texture			Meteo	
Country	Site name	Site code	N° of years	Latitude	Longitude	Elevation	Clay	Silt	Sand	Annual (summer) temperature	Annual (summer) precipitation
						m	%	%	%	°C	mm
Belgium	Brasschaat	BE-Bra	14	51° 18' 33"	4° 31' 14"	16	3	8	89	10.6 (16.9)	848 (271)
Italy	Collelongo	IT-Col	15	41° 50' 58"	13° 35' 17"	1560	32	39	29 †	7.3 (15.3)	1160 (157)
Russia	Fyodorovskoye	RU-Fyo	13	56° 27' 42"	32° 55' 19"	210*	34	45	21 †	5.1 (15.9)	524 (230)
Germany	Grillenburg	DE-Gri	7	50° 56' 58"	13° 30' 45"	385	8	79	13	8.5 (16.6)	975 (308)
Germany	Hainich	DE-Hai	11	51° 04' 45"	10° 27' 11"	421*	31	42	27 †	8.3 (16.2)	779 (216)
Finland	Hyytiälä	FI-Hyy	15	61° 50' 51"	24° 17' 42"	181	10	19	71	4.1 (14.4)	555 (231)
Germany	Klingenberg	DE-Kli	7	50° 53' 34"	13° 31' 21"	478	56	23	21	7.6 (15.7)	801 (262)
Czech Republic	Laegern	CH-Lae	7	47° 28' 41"	8° 21' 54"	846*	28	40	32 †	7.7 (15.8)	777 (271)
Spain	Las Majadas del Tietar	ES-LMa	7	39° 56' 29"	-5° 46' 24"	260	9	11	80	16.1 (25.8)	721 (32)
Italy	Lavarone	IT-Lav	11	45° 57' 22"	11° 16' 53"	1228*	31	41	28 †	6.9 (14.8)	1263 (364)
The Netherlands	Loobos	NL-Loo	15	52° 09' 60"	5° 44' 37"	25	0	0	100	10.0 (16.8)	872 (239)
France	Mauzac	FR-Mau	6	43° 23' 07"	1° 17' 32"	189	24	45	31	12.7 (20.4)	566 (105)
Portugal	Mitra IV (Tojal)	PT-Mi2	5	38° 28' 35"	-8° 01' 28"	200*	28	34	38 †	14.2 (21.6)	588 (26)
Austria	Neustift	AT-Neu	9	47° 07' 00"	11° 19' 03"	970	5	41	54	6.8 (15.4)	700 (291)
United Kingdom	Pang/Lambourne forest	UK-PL3	5	51° 27' 00"	-1° 16' 00"	119*	20	39	41 †	12.3 (17.9)	658 (199)
France	Puechabon	FR-Pue	11	43° 44' 29"	3° 35' 45"	270	39	35	26	13.6 (21.7)	894 (108)
Italy	Renon	IT-Ren	19	46° 35' 13"	11° 26' 01"	1730	14	36	50 †	4.5 (12.3)	1219 (496)
Italy	Roccarespampani 1	IT-Ro1	10	42° 24' 29"	11° 55' 48"	139*	34	33	33 †	15.6 (23.6)	840 (151)
Italy	San Rossore	IT-SRo	12	43° 43' 40"	10° 17' 04"	6	32	39	29 †	15.2 (23.1)	921 (130)
Denmark	Soroe	DK-Sor	15	55° 29' 09"	11° 38' 41"	40	24	37	39 †	8.4 (16.1)	760 (229)
Germany	Tharandt	DE-Tha	15	50° 57' 49"	13° 34' 01"	380	17	71	12	8.6 (16.7)	871 (263)
Germany	Wetzstein	DE-Wet	7	50° 27' 13"	11° 27' 27"	751*	28	38	34 †	6.5 (14.7)	971 (231)

* Elevation data from Google Maps: http://maps.google.com
† Soil texture data from Luyssaert, S., et al., CO_2 balance of boreal, temperate, and tropical forests derived from a global database. Global Change Biology, 2007. 13(12): p. 2509-2537

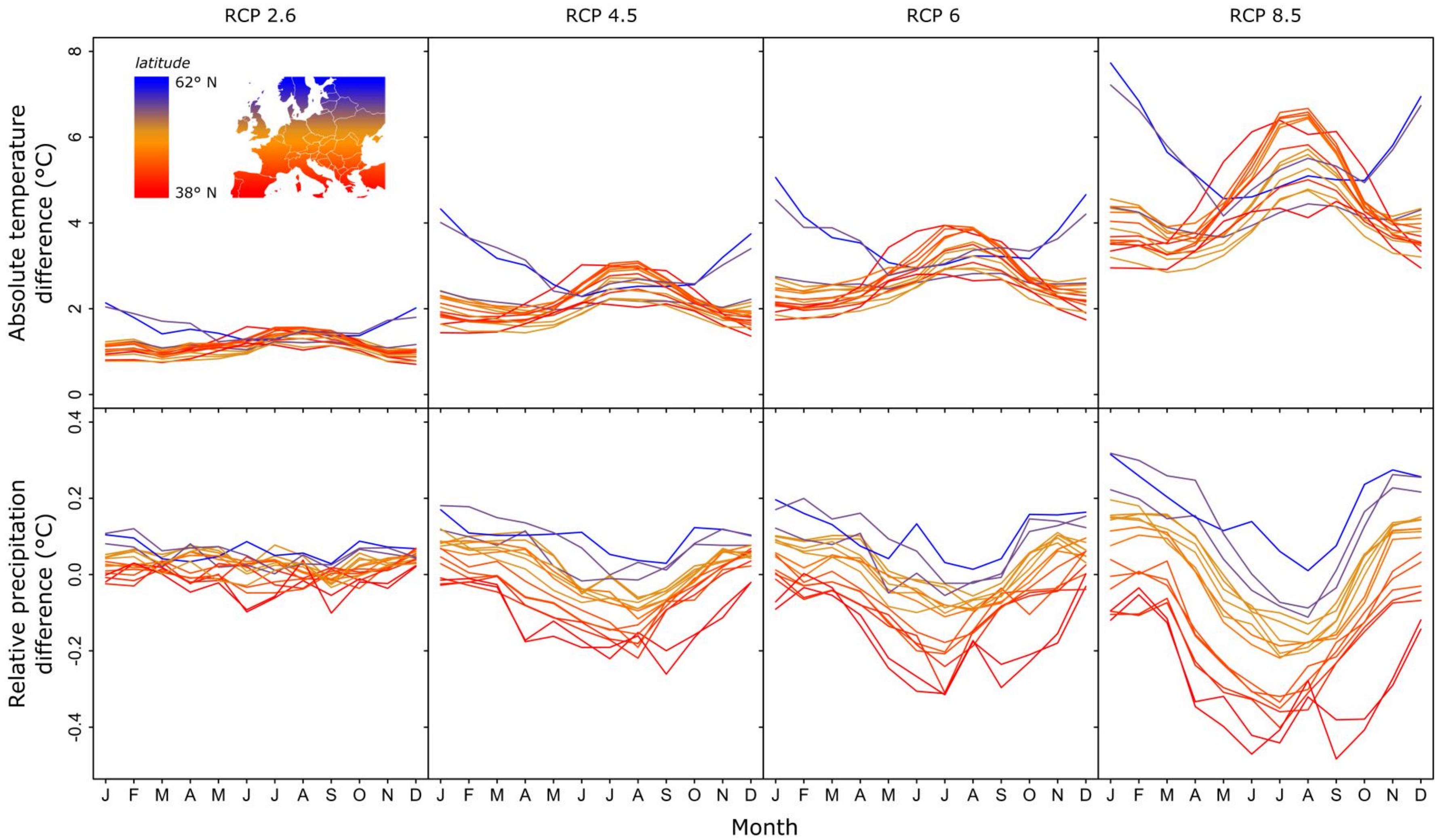


Figure 1: Annual differences in temperature and precipitation for the four RCP scenarios for the period 2081-2100. Every line stands for a different test site. The colour of the lines shows the latitude of the test sites, from blue for the most northern site to red for the most southern site.

Only 10 of these sites reported data on soil texture. Luyssaert et al. (2007) was used to retrieve soil texture data for the missing sites. They are not the observed soil fraction, but the most likely soil fraction.

2.3. Future climate data

Using the KNMI (Royal Dutch Meteorological Institute) Climate Change Atlas (http://climexp.knmi.nl/plot_atlas_form.py), monthly data were exported from the CMIP5 dataset (IPCC AR5 Atlas subset (IPCC, 2013a)). A first set of data contained the absolute difference in near-surface temperature for the future period 2081-2100 compared to the reference period 1986-2005 for RCP 2.6, 4.5, 6.0 and 8.5 across Europe. The second set of data contained the relative difference in precipitation for the future period 2081-2100 compared to the reference period 1986-2005 for RCP 2.6, 4.5, 6.0 and 8.5 across Europe.

In these datasets, we located the corresponding grid cells for every test site, and extracted the value for all twelve months and all four RCPs. The temperature and precipitation from the reference meteorological data sets were adjusted in accordance with the extracted differences.

For all sites, the temperature increased for the entire year (Figure 1, first row). For all sites, except the two most northern sites, the temperature increase was strongest during the summer period. The two most northern sites: Fyodorovskoye (RU-Fyo) and Hyytiälä (FI-Hyy) showed the reverse of this pattern. RCPs with higher atmospheric CO_2 concentrations had a larger increase in surface temperature.

The relative precipitation change did not show a seasonal pattern for RCP 2.6, but for the high emission RCPs, it evolved into a pattern of wetter winters and drier summers (Figure 1, second row). The most northern sites had a net increase in precipitation, while the southern sites had a net decrease in precipitation.

Projections for atmospheric CO_2 concentrations for the four RCP scenarios were acquired from Meinshausen et al. (2011) (Figure 2).

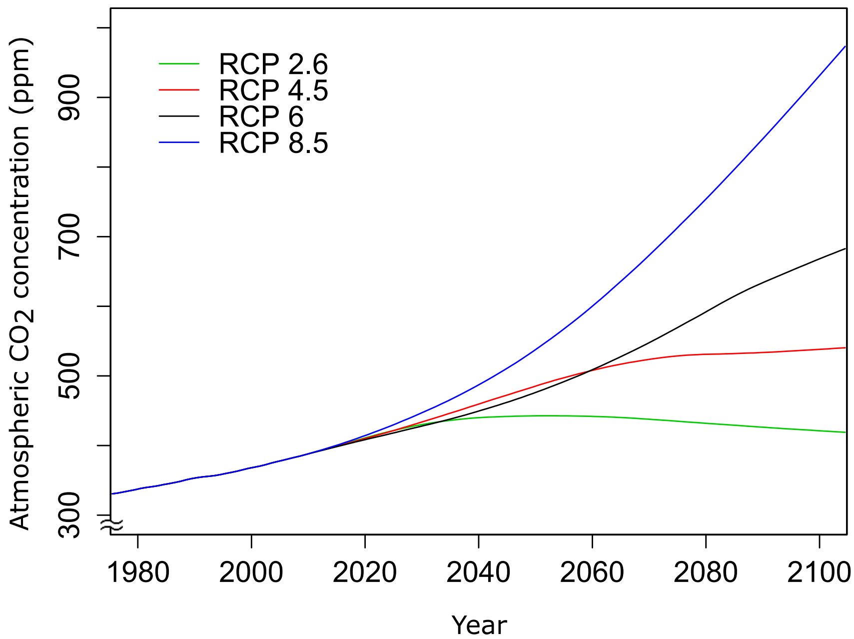


Figure 2: The atmospheric CO_2 concentrations for the four RCP scenarios from 1980 until 2100 according to Meinshausen et al. (2011), used for the ORCHIDEE-SRC model runs. Note that the CO_2 concentration does not start at zero.

2.4. Management activities

The CO_2 emissions and energy use of management activities were not calculated with ORCHIDEE-SRC, but were calculated separately from the Ecoinvent 2.1 (Frischknecht et al., 2007) database using Simapro 7.1 (PRé, 2007). We included the management activities ploughing, mechanical and chemical weeding, planting, irrigation, fertilization, harvesting and transportation (Table 2). The activities were implemented in the following configuration. Before planting, cuttings of 10 g each were transported to the plantation from a supply station over a distance of 150 km. The soil was prepared by mechanical weeding, ploughing and one chemical herbicide application. After the soil preparation, the cuttings were planted using a standard leek planter. The cuttings grew into trees, and irrigation was applied in accordance with the management scenario. Irrigation was applied weekly from April until September, and the volume was evenly distributed to cumulate to the pre-set volume over the entire year. At the end of each rotation, the plantation was harvested with a modified combine harvester and the cuttings were transported to a power station 50 km from the plantation. After the harvest, chemical herbicide was applied to prevent weed growth during the sprouting of the new stems and this cycle continued until the plantation was twenty years old. After twenty years, the trees were harvested irrespective of the rotation scheme and the stumps were removed from the soil.

ORCHIDEE-SRC assumes that the soil contains enough nutrients and does not require fertilization. In reality, fertilization might be required. SRC is usually harvested during winter, when the trees are dormant and have no leaves. The leaves and bark contain the majority of the nutrients (Kostecki et al., 2015) and this way most of the nutrients are recycled. Fertilisation with a 20-5-5 NPK fertiliser was included in with the management activities, to replace exactly the amount of nitrogen lost by the harvest, based on the yield. We assumed a nitrogen concentration in the wood of 0.2% of DM (Euring et al., 2014; Kostecki et al., 2015; Overend et al., 1985). After fertilizer application, an important N_2O flux from fertilizer denitrification might occur. We used the average of 1% of the applied amount of nitrogen (Bouwman et al., 2002). For the conversion from N_2O to CO_2, we used the 100 year global warming potential of 298.

Table 2: CO_2 emission and energy use of the applied management activities

Cost	CO_2 emission kg CO_2 ha^{-1}	Energy use MJ ha^{-1}
Ploughing	57.7	981
Mechanical weeding	14.5	295
Chemical weeding	10.0	178
Planting	90.5	1 610
Irrigation (per mm)	2.25	950
Fertilisation	24.2	398
Fertilisation (per ton biomass)	14.3	131
Fertiliser denitrification (per ton biomass)	5.96	/
Harvest	41.9	2 890
Transport (per ton per km)	0.213	3.72
Stump removal	15.7	1 810

2.5. Simulation setup

For each of the 22 sites and four RCPs, a spinup was run to initialize the soil carbon pool. This spinup was performed by running the model with the input data repeatedly, until a soil carbon equilibrium was reached after 1510 years. More detailed information about this spinup procedure can be found in De Groote et al. (2015).

All simulations, for every test site, were run for twenty years, starting in 2081 and ending in 2100. Twenty different management scenarios were used for each of the four RCP scenarios. Each management scenarios varied in rotation length and irrigation volume. Rotation length ranged from two year to five year cutting cycles. The irrigation amount ranged from 0 to 200 mm per year at 50 mm increments. After twenty years, each plantation was stopped, irrespective of the rotation length.

2.6. Data analysis

For each of the simulations, the harvestable aboveground woody biomass yield and the actual evapotranspiration were taken directly from the model outputs. For the calculation of net CO_2 uptake from the atmosphere and energy balance, additional data were used from Ecoinvent 2.1 database (Frischknecht et al., 2007).

CO_2 uptake was calculated as the net balance of (i) photosynthesis, (ii) ecosystem respiration, (iii) management CO_2 emissions, (iv) emissions from converting the biomass into electricity and (v) the saved emissions from substituting grid mix electricity with the bioelectricity produced by the biomass.

The energy balance was calculated as the net difference between the energy produced by converting the biomass into electricity and the energy used by the SRC management and biomass transport.

The effect of the RCPs and management scenarios, independent of the site, was analysed using a linear mixed effects analysis. As fixed effects, the rotation length, irrigation volume and RCP were added to the model. As random effect, site was chosen with random intercepts. P-values were obtained by ratio-likelihood tests of the full model with management and RCP against the model without the variable in question.

To attribute the difference in aboveground harvestable biomass, net CO_2 uptake from the atmosphere, actual evapotranspiration and energy balance to their drivers, a linear model was constructed using meteorological, management, RCP and soil dependent factors. Since co-variation between a number of the factors occurred, the factors were clustered using a Principal Component Analysis (PCA) to account for the difference in magnitude of the different units of the factors.

The management CO_2 and energy data were calculated using Simapro 7.1 (PRé, 2007). Input file creation and general data processing was performed using Matlab R2013a (The MathWorks Inc, 2013). The statistical analyses were performed using R 3.2.1 (R Core Team, 2014). The linear mixed effects analysis was performed using the lme4 package for R (Bates et al., 2014).

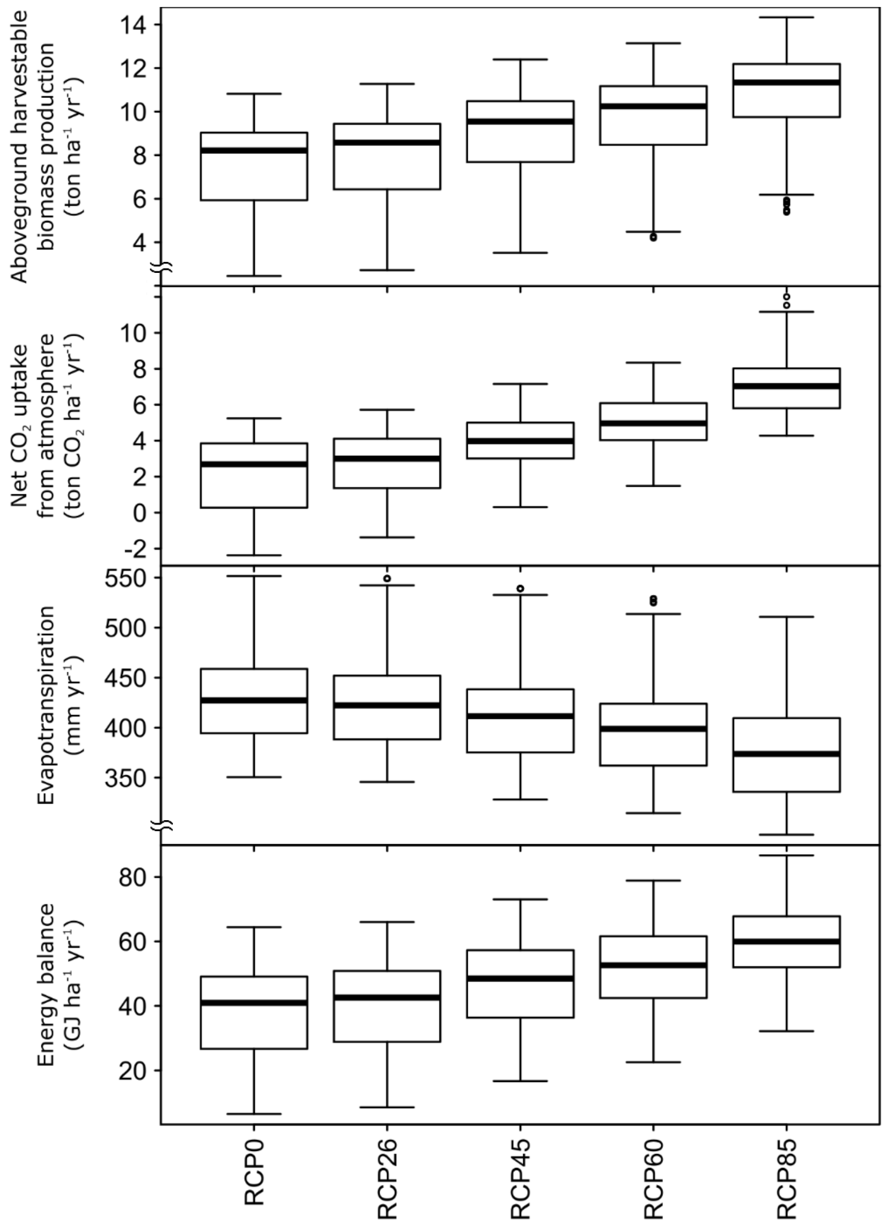


Figure 3: Box plots showing the effect of the different climate scenarios on aboveground harvestable biomass, net CO_2 uptake from the atmosphere, evapotranspiration and the energy balance. RCP0 = current climate 2000-2010, RCP26 = climate in 2081 until 2100 for RCP 2.6, RCP45 = climate in 2081 until 2100 for RCP 4.5, RCP60 = climate in 2081 until 2100 for RCP 6, RCP85 = climate in 2081 until 2100 for RCP 8.5. Note that not all axes contain zero.

3 Results

3.1. General trends of different climate scenarios

We found general trends in the effects of the different climate scenarios on aboveground harvestable biomass yield, net CO_2 uptake from the atmosphere, actual evapotranspiration and energy balance (Figure 3).

The aboveground harvestable biomass showed a positive correlation with the atmospheric CO_2 concentration. The variation among different sites and management scenarios decreased with increasing atmospheric CO_2 concentrations, suggesting that despite the increasingly drier climate in most of Europe, the biomass yield increased at all sites.

The net CO_2 uptake from the atmosphere showed the same pattern as the aboveground harvestable biomass. The CO_2 uptake increased and its range decreased with higher atmospheric CO_2 concentrations.

The actual evapotranspiration decreased for scenarios with higher atmospheric CO_2 concentrations. This is a result of the assumed increase in WUE of our model, as also suggested in many field experiments (Battipaglia et al., 2013; Liberloo et al., 2009; Scarascia-Mugnozza et al., 2006).

The energy balance showed the same pattern as the aboveground harvestable biomass and net CO_2 uptake from the atmosphere. This result was expected, since the management energy cost and the energy substitution did not change between RCP scenarios. Therefore, the energy balance followed the main changing driver, which was the aboveground harvestable biomass production.

The effect of RCP on these four variables was statistically significant according to the ratio-likelihood test ($p < 0.001$) of the linear mixed-effects models.

The increased biomass production and the decreased actual evapotranspiration showed that the water use efficiency (WUE) of the trees improved with rising atmospheric CO_2 concentrations. The WUE improved faster than the drought intensified.

3.2. Site based effects of different climate scenarios

Under current climate conditions, the aboveground harvestable biomass (Figure 4, first row) showed lower biomass yields for sites with a Mediterranean climate compared to the sites with a more temperate climate. Under future climate scenarios, the aboveground harvestable biomass increased with increasing atmospheric CO_2 concentrations for all sites, but the effect was not the same for all the sites. While the temperate sites showed an equal increase in biomass yield for all management scenarios, the Mediterranean sites showed a stronger increase in yield for the best performing management scenarios.

The net CO_2 uptake from the atmosphere (Figure 4, second row) showed a similar contrast between temperate climate sites and Mediterranean sites for the current climate. Choosing the wrong management scenario can even lead to a net CO_2 emission instead of an uptake from the atmosphere. In the future climate scenarios, the net CO_2 uptake from the atmosphere increases with increasing atmospheric CO_2 concentration. RCP 4.5, 6 and 8.5 have no scenarios with net CO_2 emission anymore. The net CO_2 uptake increased faster for the Mediterranean sites than for the temperate sites under higher atmospheric CO_2 concentrations. The spread of the net CO_2 uptake also increased for the Mediterranean sites. Under RCP 8.5 the worst performing (i.e. lowest net CO_2 uptake) management scenarios of the Mediterranean sites had a similar net CO_2 uptake as the worst performing temperate management scenarios and the best performing Mediterranean management scenarios exhibited larger uptake than the best performing temperate management scenarios (Figure 4, second row, fifth column).

The actual evapotranspiration (Figure 4, third row) under the current climate showed a large range for the Mediterranean climates and a very narrow range for the temperate climates. Under future climate simulations, the actual evapotranspiration decreased for all sites, especially at the temperate sites. The range of the actual evapotranspiration values per site decreased.

The net energy balance (Figure 4, fourth row) also showed a marked difference between the temperate and the Mediterranean sites, with the latter having lower energy balances. The future scenarios with warmer climates and higher atmospheric CO_2 concentrations had higher energy balances. The increase was stronger for the Mediterranean sites than for the temperate sites. This showed that future climates may still provide a stable, guaranteed energy production from biomass.

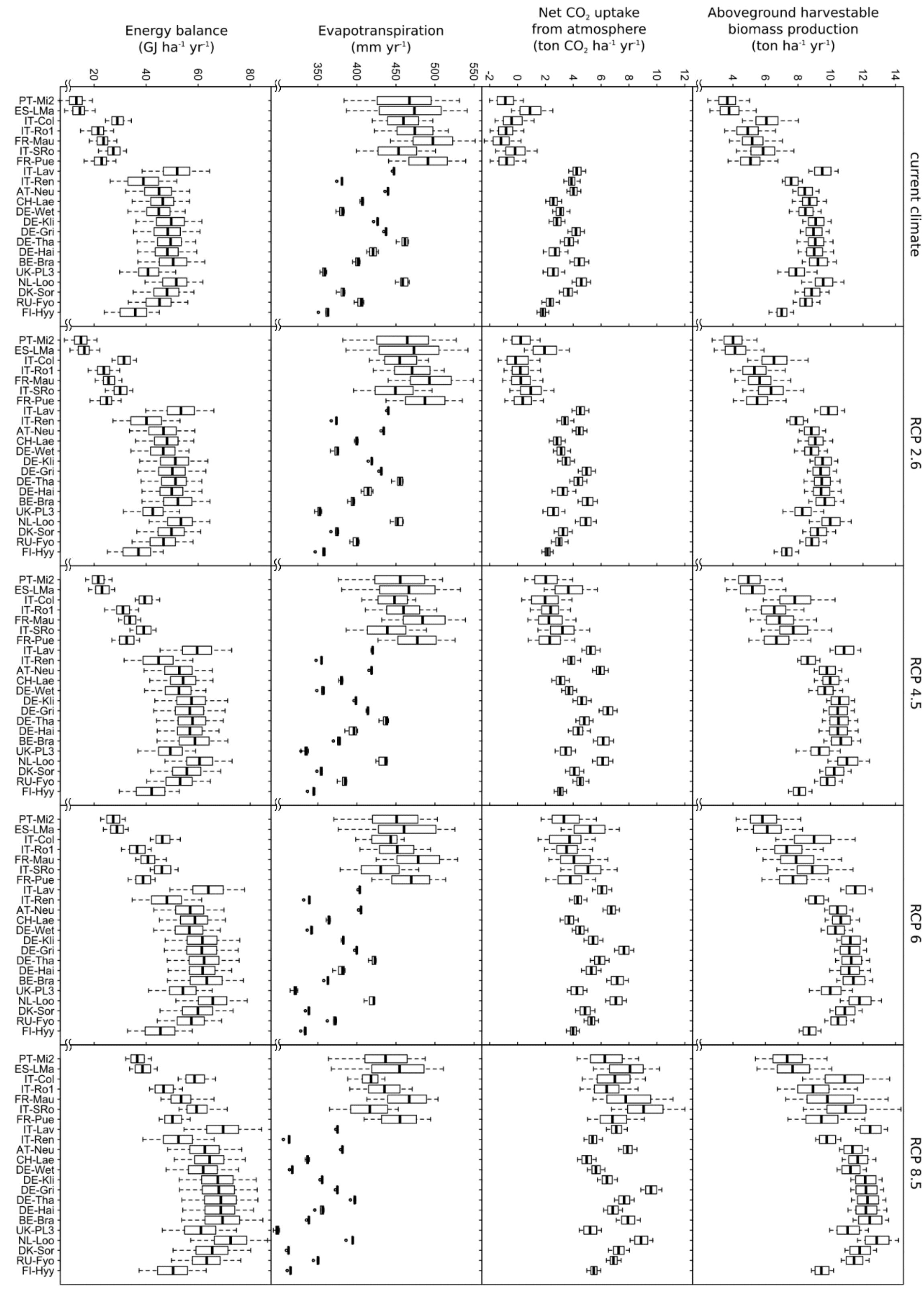


Figure 4: Boxplots showing the variation in aboveground harvestable biomass, net CO_2 uptake from the atmosphere, actual evapotranspiration and energy balance per site. The columns are different RCP scenarios. Sites are arranged from the lowest to highest latitude. Note that not all axes contain zero.

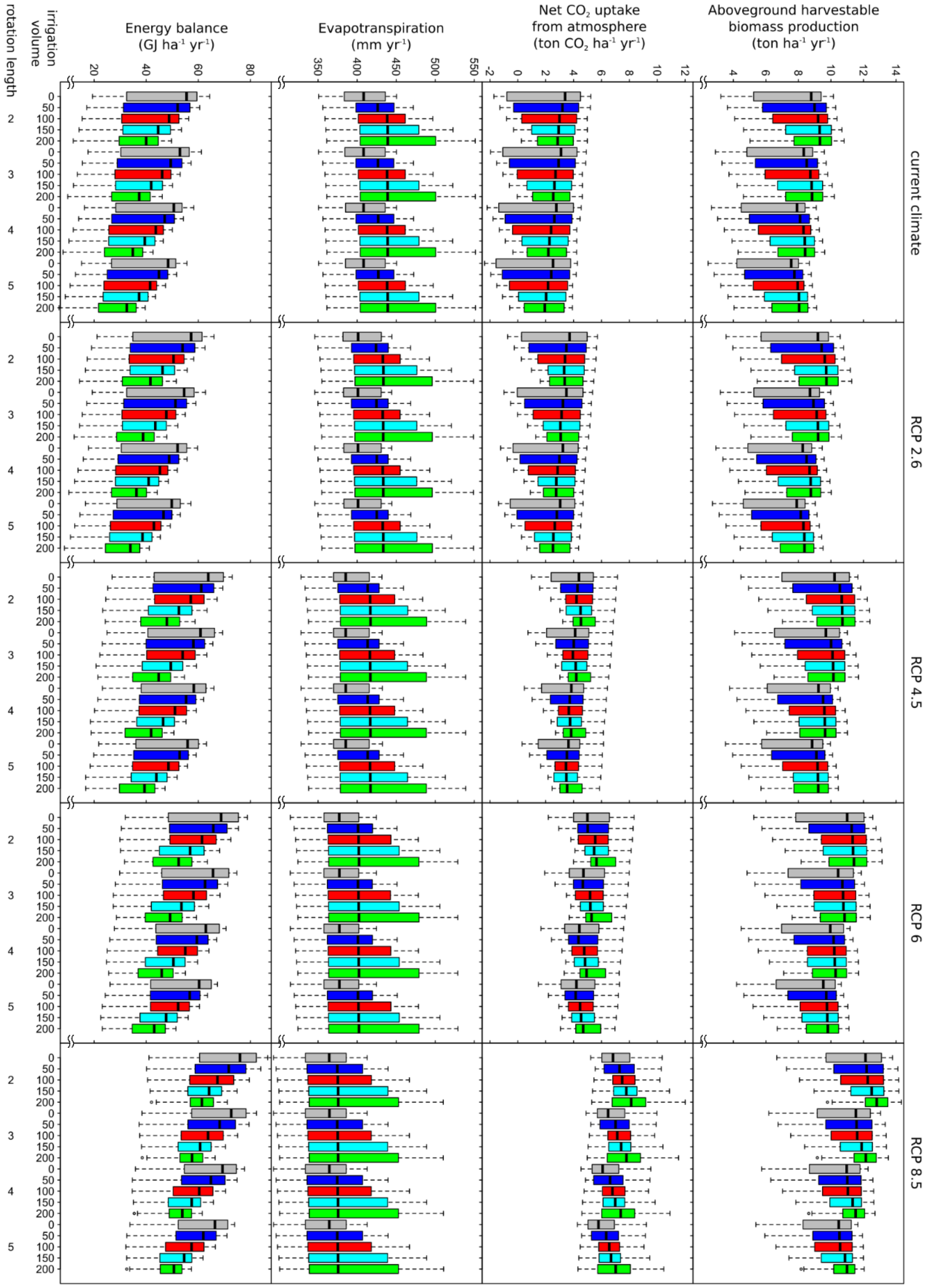


Figure 5: Boxplots showing the variation in aboveground harvestable biomass, net CO_2 uptake from the atmosphere, actual evapotranspiration and energy balance per management scenario. The columns are different RCP scenarios. The different colours denote different irrigation volumes: grey = 0 mm yr^{-1}, blue = 50 mm yr^{-1}, red = 100 mm yr^{-1}, cyan = 150 mm yr^{-1}, green= 200 mm yr^{-1}. Note that not all axes contain zero.

Under current climate, the aboveground harvestable biomass had an optimum for temperate sites, and declined for higher latitude sites and lower latitude sites. The higher atmospheric CO_2 concentrations enhanced biomass yield, but more strongly for the lower latitude sites, i.e. Mediterranean sites, although these sites had the most negative precipitation change (Figure 1). The range of biomass yields in these Mediterranean sites became larger for the high emission RCPs. The difference could be attributed to the impact of irrigation in the increasingly drier Mediterranean sites. The rainfed sites had a biomass increase comparable to the temperate sites, while the irrigated sites showed a much stronger growth.

3.3. Management based effects of different scenarios

The aboveground harvestable biomass (Figure 5, first row) showed that both shorter rotation lengths and more irrigation had a positive impact on aboveground harvestable biomass. In the future climate simulations, the biomass yield increased for all simulations, but more prominently for the more extreme RCPs. Under the high RCP scenarios, water stress is lower (Figure 6) and adding irrigation has a larger effect on the water stress. Under current climate conditions, the temperate sites already had low water stress levels, therefore the RCP effect on water stress is less prominent. In the Mediterranean sites with high water stress levels, the water stress can decrease more. Because of the favourable climate and decreasing water stress, the biomass production in the Mediterranean sites can catch up with the production in the temperate sites. The range of biomass yields became smaller for the higher RCPs, which implied a more certain biomass yield across different sites.

The net CO_2 uptake from the atmosphere (Figure 5, second row) decreased for longer rotations and for more irrigation, because of the large CO_2 output of irrigation pumps. For RCP 8.5, however, the net CO_2 uptake from the atmosphere increases with higher irrigation volumes. The irrigation effect on the Mediterranean sites surpassed the temperate sites' CO_2 uptake in RCP 8.5 (Figure 4, second row). The scenarios with higher atmospheric CO_2 had overall higher CO_2 uptake and the range became smaller.

The actual evapotranspiration (Figure 5, third row) did not differ noticeably between rotation lengths, but it increased with irrigation volume. With increasing atmospheric CO_2 concentration the actual evapotranspiration decreased, but the overall pattern did not change.

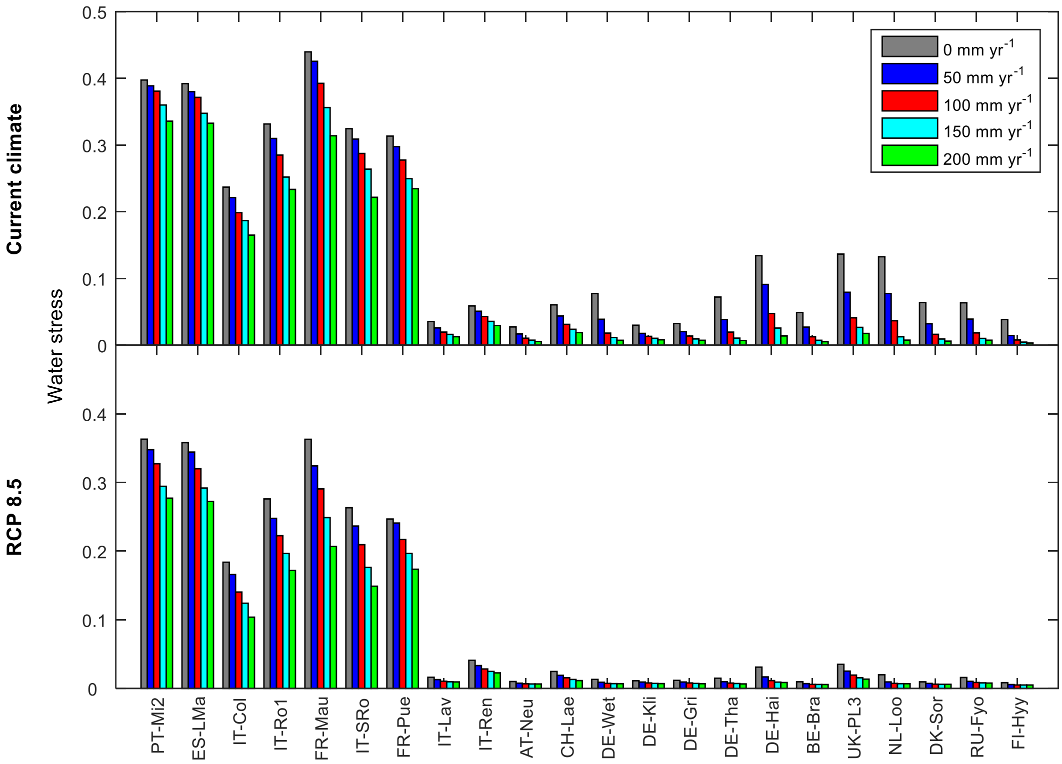


Figure 6: The mean annual relative water stress for 2 year rotations, using an irrigation volume of 0, 50, 100, 150 and 200 mm yr^{-1}. Sites are ordered from south to north.

The energy balance (Figure 5, fourth row) was larger for shorter rotation lengths or lower irrigation volumes. The latter was caused by the enormous energy cost of the irrigation pumps. The negative effect of irrigation is also more prominent than the negative effect of longer rotations. With higher atmospheric CO_2 concentrations the energy balance increased, because of the higher biomass production, while the management energy costs remained the same.

3.4. Attribution to drivers

A PCA was performed using minimum summer temperature, mean summer temperature, maximum summer temperature, summer precipitation, summer incoming radiation, rotation length, irrigation, soil sand content, soil clay content and RCP scenario. The first five components explained 88% of the total variance (Table 3).

The first component had the highest loading of the meteorological indicators: minimum summer temperature, mean summer temperature, maximum summer temperature, summer precipitation and summer incoming radiation (Figure 7, Table 3) and explained 40% of the variance. The second component mainly reflected soil defining characteristics: soil sand and clay content (Figure 7, Table 3) and explained 17% of the variance. The third component had the highest loading of the RCP scenarios, but also had some climate influence, mainly summer incoming radiation (Figure 7, Table 3) and explained 11% of the variance. Components 4 and 5 each explained 10% of the variance and consisted of irrigation volume and rotation length respectively (Figure 7, Table 3).

All five principal components were significant in explaining the variance of aboveground harvestable biomass, net CO_2 uptake from the atmosphere, evapotranspiration and energy balance ($p < 0.001$, Table 4), except for component five, rotation length, which wasn't significant for explaining actual evapotranspiration. The third component, which consisted mainly of RCP, had the largest effect on these four variables.

The different RCP scenarios had different effects for different sites (Figure 4), and managements (Figure 5). This finding was also supported by the PCA linear models, where the RCP component had significant interactions with climate, soil, irrigation and rotation length for all predicted variables. Only net CO_2 balance and evapotranspiration, lacked the RCP interaction with rotation length.

Table 3: The loadings of the first five principal components of the PCA and the proportion of the variance explained.

	Comp.1	Comp.2	Comp.3	Comp.4	Comp.5
Minimum summer temperature	-0.421	-0.124	0.255	-	-
Mean summer temperature	-0.489	-	-	-	-
Maximum summer temperature	-0.467	-	-0.105	-	-
Total summer precipitation	0.420	-	0.294	-	-
Total summer incoming radiation	-0.353	0.185	-0.420	-	-
Rotation length	-	-	-	-	1.000
Irrigation	-	-	-	1.000	-
Soil sand content	-	-0.674	-0.246	-	-
Soil clay content	-0.113	0.673	0.122	-	-
RCP	-0.228	-0.174	0.764	-	-
Standard deviation	1.99	1.32	1.05	1.00	1.00
Proportion of Variance	0.396	0.173	0.110	0.100	0.100
Cumulative Proportion	0.396	0.569	0.679	0.779	0.879

Table 4: The significant coefficients and their significance codes for the models using the first five principal components to explain aboveground harvestable biomass, net CO_2 uptake from the atmosphere, actual evapotranspiration and the energy balance.

	Aboveground harvestable biomass	Net CO_2 uptake from atmosphere	Actual evapotranspiration	Energy balance
Intercept	(***) 9.030	(***) 4.002	(***) 408.91	(***) 46.705
comp. 1	(***) 0.290	(***) -0.126	(***) -11.52	(***) 1.850
comp. 2	(***) -0.334	(***) -0.770	(***) 7.81	(***) -2.133
comp. 3	(***) 1.637	(***) 1.477	(***) -31.06	(***) 10.445
comp. 4	(***) 0.387	(***) 0.193	(***) 14.23	(***) -4.250
comp. 5	(***) -0.564	(***) -0.335	-	(***) -3.155
comp. 1 : comp. 2	(***) 0.178	(***) 0.243	-	(***) 1.138
comp. 1 : comp. 3	(***) -0.179	(***) -0.270	(***) -3.63	(***) -1.139
comp. 2 : comp. 3	(***) 0.152	(***) 0.228	(***) 2.01	(***) 0.971
comp. 1 : comp. 4	(***) -0.177	(***) -0.227	(***) -6.52	(***) -1.130
comp. 2 : comp. 4	(**) 0.043	(*) 0.037	(*) 1.25	(**) 0.275
comp. 3 : comp. 4	(***) -0.172	(***) -0.187	(***) -9.25	(***) -1.101
comp. 1 : comp. 5	-	-	-	-
comp. 2 : comp. 5	-	-	-	-
comp. 3 : comp. 5	(***) -0.068	-	-	(***) -0.439
comp. 4: comp. 5	-	-	-	-

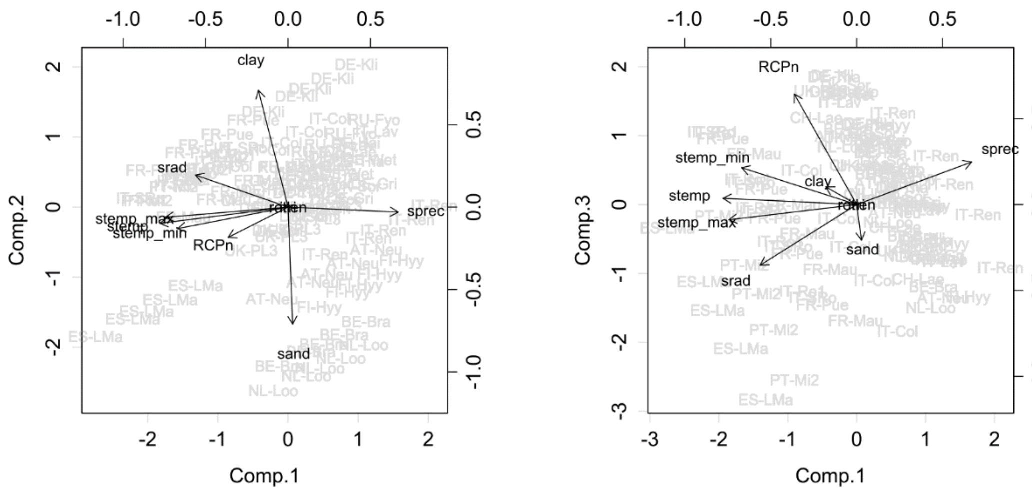
Significance codes: 0 < *** ≤ 0.001 < ** ≤ 0.01 < * ≤ 0.05

4 Discussion

4.1. General discussion

Scarascia-Mugnozza et al. (2006) found an average aboveground biomass increase of 20% in an irrigated SRC with elevated CO_2 (550 ppm) comparable to the levels in our RCP 4.5 simulations, which matched our results.

Our results showed an increase in WUE under future climate, that improved faster than the drought intensified. The increased atmospheric CO_2 concentration resulted in a lower stomatal conductance, and a subsequent lower plant transpiration (Field et al., 1995). Battipaglia et al. (2013) found an increase in poplar WUE of 75% under elevated CO_2 levels comparable to our RCP 4.5 simulations. In our model, ORCHIDEE-SRC, the carbon



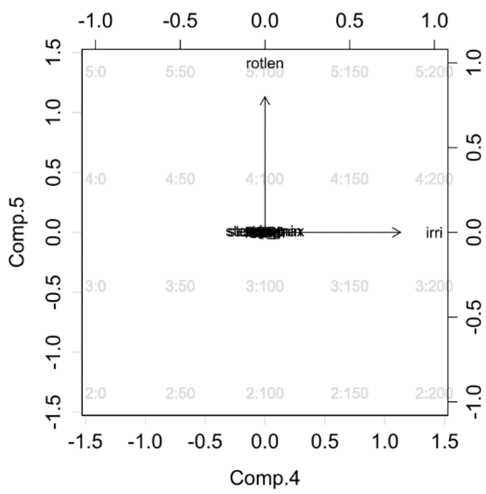


Figure 7: Biplots of the first five components of the PCA. stemp_min = minimum summer temperature, stemp = mean summer temperature, stemp_max = maximum summer temperature, srad = cumulated incoming summer irradiation, sprec = total summer precipitation, sand = soil sand fraction, clay = soil clay fraction, irri = irrigation volume, rotlen = rotation length, RCPn = RCP.

assimilation and stomatal conductance were calculated mechanistically following Farquhar et al. (1980) and Ball et al. (1987) respectively. A number of field studies found an acclimation of trees to elevated CO_2 levels (Ainsworth et al., 2005). This acclimation was found to be linked to a reduction in the maximum carboxylation rate and the maximum rate of electron transport of the photosynthesis, caused by nitrogen limitation. Since our simulations included fertilization, this acclimation should not manifest itself.

The simulated biomass yields in the southern European sites are lower than the average reported yields for this region (Djomo et al., 2015). We found values of 2 up to 8 ton ha^{-1} yr^{-1}, while values for the 17 reported Mediterranean sites go up to 20 ton ha^{-1} yr^{-1} and average at 10 ton ha^{-1} yr^{-1}.This is possibly related to the fixed LAI_{max} which is used by ORCHIDEE. Poplar trees in the Mediterranean region can reach higher LAI values than those on more northern sites (personal communications with R. Ceulemans, 2014), to make more efficient use of the abundant sunlight. As our model limits this LAI, the Mediterranean trees in our model cannot exploit this advantage. For the temperate sites, our simulated biomass production is similar to the reported average of the 30 temperate sites of 8.5 ton ha^{-1} yr^{-1} (Djomo et al., 2015).

We found a two year rotation cycle to be optimal in all scenarios. This contradicts prior studies, where five year rotations were found to be optimal (Hofmann-Schielle et al., 1999; Kauter et al., 2003; Willebrand et al., 1993). This might be caused by a flaw in the vegetation model. ORCHIDEE-SRC did slightly overestimate the belowground biomass production (De Groote et al., 2015). Because of this, root production can stop earlier with carbon allocation shifting to aboveground woody tissues, making shorter rotations preferable. Moreover, in real life shorter rotations can be more demanding for the trees and might promote earlier mortality or a decreased long term yield. This effect is not well studied yet, and possibly genotype specific. Dillen et al. (2011), shows a mortality ranging from 9% to 92% for different genotypes after 15 years.

The patterns of the aboveground harvestable biomass were similar to the net CO_2 uptake from the atmosphere and the energy balance. This could be explained by the important role of biomass yield for the two latter factors. While the CO_2 uptake from the larger biomass increased, the management related CO_2 emissions stayed the same. The energy output increased because of the increased biomass yield, while the energy input of the management activities stayed the same. The increase in energy output was, however, not large enough to overcome the large costs of irrigation. Therefore, from an energetic point of view, irrigation was not favourable. For the Mediterranean sites, however, other studies found irrigation to be critical for tree survival in Mediterranean sites (Bergante et al., 2010; Fichot et al., 2015). Therefore, at these sites, irrigation is needed, but comes at a high energetic expense, substantially reducing the net energy balance despite the higher productivity.

4.2. Choosing a management

The choice of the optimal management for SRC is dependent on the optimization aim. The farmer, whose income is dependent on the biomass yield, would prefer a scenario with much irrigation and two year rotations. However, irrigation and harvesting also cost money, so a financial analysis should be made by the farmer, to compare the income of the increased yield with the management cost. Whichever management the farmer chooses, in a future climate, his yield will increase.

The management can also be optimized for carbon sequestration. For temperate sites, shorter rotations without irrigation have the highest net CO_2 uptake from the atmosphere and should be preferred. For Mediterranean sites, irrigation is necessary to obtain high yields and have optimal carbon sequestration. Here again, under a future climate, the CO_2 uptake will increase thus making SRC an even more promising renewable energy source. The numbers used in this paper assume that all management is performed using fossil fuels. In these future scenarios, renewable energy might be more common, and can therefore reduce the CO_2 cost of the management, making irrigation a viable option for all sites.

Finally, management can also be optimized for maximal net energy production. From an energetic point of view, irrigation is highly inefficient. The energy consumed by the irrigation pumps greatly reduces the net energy balance. Therefore, from an energetic point of view, two year rotations without irrigation should be chosen. As discussed before, in a Mediterranean climate, irrigation should be applied to insure tree survival during droughts. Also here, under all future climate scenarios, the net energy production increases with increasing atmospheric CO_2 concentrations, making SRC an even more viable renewable energy source.

4.3. Possible improvements

The meteorological input files for our simulations are synthetic. Averaging of the meteorological years, can have unwanted side effects, such as spreading out precipitation. Short term, high intensity, meteorological events will be lost by our approach. We did, however, choose to use this approach to make the comparison of the management scenarios as objective as possible. By using the same average year for all simulations, there will be no hidden positive or negative influences of extreme weather conditions during a crucial stage in the development of the trees. Figure 18 (Chapter S), shows that there is no problem for temperature. But there is a significant effect on precipitation (Chapter S , Figures 15 – 17). The number of days without irrigation is drastically reduced, causing a more evenly spread irrigation. This effect is stronger for the temperate sites than for the Mediterranean sites, as the Mediterranean sites have a seasonal precipitation pattern, with low summer precipitation, that is retained in the averaged meteorological data. Using these averaged meteorological input files will possibly lead to an underestimation of the water stress levels, and therefore underestimate the irrigation requirements.

For the future meteorological data that we generated for this study, we perturbed the current climate averaged meteorological input file linearly according to the RCP projections.

The climate may evolve towards the occurrence of more extreme events. With more short intense rainfall and droughts (IPCC, 2007a), instead of the even distribution that we used. Therefore, in our analysis, the drought effect under a future climate is probably underestimated. More severe droughts will have a negative impact on soil water availability, and therefore on plant water stress, making more irrigation a requirement for plant survival. A more complex weather generator, that accounts for these changing patterns, could produce more representative meteorological input files for simulating future climate scenarios.

Our analysis assumed an average European grid mix electricity production and fossil energy for the management. Some countries, e.g. France and Belgium, produce a large amount of their electricity using nuclear energy (Eurostat, 2015), and therefore have much lower grid mix CO_2 emissions. The net CO_2 uptake from the atmosphere could therefore be reanalysed for each country. Furthermore, in the future, renewable energy sources might become more widespread, also for agricultural vehicles. Therefore, our analysis could be extended for different levels of renewable fuel used for SRC management activities, to study their effect on the CO_2 balance of the different scenarios.

5 Conclusion

Generally, the projected future climate improved the potential for SRC plantations. From the perspective of renewable energy, the optimal management for all RCPs is a two year rotation without irrigation. Under elevated atmospheric CO_2 concentrations, aboveground harvestable biomass increases considerably and has the highest yields when irrigated. From an energetic point of view, irrigation is suboptimal. For carbon sequestration, irrigation is not recommended, except for the summer dry Mediterranean climate.

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