Combining a land surface model with life cycle assessment for identifying the optimal management of short rotation coppice in Belgium

Reference:

Njakou Djomo S., De Groote Toon, Gobin A., Ceulemans Reinhart, Janssens Ivan.- Combining a land surface model w ith life cycle assessment for identifying the optimal management of short rotation coppice in Belgium
Biomass and bioenergy - ISSN 0961-9534 - 121(2019), p. 78-88
Full text (Publisher's DOI): https://doi.org/10.1016/J.BIOMBIOE.2018.12.010
To cite this reference: https://hdl.handle.net/10067/1560440151162165141

Combining a land surface model with life cycle assessment for identifying the optimal management of short rotation coppice in Belgium

S. Njakou Djomo[a,], T. De Groote[b,c], A. Gobin[c], R. Ceulemans[b,d] I. A. Janssens[b]

[a] Department of Agroecology, Aarhus University, Blichers Allé 20, DK-8830, Tjele, Denmark

[b] Research Center of Excellence on Plants and Ecosystems, Department of Biology,
University of Antwerp, Universiteitsplein 1, BE-2610 Wilrijk, Belgium

[c] Flemish Institute for Technological Research, VITO, Boeretang 200, B-2400 Mol, Belgium

[d]Slovenian Forestry Institute, Vecna Pot 2, 1000 Ljubljana, Slovenia

Corresponding author: S. Njakou Djomo (sylvestre.njakoudjomo@agro.au.dk)

Abstract

Poplar *(Populus spp.)* and willow *(Salix spp.)* short rotation coppice (SRC) are attractive feedstock for conversion to renewable electricity. Site managers typically optimize biomass production at their sites. However, maximum biomass production does not necessarily equate an optimal CO_2 balance, water use and energy production. This is because many operational actions consume water and energy and emit CO_2, either on-site or off-site. Coupling a land surface model (ORCHIDEE-SRC) with life cycle assessment enabled us to determine the optimal management for SRC in Belgium. We simulated 120 different management scenarios for each of two well-studied Belgian SRC sites (i.e. Boom and Lochristi). Simulated soil carbon changes suggested substantial carbon losses of 20-30 Mg ha^{-1} over a time period of 20 years, which were within observation-based uncertainty bounds. Results showed that in Belgium, which has a temperate maritime climate, optimal management of SRC has a rotation cycle of two years without irrigation. Energy inputs for this optimal management were 5.2 GJ ha^{-1} yr^{-1} for the Boom site and 5.3 GJ ha^{-1} yr^{-1} for the Lochristi site, while the biomass yields at Boom and Lochristi were 9.0 Mg ha^{-1} yr^{-1} and 9.4 Mg ha^{-1} yr^{-1}, respectively. The energy ratio (i.e., ratio of bioelectricity output to cumulative energy input) for this optimal management was 12, on average. Planting density turned out to be unimportant, while rotation length turned out to be most important to obtain the highest energy ratio and still maintain high biomass yield. Scenarios with high energy-input generated more bioenergy outputs, but the energy gains did not compensate for the increased energy inputs. Reductions in energy consumption per unit of bioenergy output should target the agricultural stage since it accounted for the largest energy share in the production chain.

Keywords: Poplar; Willow; biomass yield; water use; bioenergy; carbon balance; energy balance

1. Introduction

The increasing global energy demand and concerns about the negative effects of greenhouse gas (GHG) emissions from fossil fuels call for renewable, less-polluting, and low-cost energy sources [1-4]. Biomass is an alternative energy source that can be used to produce heat, power, and fuels for transport at competitive costs and in large quantities [5]. It can thus play a crucial role in securing energy supply and in reducing GHGs.

Among the non-food biomass for energy production, poplar (*Populus spp.*) and willow *(Salix spp.)* short rotation coppice (SRC) are the most used in Europe [6-9]. SRC has fast growth, high yield, requires few agri-chemicals and grows well in poor soils. The use of SRC for energy production is presented as a near CO_2 neutral process [10], because CO_2 emitted into the atmosphere through biomass burning was first taken-up from the atmosphere during tree growth. Other benefits attributed to SRC include soil carbon storage, reduced erosion, and improved soil quality [11]. Whether SRC can be produced without negative impacts on these ecosystem services depends on how SRC is established and managed [12].

SRC plantations are established, managed and harvested using agricultural and forestry machines. The establishment includes ploughing, initial weeding and the planting of cuttings, which have to be transported from a nursery to the plantation. After the establishment and depending on site conditions and the management intensity, fertilisation, weed control, and supplementary irrigation may be required. After full maturity, harvesting, and the transport of the harvested biomass to the bioenergy production plant is carried out. The machineries (e.g. tractors) and equipment (e.g. irrigation pumps) involved in all these cultivation steps consume energy and therefore emit CO_2 when operating, adding to the non-biogenic carbon emissions of SRC. Thus, SRC-derived bioenergy is not entirely CO_2 neutral.

The selection of the most suitable management for a given SRC is important because it will determine the plantation's biomass yield, bioenergy production, and the CO_2 balance. However, not only the productivity (i.e. biomass yield) and the CO_2 balance are of importance when considering the management of SRCs. Also the water consumption, nutrient use, planting density, and net energy balance of the SRC plantation are key factors in determining the optimal management. In water-limited regions irrigation may be necessary to achieve high yields in SRC plantations, but has consequences for the region's water availability and environment [13]. Moreover, irrigation requires high energy inputs, thereby potentially lowering the SRC's energy balance, despite the positive impact on the productivity. Fertiliser application is beneficial in nutrient-poor soils or in marginal lands to ensure high yields and subsequent biomass production. When not really required, irrigation and fertiliser unnecessarily increase the energy consumption of the plantation. From an energetic point of view, it is important to maximise the difference between the energy contained in the harvested biomass and that required for the site's management, as this would maximise the energy efficiency and CO_2 balance of the SRC system [14].

SRC is established according to two different planting layouts: in Europe (Sweden, Denmark, UK) and in the USA, many SRC systems are based on a double-row configuration with a density of 10,000-25,000 cuttings per hectare, which facilitates the use of agricultural equipment [15]. In Canada, the planting configuration consists of a single row design with a planting density ranging from 18,000-20,000 cuttings per hectare, which facilitates weed control during the establishment phase, and thus the rooting and growth of SRC [16]. While the design choice mostly depends on the machinery available for planting and harvesting, the yields and the desired dimension of end products are affected by factors such as rotation length, soil type, climate conditions and the initial planting density [17]. Consequently, failure to match the SRC genotypes and the site characteristics, with the planting densities, irrigation volumes, and rotation cycles could reduce the sustainability of bioenergy from SRC i.e., to reduce the net energy yield or increase carbon emissions. Based on two well-documented SRC plantations in Belgium, the aim of this study was to identify the optimal management scenario that maximizes yield and energy production at minimal energy consumption, water use and GHG emissions from SRC-based electricity production.

2. Materials & Methods

2.1 Site descriptions

Two well-studied and well-documented SRC plantations were 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, province of Antwerp, 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 [18]. The cuttings were planted in a double-row design with inter-row distances of 0.75 m and 1.50 m and an intra-row spacing of 0.90 m, resulting in a planting density of 10000 cuttings ha^{-1}. The climograph of the measured years at the Boom site (Figure 1a) shows the monthly average precipitation, the minimum, maximum, and average temperature. The average annual temperature at the site was 11.1 °C and the average annual precipitation was 800 mm. The former landfill was covered with a loam soil. No irrigation or fertilization was applied. A more complete description of the site and the plant materials has been provided elsewhere [19, 20]. The evolution of growth, biomass production and of yield have been previously described in detail ([18, 21]).

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 cuttings were planted 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 at the Lochristi site (Figure 1b) shows the monthly average precipitation the minimum, maximum, and average temperature. The average annual temperature at the site was 10.6 °C and the average annual precipitation was 800 mm. Soil texture is loamy sand [14]. No irrigation or fertilization was applied. A complete description of this site has been previously published [22] and can also be found on the website http://uahost.uantwerpen.be/popfull. Eddy covariance flux measurements of all greenhouse gases have been conducted and described in detail [23-26] and the plantation’s carbon budget was previously calculated [27].

2.2 Management scenarios

The ORCHIDEE-SRC model [28] is a modification of the ORCHIDEE model, a mechanistic land surface model widely used to simulate ecosystem productivity and carbon balance [29-31]. ORCHIDEE-SRC was used in this study to simulate the biomass production and the carbon balance of the two studied SRC plantations. For both sites, a number of different management scenarios were simulated. In these management scenarios, four management options were varied: (i) planting density was varied from 5000 cuttings ha^{-1} in steps of 5000 up to 15000 cuttings ha^{-1}; (ii) rotation length was 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 yr^{-1}, in steps of 50 mm yr^{-1}. The total irrigation volume was divided by the number of applications. This volume was applied weekly from April to September, independent of rainfall, and assuming sprinkler irrigation. This resulted in a total of 120 different management scenarios for each site, and each of these 120 management scenarios was simulated for 20 years, chosen as the lifetime of the plantations.

To enable proper simulations of SRC plantations, several modifications were implemented in the ORCHIDEE model. These included: (i) the management, (ii) growth, (iii) carbon allocation, and (iv) parameterisation (see [28]). Data required to run the model include meteorological data, such as short-, and long-wave incoming radiation, air temperature, specific humidity, wind speed, precipitation, atmospheric pressure, as well as site-specific parameter data such as longitude, latitude, soil texture, meteorological instrument height, planting density and plantation rotation cycle. Meteorological data 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.

These average meteorological data were used for the simulations; so the output of the modelling was not dependent on the occurrence of coincidental extreme weather events. For the Boom site, we averaged the data from 1996 to 2007; for the Lochristi site we averaged the data of 2010 to 2012. Prior to the actual simulations, we performed a model spin-up (i.e. the process of running a model to reach a state of equilibrium under the applied forcing) during 1510 years in order to bring the soil carbon pool to equilibrium. Because of the heterogeneity of the Boom site which was a former landfill, the soil textural measurements varied strongly. We therefore used the average of the measurements (49% sand, 29% silt and 22% clay) as model input. For the Lochristi site soil texture measurements varied less and the measured average values of 86% sand, 3% silt and 11% clay were used for the simulations.

2.3 LCA system boundary

A cradle-to-power production boundary was adopted in this study; thus all inputs of the whole life cycle from raw material acquisition, through the production of SRC, to the generation of electricity were included in the analysis (Figure 2). The LCA was performed following the ISO 14040-44 standards [32]. Stages considered in the LCA included the conversion of land to SRC plantation, the cultivation of SRC, the biomass harvesting, transport, and its conversion to electricity in a power plant (Figure 2). We accounted for the direct land use change which in this study was limited to the analysis of change in soil carbon stock; changes in vegetation due to direct land use changes were not considered. Although indirect land use changes influence the GHG intensity of bioenergy systems, they were not considered in this study due to lack of data and uncertainties [33]. We also considered the direct energy use (i.e., diesel, lubricant, or electricity) and CO_2 emissions for each operation as well as the indirect energy and CO_2 emissions for manufacturing tractors/machineries, agri-chemicals, irrigation pumps, and for the production of cuttings. However, the energy and CO_2 emissions associated with the construction of the power plant were assumed negligible and thus excluded from the analysis. Since no co-product is generated during the production of SRC and because a conventional generation was assumed for the conversion of SRC to electricity, the multi-functionality issue did not occur in this study, and allocation was not necessary. The cumulative energy demand and the IPCC GWP_{100} [34] characterisation factors were used to quantify the primary energy use and GHG emissions. Inventory data originated from several sources, including literature data, Ecoinvent database [35], and data from the POPFULL project (http://uahost.uantwerpen.be/popfull).

2.4 Direct land use change

Site level analyses were carried out to estimate the effects of direct land use change to SRC on soil carbon storage. To this end, the ORCHIDEE model was run to equilibrium assuming a ‘temperate broadleaved summer green forest’ as a proxy for the previous agricultural land use. This means that at the start of the SRC experiment, the soil carbon pool was that of a temperate broadleaved summer green forest. The initial soil carbon stock of the soil in Lochristi was simulated to amount to 150 Mg $ha^{-1}$of carbon, while that of the Boom site was 200 Mg ha^{-1} of carbon. In the model simulations, the SRC was assumed to be grown on this soil for 20 years, and we established for each site the change in soil organic carbon stock by comparing the initial soil carbon stock and the soil carbon stock level 20 years after establishment of SRC plantation.

2.5 Operational energy and CO_2 emissions

Operating an SRC plantation is more intensive than traditional forestry. The management actions involved in the establishment and operation of SRC plantations consume energy and thus emit CO_2. The farm activities considered in this study included: ploughing, weeding, planting, harvesting and chipping, the transport of materials to the farm, and the transport of harvested SRC chips to the power plant. Although planting at the Boom site was done manually, for fair comparison, we assumed that planting at both sites was carried-out using a leek planter. The direct energy use (and CO_2 emissions) for a given farm activity was estimated by adding the amount of energy in the diesel and lubricant used for that activity. The indirect energy use (and CO_2 emissions) of tractors and farm machineries used for a given farm activity was calculated by multiplying the weight of each tractor, by the embodied energy to produce the tractor, the field performance, and divided by the life-time of the tractor. We followed similar computation steps to estimate the indirect energy use and CO_2 emissions of irrigation pumps and equipment. Electricity consumption for irrigation was obtained from [35]. We then summed-up the direct and indirect energy use for each farm activity to obtain the total energy use (and CO_2 emissions). The energy use for transporting the cuttings to the farms was calculated as the product of the energy intensity of freight transport (i.e., 3.72 MJ Mg^{-1} km^{-1} [35]), the transport distance (assumed 150 km in this study), the weight of the cutting (10 g $plant^{-1}$), and the planting density (plant ha^{-1}) in each scenario. We repeated the same procedure to estimate CO_2 emissions associated to the transport of cuttings. The energy use (and CO_2 emissions) for transporting the harvested SRC chips to the thermal power plant was computed in a similar manner as above, and assuming a round trip of 50 km distance [18].

2.6 Energy balance and CO_2 emission savings

Two efficiency indicators (energy ratio and net energy production) were used to evaluate the energy balance of the SRC-based electricity system. The energy ratio was calculated by dividing the amount of electricity produced by the primary energy inputs to produce it. The net energy production was computed as the difference between the amount of electricity output and the primary energy inputs to the SRC-based electricity system. The CO_2 emission savings were calculated by comparing the CO_2 emissions from the SRC-based electricity to the carbon intensity of the non-renewable power mix in Belgium. We therefore first calculated the amount of electricity produced per g CO_2 in the biomass using equation 1.

$$\omega = \frac{\Upsilon * \eta * m}{\alpha * M} \qquad \text{eq. 1.}$$

In this equation, ω (kJ g^{-1} of CO_2) is the amount of electricity produced by the SRC, Υ is the energy content of the SRC (i.e. 18.5 kJ g^{-1} [36]), η is the conversion efficiency (i.e., 37.2% [20]), m is the atomic mass of carbon (12 g mol^{-1}), α is the carbon content of the biomass (i.e. 50 g of carbon per 100 g of biomass [36]), and M is the molecular mass of CO_2 (44 g mol^{-1}). We then calculated the energy production per unit CO_2 emitted as the inverse of the carbon intensity of the non-renewable power mix in Belgium (see equation 2).

$$\theta = \frac{1}{\mathcal{E} * \mu} \qquad \text{eq. 2.}$$

where θ is the energy production per unit CO_2 emitted, $\mathcal{E}$ is the carbon intensity of the Belgian non-renewable grid mix electricity (CO_{2eq}, 564g kWh^{-1} [21]), and μ is the conversion factor of kilowatt-hour to megajoule (i.e. 3.6 MJ kWh^{-1}). The above calculations resulted in 3.75 kJ g^{-1} of CO_{2eq} for the SRC-based electricity and 6.38 kJ g^{-1} of CO_{2eq} for the non-renewable grid mix electricity.

3. Results

3.1. Land use change impacts on soil carbon stock

The simulated soil carbon stock changes for the Lochristi and the Boom site are shown in Figure 3. The conversion of land to SRC plantation resulted in a continuing decline of soil organic carbon, which was due to combined effects of high initial soil organic carbon and the low carbon inputs from SRC plants to counteract losses of carbon by soil respiration. The rate of loss of soil organic carbon was 1.5 Mg ha^{-1} yr^{-1} for the Boom site and 1 Mg ha^{-1} yr^{-1} for the Lochristi site. The losses of soil carbon were higher at the Boom site than at the Lochristi site (Figure 3). The influence of planting density on soil organic carbon was negligible at both sites.

3.2. Biomass yields

Observed annual biomass yields were very well reproduced by the model, and this at both sites (Figure 4-6). Depending on the scenario analysed, simulated annual biomass yields at the Boom site ranged from 7.5 to 9.3 Mg ha^{-1} yr^{-1}, while at the Lochristi site the biomass production varied from 7.9 to 10.4 Mg ha^{-1} yr^{-1} (Figure 4-6). Also the sites' gross primary production and ecosystem respiration were very well simulated (data shown in [25] for gross primary production: R^2 = 0.95, NRMSE = 0.064, PCC = 0.89; for ecosystem respiration: R^2 = 0.95, NRMSE=0.078, PCC = 0.91). Soil temperature and soil moisture were simulated adequately, though we noted some discrepancies originating from the simplicity of the soil moisture simulation in ORCHIDEE-SRC, which also influenced the latent heat flux [28]. Among all management options, changes in rotation length elicited the largest differences in biomass yield (different symbols in Figure 4), with shorter rotations yielding higher biomass. Changes in irrigation and the implementation of an establishment year cut had a smaller impact on yields, while varying the initial plantation density did not change yields in the simulations.

3.3. Carbon balance

The modelled 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 4a). The harvestable woody biomass contained more carbon than the net carbon uptake from the atmosphere, indicating a loss of soil carbon for both sites (Figure 4a). Because of the higher soil carbon losses at the Boom site (see 3.1), the net atmospheric CO_2 uptake was lower on this site than on the Lochristi site. 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 4b; 5-30% for Boom; 2-8% for Lochristi). Irrigation was the management option causing the highest CO_2 emissions (Figure 4b). Although these non-biogenic CO_2 emissions were not very large, between 0.2 and 0.7 Mg ha^{-1} yr^{-1}, they caused a very noticeable difference in the net carbon emission patterns of the different management scenarios (Figure 4a-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 4c). 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 yield stimulus at 100 mm. Up to this level, biomass production increased more than the net CO_2 emissions. Above 100 mm the CO_2 emissions continued to increase, while biomass production no longer increased. This was in contrast with the loamy-sandy Lochristi site that had a much lower water retention capacity due to its sandy texture, and where more irrigation continued to increase the biomass production, as well as the uptake of CO_2 from the atmosphere. For the Lochristi site, the increase in CO_2 uptake from zero to 50 mm irrigation was three to four times larger than for Boom. Adding more irrigation still had a positive impact on biomass production and CO_2 emissions, albeit much smaller than that of the 50 mm application.

A clear difference occurred between the two sites when the CO_2 credits for the displaced grid electricity production were considered (Figure 4d). At Boom, the SRC-based bioelectricity system lost carbon, thus had a negative carbon balance, which however, turned positive (i.e. became a CO_2 sink) when the substitution effects were considered. The optimal management scenario for the CO_2 balance at this site had two year rotations and no irrigation. Adding irrigation increased the biomass production slightly, but also reduced the carbon sink potential of the SRC plantation. At the Lochristi site, the SRC-based bioelectricity system was a net CO_2 sink, which became almost zero when the CO_2 emissions from energy consumption during the management of SRC plantation was considered, but SRC-based bioelectricity became a larger sink thanks to the substitution effects. For this site (i.e. Lochristi) the shortest rotation of two years, gave the best CO_2 emission savings (Table S1). Adding 50 mm of irrigation increased the biomass production by about 0.5 Mg ha^{-1} yr^{-1}, compared to the no-irrigation scenarios, while the net CO_2 emission was not altered. 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.

3.4. Water use

The mean annual evapotranspiration was correlated with the annual harvestable aboveground biomass (Figure 5). A detailed model analysis of the water balance showed that 50% of the incoming (rain + irrigation) water was evapotranspired. In the irrigated scenarios, the increase in evapotranspiration was equal to only 5% of the irrigation water volume. Another 5% of this irrigation water was lost as runoff and the remaining 90% was lost as drainage. For both sites, differences among the management scenarios were, nonetheless, due only to differences in irrigation volumes, with increased irrigation resulting in increased evapotranspiration. This effect of irrigation on evapotranspiration, however, remained small: adding 200 mm water only added about 10 mm of annual evapotranspiration at both sites. Neither the planting density, nor changes in irrigation frequencies (e.g. daily instead of weekly) had noticeable effects on annual evapotranspiration at these sites.

3.5. Energy balance

Depending on the management options adopted, the energy inputs for the production of bioenergy (i.e. electricity) ranged from 3.6 to 24.3 GJ ha^{-1} yr^{-1} at the Boom site, and from 3.7 to 24.7 GJ ha^{-1} yr^{-1} at the Lochristi site (Figure 6). Irrigation appeared to be the most energy consuming activity at both sites (0 - 84%), followed by transport (13 - 79%) and harvesting (2.5 - 31%). Relatively little energy input was consumed for ploughing (0.2 - 1.4%), planting (0.3 - 2.3%), and weeding (0.2 - 2.2%). Within-site variation in energy outputs was due to management choices (i.e. which rotation cycle, which amount of irrigation, planting density etc.). The annual bioelectricity produced from the harvested biomass varied from 51.7 to 64.2 GJ ha^{-1} yr^{-1} for the Boom site, and from 54.2 to 71.3 GJ ha^{-1} yr^{-1} for the Lochristi site, depending on the scenario. Each 50 mm increase of irrigation came at the expense of around 5 GJ ha^{-1} yr^{-1} energy inputs. Scenarios with an irrigation of 200 mm consumed five times more energy than scenarios without irrigation, but also resulted in increased biomass yields. However, the increase in biomass energy production due to increased irrigation represented only 10% of the increase in energy inputs.

Energy ratios decreased with rotation lengths at both sites, with shorter rotations having higher energy ratios in all scenarios (Figure 6). Although shorter rotations required higher energy inputs, mainly due to the more frequent harvests, they also yielded a higher biomass production (thus higher energy production). Since the differences in biomass yield (i.e., energy output) between rotation lengths were always higher than the differences in energy inputs for the production of SRC, shorter rotations had higher energy ratios (Figure 6). We found, however, no impact of the planting density on the energy ratios. Overall our estimates of energy ratios ranged from 2.3 to 12.1 depending on the site and management scenario (Figure 6), indicating that these SRC-based bioelectricity systems were energetically viable.

The highest energy ratios were simulated for two-year rotations without irrigation. This scenario had an energy ratio of 12, on average. As expected, variation in energy input due to irrigation influenced the energy ratios more than any other parameter. Indeed, both sites showed a substantial reduction in energy ratios when 50 mm yr^{-1} water was added to the two-years rotation scenario, compared to the same scenario without irrigation (Figure 6). The energy ratios further dropped to 2.3 and 2.6 for the sites in Boom and Lochristi, respectively, when 200 mm yr^{-1} water was supplied to the two-year rotation scenario. Similar trends were found for other rotation lengths. Both sites exhibited similar net energy balances, although this balance was somewhat lower for the Boom site, because of the lower biomass production. As with the energy ratios, the scenario with the highest net energy production included two year rotations without irrigation (Figure 7; Table S2).

4. Discussion

4.1 Land use change, biomass yields, carbon balance, water use, and energy balance

Land use change is a key factor which influences soil organic carbon stocks as well as the life cycle GHG emissions of bioenergy crops [37, 38]. Our model simulations suggested that land conversion to SRC plantations reduced soil carbon over the lifetime of the SRC plantation (i.e. 20 years). Our findings of decreased soil organic carbon stocks under SRC plantations are consistent with published studies that all reported soil carbon losses following conversion from cropland to SRC [39] and conversion of forest to SRC plantations [40-43]. However, while our simulated soil carbon losses (1-1.5 Mg $ha^{-1}yr^{-1}$ depending on the site, Figure 3) were within the estimates for the Lochristi site reported by [39], they were near the lower end of the measured range. The reader must be informed that our simulated soil carbon losses may be overestimated because our model was run to equilibrium assuming a deciduous forest cover. In reality, the assessed SRC plantations were established on former cropland (Lochristi) and on a municipal waste site (Boom).

The observed and simulated annual biomass yields (7.5 - 10.4 Mg ha^{-1} yr^{-1}) across sites and scenarios demonstrated that SRC can be grown on a wide range of soil types, including low quality soils such as landfill sites [44]. The simulated biomass yields were consistent with measured yields at both the Boom [18], and the Lochristi site [45]. They also agreed with the simulated yields of SRC in United Kingdom (4.9 - 10.7 Mg ha^{-1} yr^{-1} [46]), Germany (2.6 – 16.3 Mg ha^{-1} yr^{-1} [47]), northern Europe and nearby countries (4.5 – 7 Mg ha^{-1} yr^{-1} [48]). SRC trials without use of fertiliser in Canada showed higher biomass yields (16.9-18.1 Mg ha^{-1} yr^{-1} [49]) than in this study. The high yields found in these trials were attributed to high soil quality, good soil drainage, use of improved genotypes, and absence of diseases. Our simulation did not account for the improvement in plan breeding and genetic modification, which can increase biomass productivity [50, 51].

With regard to the net carbon balance, the Boom site was a source of carbon to the atmosphere, while the Lochristi site was a small sink of carbon to the atmosphere. The former (i.e. Boom site) was established on a landfill covered by loamy soil. This causes a huge disturbance, which rendered large amounts of physically protected soil organic matter available for decomposition. Moreover, it can also not be excluded that organic waste in the landfill might have produced large amounts of CO_2 and/or methane that subsequently oxidized during its upward diffusion through the soil. The site in Lochristi had a sandy texture. This inter-site difference shows that site characteristics play a crucial role, in our case not in the biomass yield, but in the carbon balance and sustainability of SRC plantations. Soil characteristics such as soil type and fertility can affect root biomass production and distribution in the soil, which may impact on soil carbon stock [52]. Soil fertility may also impact soil carbon storage, where fertile sites may have higher soil organic carbon stocks than unfertile soils [53]. We limited our study to two Belgian sites; 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, and net carbon balance.

Differences in evapotranspiration between these two sites were due to differences in soil properties and the microclimatic conditions. For instance, the SRC site in Lochristi had a much sandier soil compared to that in Boom. The water holding capacity of sandy soil is low, explaining the increased benefit of added irrigation at the Lochristi site. The benefit of added irrigation on biomass production was, however, small, i.e. less than 0.5 Mg ha^{-1} yr^{-1} for the Boom site and less than 1 Mg ha^{-1} yr^{-1} for the Lochristi site, which was probably attributable to the temperate maritime climate in Belgium. These findings corroborated studies that reported no or only limited effects of irrigation on SRC biomass yields [54], but also contrasted with other studies in regions with a larger water deficit during the growing season, which did find substantial increases in biomass yield due to irrigation [55-57]. Water use and water use efficiency vary substantially among hybrid poplar clones [58, 59]. Therefore, in water limited regions, clonal selection in addition to management are important strategies for minimizing water use impacts of SRC. Given that rainfall is highly variable within and among years, the use of average rainfall to estimate evapotranspiration – as in this study – does not provide a complete understanding of the effects of SRC plantations on water use. The computed annual evapotranspiration at both sites agreed with studies that observed low (325 – 481 mm [60-63]) or moderate (550 – 620 mm [61, 64, 65]) annual evapotranspiration for SRC. It disagreed however, with studies that observed high annual evapotranspiration for both non-fertilised (725 – 870 mm [65, 66]) and fertilised (755 – 2090 mm [65, 67-69]) SRC plantations. It also refuted the perception that SRC consumes more water than *e.g.* forests [70]. Differences in evapotranspiration estimates between studies in literature and ours can be explained by site-specific factors such as local temperature and precipitation, soil types, species of SRC, crops' age and use of fertiliser.

A proper combination of planting density and rotation length can increase biomass yields by 33% [71, 72]. Indeed, several studies have pointed to increases in biomass yields of SRC, which are directly dependent on planting density [72-74]. However, in our study we did not find any effects of planting density on SRC yields. The wide simulated range of planting density produced similar biomass yields at both sites. This corroborated studies that reported minor or no effects of planting density on biomass productivity of SRC [75-77]. Higher planting densities may even decrease yields due to excessive mortality [78, 79]. With regard to the rotation cycle, our results corroborated a UK study that found a two-year rotation cycle as the optimal harvesting frequency for high yielding, high density planting of SRC [80]. However, high biomass yields have been associated to longer rotation cycle in other studies. In Germany for instance, a SRC plantation harvested each seven-years was reported to have higher biomass yields than a SRC plantation with a three-year cutting cycle [81], while biomass yields were higher in SRC plantation with a three-year rotation cycle than a SRC plantation with two-year rotation length in the USA [82]. These studies, however, did not assess the effects of the cutting cycle on energy ratios. In Italy, one study reported higher biomass yields and energy ratios for a triennial cutting cycle as compared to a biennial harvest cycle [83], whereas another study found that SRC plantation with a longer rotation cycle (> two-year rotation cycle) had higher biomass yields and energy ratios relative to SRC plantation with a shorter cutting cycle (two years) [84].

Studies on effects of planting densities and/or rotation cycles on biomass yields and/or energy ratios are inconclusive, with some showing increasing yields and high energy ratios, and others showing decreasing yields and/or low energy ratios associated with higher planting densities and/or longer rotation cycles. Such contradictions reinforce the belief that the biomass yields (thus the energy yield) of SRC result from complex interactions between different factors such as soil quality, planting density, management practices, pest/diseases, and rotation length [85]. The high energy ratio obtained for two-year rotation cycle in this study was explained by the combined effect of high biomass yields, absence of fertiliser application, and absence of pest infestation, which compensated for the energy inputs incurred by the increasing number of harvests for shorter rotation cycles.

Overall, all management scenarios showed energy ratios far larger than unity (2.3 – 12.1; Figure 6), confirming literature findings that SRC-based electricity systems are efficient energy systems for reducing reliance on fossil energy resources [86, 87]. This also placed SRC-bioelectricity in slightly favourable position relative to photovoltaics (2- 4 [88]) and in similar position relative to wind power (4 - 16 [88]). The computed energy ratios remained, however, lower than the energy ratios of coal - (30 [88]), and natural gas - (28 [88]) fired power without carbon capture and storage. Carbon capture and storage requires about 23-40% additional energy consumption, depending on the power plants' efficiency [89]. Thus, in some scenarios, SRC-based bioelectricity would even be competitive with natural gas and/or coal power with carbon capture and storage. Estimates of energy ratios in this study were consistent with the range of values reported in the literature [86]. Note that direct comparison of estimates among studies is hampered by assumptions on yields, cutting cycles, conversion efficiencies and system boundaries.

4.2 Finding the optimal management

When deciding on a general optimal management scenario, the focus should be on yield, because this determines the income for the farmer. However, the site's water use, energy and CO_2 balance should also be included in the decision-making algorithm (and eventual subsidy system). Otherwise, farmers might adopt wasteful energy and water use practices that increase biomass production at the expense of high energy inputs or high greenhouse gas emissions. For example, we showed that in all simulated scenarios, energy ratios at both sites dropped significantly when irrigation was added. This suggests that the additional water input (and thus energy inputs) to the SRC system did not lead to substantial increase in biomass yields (i.e. energy output), and was thus detrimental to the energy balance of the SRC-based electricity system. Irrigation thus had limited effects on SRC biomass yields in Belgium where there is enough precipitation. Our study aimed to find an optimal management, for which the highest yield is attained at the minimal water use and best possible energy and CO_2

balance. Since the energy ratio tends towards lower energy values whereas the net energy balance provides a net energy production value, the latter indicator was adopted for identifying the optimal management for SRC-based electricity in this study. On the basis of the net energy value, a two-year rotation cycle without irrigation was identified as the key determinant of the optimal management scenario for SRC-based bioelectricity at both studied sites. When the carbon balance was considered, a two-year rotation without irrigation was optimal for the Boom site, while for the site in Lochristi a two-year rotation with 50 mm yr^{-1} of irrigation was optimal. However, given that the added energy of the irrigation outweighs the small net carbon gain realised by irrigation, we concluded that a two-year rotation cycle without irrigation would be optimal for both sites.

Our identification of the optimal management scenario, however, was aimed at bioenergy production. If the objective had been production of pulpwood, other important factors like the bark, limbs and the foliage content of the harvested SRC biomass would have come into play. The bark, limb and foliage content of SRC biomass decrease as the rotation length increase [90, 91] and limited amounts of these organs in the wood products are desirable in SRC biomass destined for pulpwood. However, when utilized as an energy crop, rotation length does not need to be lengthened because bark, limbs, and foliage have negligible adverse effects on SRC-based power, heat, or fuel production.

Economic factors also influence decision-making on the optimal management scheme. The cultivation of SRC requires high initial investments related to establishment costs [92]. Financial returns occur at each cutting event, and the financially most optimal rotation length therefore shortens as interest rates increase. On the other hand, harvest costs also occur more regularly with shorter rotation cycles and may be as important as the stand establishment costs. We thus caution against generalisation of the results of this study.

5. Conclusion

Under Belgian conditions of mild temperatures and sufficient rainfall during the growing season the optimal SRC management for power or heat production does not involve irrigation and has two-year rotation cycles. In this scenario the farmer achieves almost the highest biomass yield, and especially the highest benefit for the environment in terms of net energy and carbon balance. The analyses of energy ratio under different management options revealed that increases in energy inputs not necessarily yield equivalent increases in energy outputs. From the energy and carbon balance point of view, this means that high energy-input systems may generate more bioenergy outputs, but that the gains may not compensate for the increased energy inputs. Given that the agricultural stage accounted for the largest energy share in the production chain, a reduction in energy consumption per unit of bioenergy output must necessarily come about through a lowering of energy consumption in this phase.

Acknowledgements

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), ERC grant agreement n° 242564 (DOFOCO), ERC grant n° 2013-SyG 610028 (IMBALANCE-P), 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). T. De Groote was a Ph. D. fellow of the Research Foundation – Flanders (FWO) and the Flemish Institute for Technological Research (VITO).

References

[1] A.J. Ragauskas, C.K. Williams, B.H. Davison, G. Britovsek, J. Cairney, C.A. Eckert, W.J. Frederick, J.P. Hallett, D.J. Leak, C.L. Liotta, J.R. Mielenz, R. Murphy, R. Templer, T. Tschaplinski, The Path Forward for Biofuels and Biomaterials, Science 311 (2006) 484-489.

[2] Y. Pu, D. Zhang, M. Singh Preet, J. Ragauskas Arthur, The new forestry biofuels sector, Biofuels, Bioproducts and Biorefining 2 (2007) 58-73.

[3] E.M. Rubin, Genomics of cellulosic biofuels, Nature 454 (2008) 841-845.

[4] A. Carroll, C. Somerville, Cellulosic biofuels, Annual Review of Plant Biology 60 (2009) 165-82.

[5] P. Sannigrahi, J. Ragauskas Arthur, A. Tuskan Gerald, Poplar as a feedstock for biofuels: A review of compositional characteristics, Biofuels, Bioproducts and Biorefining 4 (2010) 209-226.

[6] IEA, Good Practice Guidelines: Bioenergy Project Development & Biomass Supply, International Energy Agency, 2007.

[7] M.J. Aylott, E. Casella, I. Tubby, N.R. Street, P. Smith, G. Taylor, Yield and spatial supply of bioenergy poplar and willow short-rotation coppice in the UK, New Phytologist 178 (2008) 358-370.

[8] R.L. Rowe, N.R. Street, G. Taylor, Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK, Renewable Sustainable Energy Reviews 13 (2009) 260-279.

[9] G. Berndes, M. Hoogwijk, R. van den Broek, The contribution of biomass in the future global energy supply: a review of 17 studies, Biomass & Bioenergy 25 (2003) 1-28.

[10] R. Righelato, D.V. Spracklen, Environment - Carbon mitigation by biofuels or by saving and restoring forests?, Science 317 (2007) 902-902.

[11] H. Langeveld, F. Quist-Wessel, I. Dimitriou, P. Aronsson, C. Baum, U. Schulz, A. Bolte, S. Baum, J. Koehn, M. Weih, H. Gruss, P. Leinweber, N. Lamersdorf, P. Schmidt-Walter, G. Berndes, Assessing Environmental Impacts of Short Rotation Coppice (SRC) Expansion: Model Definition and Preliminary Results, Bioenergy Research 5 (2012) 621-635.

[12] J. Dauber, M.B. Jones, J.C. Stout, The impact of biomass crop cultivation on temperate biodiversity, GCB Bioenergy 2 (2010) 289-309.

[13] S. Hughes, L. Partzsch, J. Gaskell, The Development Of Biofuels Within The Context Of The Global Water Crisis, Sustainaible Development Law Policy 7 (2007) 58-78.

[14] S.N. Djomo, A, T. Zenone, T. De Groote, S. Bergante, G. Facciotto, H. Sixto, P. Ciria Ciria, J. Weger, R. Ceulemans, Energy performances of intensive and extensive short rotation cropping systems for woody biomass production in the EU, Renewable Sustainable Energy Reviews 41 (2015) 845-854.

[15] L.P. Abrahamson, T.A. Volk, R.F. Kopp, E.H. White, J.L. Ballard, Willow Biomass Producer's Handbook (revised), SUNY-ESF, Syracuse, NY, 2002.

[16] W. Guidi, C. Tozzini, E. Bonari, Estimation of chemical traits in poplar short-rotation coppice at stand level, Biomass & Bioenergy 33 (2009) 1703-1709.

[17] G.A. Keoleian, T.A. Volk, Renewable energy from willow biomass crops: Life cycle energy, environmental and economic performance, Critical Review in Plant Science 24 (2005) 385-406.

[18] S.Y. Dillen, S. Njakou Djomo, S. Vanbeveren, R. Ceulemans, Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years, Biomass & Bioenergy 56 (2013) 157-165.

[19] I. Laureysens, W. Deraedt, T. Indeherberge, R. Ceulemans, Population dynamics in a 6-year old coppice culture of poplar. I. Clonal differences in stool mortality, shoot dynamics and shoot diameter distribution in relation to biomass production, Biomass & Bioenergy 24 (2003) 81-95.

[20] E. Casella, R. Ceulemans, Spatial distribution of leaf morphological and physiological characteristics in relation to local radiation regime within the canopies of 3-year-old Populus clones in coppice culture, Tree Physiology 22 (2002) 1277-1288.

[21] S.Y. Dillen, S. Vanbeveren, N. al Afas, I. Laureysens, S. Croes, R. Ceulemans, Biomass production in a 15-year-old poplar short-rotation coppice culture in Belgium, Aspects of Applied Biology 112 (2011) 99-106.

[22] L.S. Broeckx, M.S. Verlinden, R. Ceulemans, Establishment and two-year growth of a bio-energy plantation with fast-growing Populus trees in Flanders (Belgium): Effects of genotype and former land use, Biomass & Bioenergy 42 (2012) 151-163.

[23] D. Zona, I.A. Janssens, M. Aubinet, B. Gioli, S. Vicca, R. Fichot, R. Ceulemans, Fluxes of the greenhouse gases (CO_2, CH_4 and N_2O) above a short-rotation poplar plantation after conversion from agricultural land, Agricultural and Forest Meteorology 169 (2013) 100-110.

[24] D. Zona, I.A. Janssens, B. Gioli, H.F. Jungkunst, M. Camino Serrano, R. Ceulemans, N_2O fluxes of a bio-energy poplar plantation during a two years rotation period, GCB Bioenergy 5 (2013) 536-547.

[25] D. Zona, B. Gioli, S. Fares, T. De Groote, K. Pilegaard, A. Ibrom, R. Ceulemans, Environmental controls on ozone fluxes in a poplar plantation in Western Europe, Environmental Pollution 184 (2014) 201-210.

[26] T. Zenone, M. Fischer, N. Arriga, L.S. Broeckx, M.S. Verlinden, S. Vanbeveren, D. Zona, R. Ceulemans, Biophysical drivers of the carbon dioxide, water vapor, and energy exchanges of a short-rotation poplar coppice, Agricultural and Forest Meteorology 209 (2015) 22-35.

[27] M.S. Verlinden, L.S. Broeckx, D. Zona, G. Berhongaray, T. De Groote, M. Camino Serrano, I.A. Janssens, R. Ceulemans, Net ecosystem production and carbon balance of an SRC poplar plantation during its first rotation, Biomass & Bioenergy 56 (2013) 412-422.

[28] T. De Groote, D. Zona, L.S. Broeckx, M.S. Verlinden, S. Luyssaert, V. Bellassen, N. Vuichard, R. Ceulemans, A. Gobin, I.A. Janssens, ORCHIDEE-SRC v1.0: an extension of the land surface model ORCHIDEE for simulating short rotation coppice poplar plantations, Geoscience. Model Development 8 (2015) 1461-1471.

[29] N.I. Ducoudre, K. Laval, A. Perrier, Sechiba, a New Set of Parameterizations of the Hydrologic Exchanges at the Land Atmosphere Interface within the Lmd Atmospheric General-Circulation Model, Journal Climate 6 (1993) 248-273.

[30] G. Krinner, N. Viovy, N. de Noblet-Ducoudre, J. Ogee, J. Polcher, P. Friedlingstein, P. Ciais, S. Sitch, I.C. Prentice, A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biochemical Cycles 19 (2005) GB1015.

[31] V. Bellassen, G. Le Maire, J.F. Dhote, P. Ciais, N. Viovy, Modelling forest management within a global vegetation model Part 1: Model structure and general behaviour, Ecological Modelling 221 (2010) 2458-2474.

[32] ISO, Environmental Management - Life Cycle Assessment -Requirements and Guidelines. Geneva, Switzerland: International Organisation for Standardisation (ISO), EN. ISO14044, Geneva, Switzerland, 2006.

[33] L. Di Lucia, S. Ahlgren, K. Ericsson, The dilemma of indirect land-use changes in EU biofuel policy - an empirical study of policy-making in the context of scientific uncertainty, Environmental Science and Policy 16 (2012) 9-19.

[34] IPCC, Climate change, The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, USA, 2013

[35] R. Frischknecht, N. Jungbluth, H. Althaus, C. Bauer, G. Doka, R. Dones, Implementation of life cycle impact assessment methods; No. 3; Swiss Centre for Life Cycle Inventory: Dubendorf, Switzerland, 2007.

[36] M. Liberloo, S. Luyssaert, V. Bellassen, S. Njakou Djomo, M. Lukac, C. Calfapietra, I.A. Janssens, M.R. Hoosbeek, N. Viovy, G. Churkina, G. Scarascia-Mugnozza, R. Ceulemans, Bio-Energy Retains Its Mitigation Potential Under Elevated CO_2, PLOS ONE 5 (2010) e11648.

[37] K.J. Anderson-Teixeira, S.C. Davis, M.D. Masters, E.H. Delucia, Changes in soil organic carbon under biofuel crops, GCB Bioenergy 1 (2009) 75-96.

[38] A. Don, B. Osborne, A. Hastings, U. Skiba, M.S. Carter, J. Drewer, H. Flessa, A. Freibauer, N. Hyvönen, M.B. Jones, G.J. Lanigan, Ü. Mander, A. Monti, S.N. Djomo, J. Valentine, K. Walter, W. Zegada-Lizarazu, T. Zenone, Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon, GCB Bioenergy 4 (2011) 372-391.

[39] G. Berhongaray, M.S. Verlinden, L.S. Broeckx, I.A. Janssens, R. Ceulemans, Soil carbon and belowground carbon balance of a short-rotation coppice: assessments from three different approaches, GCB Bioenergy 9 (2016) 299-313.

[40] L.B. Guo, R.M. Gifford, Soil carbon stocks and land use change: a meta analysis, Global Change Biology 8 (2002) 345-360.

[41] A. Don, J. Schumacher, A. Freibauer, Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis, Global Change Biology 17 (2010) 1658-1670.

[42] C. Poeplau, A. Don, L. Vesterdal, J. Leifeld, B.A.S. Van Wesemael, J. Schumacher, A. Gensior, Temporal dynamics of soil organic carbon after land-use change in the temperate zone – carbon response functions as a model approach, Global Change Biology 17 (2011) 2415-2427.

[43] C. Ferré, R. Comolli, A. Leip, G. Seufert, Forest conversion to poplar plantation in a Lombardy floodplain (Italy): effects on soil organic carbon stock, Biogeosciences 11 (2014) 6483-6493.

[44] D.J. Nixon, W. Stephens, S.F. Tyrrel, E.D.R. Brierley, The potential for short rotation energy forestry on restored landfill caps, Bioresource Technology 77 (2001) 237-245.

[45] M.S. Verlinden, L.S. Broeckx, R. Ceulemans, First vs. second rotation of a poplar short rotation coppice: Above-ground biomass productivity and shoot dynamics, Biomass & Bioenergy 73 (2015) 174-185.

[46] J. Aylott Matthew, E. Casella, I. Tubby, N.R. Street, P. Smith, G. Taylor, Yield and spatial supply of bioenergy poplar and willow short-rotation coppice in the UK, New Phytologist 178 (2008) 358-370.

[47] C. Aust, J. Schweier, F. Brodbeck, H. Sauter Udo, G. Becker, J.-P. Schnitzler, Land availability and potential biomass production with poplar and willow short rotation coppices in Germany, GCB Bioenergy 6 (2013) 521-533.

[48] B. Mola-Yudego, J. Rahlf, R. Astrup, I. Dimitriou, Spatial yield estimates of fast-growing willow plantations for energy based on climatic variables in northern Europe, GCB Bioenergy 8 (2015) 1093-1105.

[49] M. Labrecque, T.I. Teodorescu, Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern Quebec (Canada), Biomass & Bioenergy 29 (2005) 1-9.

[50] H. Sims Ralph E, A. Hastings, B. Schlamadinger, G. Taylor, P. Smith, Energy crops: current status and future prospects, Global Change Biology 12 (2006) 2054-2076.

[51] G. Taylor, K.P. Beckett, K.M. Robinson, K. Stiles, A.M. Rae, Identifying QTL for yield in UK biomass poplar, Aspects of Applied Biology, 65 (2001) 173-182.

[52] L. Bonin Catherine, R. Lal, Aboveground productivity and soil carbon storage of biofuel crops in Ohio, GCB Bioenergy 6 (2012) 67-75.

[53] C.S. Zan, J.W. Fyles, P. Girouard, R.A. Samson, Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec, Agriculture, Ecosystems & Environment 86 (2001) 135-144.

[54] M. Weih, N.E. Nordh, Determinants of biomass production in hybrid willows and prediction of field performance from pot studies, Tree physiology 25 (2005) 1197-206.

[55] P.J. Kowalik, P.F. Randerson, Nitrogen and phosphorus removal by willow stands irrigated with municipal waste water—A review of the Polish experience, Biomass & Bioenergy 6 (1994) 133-139.

[56] H.G. Adegbidi, T.A. Volk, E.H. White, L.P. Abrahamson, R.D. Briggs, D.H. Bickelhaupt, Biomass and nutrient removal by willow clones in experimental bioenergy plantations in New York State, Biomass & Bioenergy 20 (2001) 399-411.

[57] S. Bergante, G. Facciotto, G. Minotta, Identification of the main site factors and management intensity affecting the establishment of Short-Rotation-Coppices (SRC) in Northern Italy through stepwise regression analysis, Central European Journal of Biology 5 (2010) 522-530.

[58] J. Bloemen, R. Fichot, J.A. Horemans, L.S. Broeckx, M.S. Verlinden, T. Zenone, R. Ceulemans, Water use of a multigenotype poplar short-rotation coppice from tree to stand scale, GCB Bioenergy 9 (2017) 370-384.

[59] M. Fischer, T. Zenone, M. Trnka, M. Orság, L. Montagnani, E.J. Ward, A.M. Tripathi, P. Hlavinka, G. Seufert, Z. Žalud, J.S. King, R. Ceulemans, Water requirements of short rotation poplar coppice: Experimental and modelling analyses across Europe, Agricultural and Forest Meteorology 250 (2018) 343-360.

[60] R. Bungart, R.F. Hüttl, Growth dynamics and biomass accumulation of 8-year-old hybrid poplar clones in a short-rotation plantation on a clayey-sandy mining substrate with respect to plant nutrition and water budget, European Journal of Forest Research 123 (2004) 105-115.

[61] W. Stephens, T. Hess, J. Knox, Review of the effects of energy crops on hydrology. Institute of Water and Environment, Cranfield Univeristy, Silsoe, Bedford MK45 4DT, UK, 2001.

[62] G. Persson, Willow stand evapotranspiration simulated for Swedish soils, Agricultural Water Management 28 (1995) 271-293.

[63] M.-L. Linderson, Z. Iritz, A. Lindroth, The effect of water availability on stand-level productivity, transpiration, water use efficiency and radiation use efficiency of field-grown willow clones, Biomass & Bioenergy 31 (2007) 460-468.

[64] G. Persson, A. Lindroth, Simulating evaporation from short-rotation forest: variations within and between seasons, Journal of Hydrology 156 (1994) 21-45.

[65] W. Guidi, E. Piccioni, E. Bonari, Evapotranspiration and crop coefficient of poplar and willow short-rotation coppice used as vegetation filter, Bioresource Technology 99 (2008) 4832-40.

[66] P.J. Martin, W. Stephens, Willow growth in response to nutrients and moisture on a clay landfill cap soil. I. Growth and biomass production, Bioresource Technology 97 (2006) 437-48.

[67] P. Gregersen, H. Brix, Zero-discharge of nutrients and water in a willow dominated constructed wetland, Water science and technology : a journal of the International Association on Water Pollution Research 44 (2001) 407-12.

[68] C. Pistocchi, W. Guidi, E. Piccioni, E. Bonari, Water requirements of poplar and willow vegetation filters grown in lysimeter under Mediterranean conditions: Results of the second rotation, Desalination 246 (2009) 137-146.

[69] S. Curneen, L.W. Gill, Willow-based evapotranspiration systems for on-site wastewater effluent in areas of low permeability subsoils, Ecological Engineering 92 (2016) 199-209.

[70] R.L. Hall, S.J. Allen, P.T.W. Rosier, R. Hopkins, Transpiration from coppiced poplar and willow measured using sap-flow methods, Agricultural and Forest Meteorology 90 (1998) 275-290.

[71] J.M. Wilkinson, E.J. Evans, P.E. Bilsborrow, C. Wright, W.O. Hewison, D.J. Pilbeam, Yield of willow cultivars at different planting densities in a commercial short rotation coppice in the north of England, Biomass & Bioenergy 31 (2007) 469-474.

[72] M.J. Bullard, S.J. Mustill, S.D. McMillan, P.M.I. Nixon, P. Carver, C. P. Britt, Yield improvements through modification of planting density and harvest frequency in short rotation coppice Salix spp.—1. Yield response in two morphologically diverse varieties, Biomass & Bioenergy 22 (2002) 15-25.

[73] S. Puri, V. Singh, B. Bhushan, S. Singh, Biomass production and distribution of roots in three stands of Populus deltoides, Forest Ecology and Management 65 (1994) 135-147.

[74] E. Willebrand, T. Verwijst, Population dynamics of willow coppice systems and their implications for management of short-rotation forests, The Forestry Chronicle 69 (1993) 699-704.

[75] D.S. DeBell, G.W. Clendenen, C.A. Harrington, J.C. Zasada, Tree growth and stand development in short-rotation Populus plantings: 7-year results for two clones at three spacings, Biomass & Bioenergy 11 (1996) 253-269.

[76] I. Cañellas, P. Huelin, M.J. Hernández, P. Ciria, R. Calvo, G. Gea-Izquierdo, H. Sixto, The effect of density on short rotation Populus sp. plantations in the Mediterranean area, Biomass & Bioenergy 46 (2012) 645-652.

[77] W.D. Johnstone, The Effects of Initial Spacing and Rectangularity on the Early Growth of Hybrid Poplar, Western Journal of Applied Forestry 23 (2008) 189-196.

[78] T. Verwijst, B. Telenius, Biomass estimation procedures in short rotation forestry, Forest Ecology and Management 121 (1999) 137-146.

[79] G.R. Larocque, Performance and morphological response of the hybrid poplar DN-74 (Populus deltoides x nigra) under different spacings on a 4-year rotation, Annals Forest Science 56 (1999) 275-287.

[80] M.J. Bullard, S.J. Mustill, P.M.I. Nixon, S.D. McMillan, C.P. Britt, The effect on yield of initial planting density of short rotation coppice, Aspects of Applied Biology 65 (2001) 167-171.

[81] J. Schweier, S. Molina-Herrera, A. Ghirardo, R. Grote, E. Díaz-Pinés, J. Kreuzwieser, E. Haas, K. Butterbach-Bahl, H. Rennenberg, J.P. Schnitzler, G. Becker, Environmental impacts of bioenergy wood production from poplar short-rotation coppice grown at a marginal agricultural site in Germany, GCB Bioenergy 9 (2016) 1207-1221.

[82] R.F. Kopp, L.P. Abrahamson, E.H. White, K.F. Burns, C.A. Nowak, Cutting cycle and spacing effects on biomass production by a willow clone in New York, Biomass & Bioenergy 12 (1997) 313-319.

[83] N. Nassi o Di Nasso, W. Guidi, G. Ragaglini, C. Tozzini, E. Bonari, Biomass production and energy balance of a 12-year-old short-rotation coppice poplar stand under different cutting cycles, GCB Bioenergy 2 (2010) 89-97.

[84] J. Bacenetti, S. González-García, A. Mena, M. Fiala, Life cycle assessment: an application to poplar for energy cultivated in Italy, Journal of Agricultural Engineering; 43, (2012), e11.

[85] D. Lazdina, A. Lazdinš, Z. Karinš, V. Kāposts, Effect of sewage sludge fertilization in short-rotation willow plantations, Journal of Environmental Engineering and Landscape Management 15 (2007) 105-111.

[86] S. Njakou Djomo, O. El Kasmioui, R. Ceulemans, Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review, GCB Bioenergy 3 (2010) 181-197.

[87] S. Njakou Djomo, O. El Kasmioui, T. De Groote, L.S. Broeckx, M.S. Verlinden, G. Berhongaray, R. Fichot, D. Zona, S.Y. Dillen, J.S. King, I.A. Janssens, R. Ceulemans, Energy and climate benefits of bioelectricity from low-input short rotation woody crops on agricultural land over a two-year rotation, Applied Energy 111 (2013) 862-870.

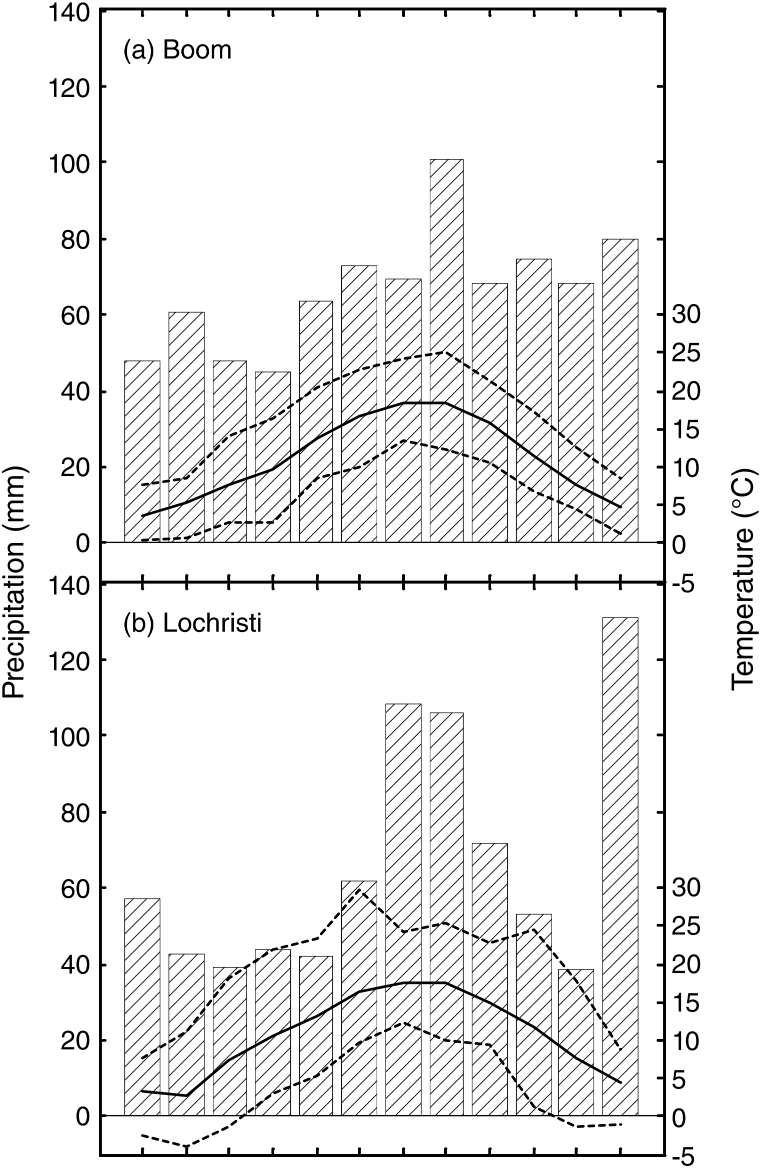
[88] D. Weißbach, G. Ruprecht, A. Huke, K. Czerski, S. Gottlieb, A. Hussein, Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants, Energy 52 (2013) 210-221.

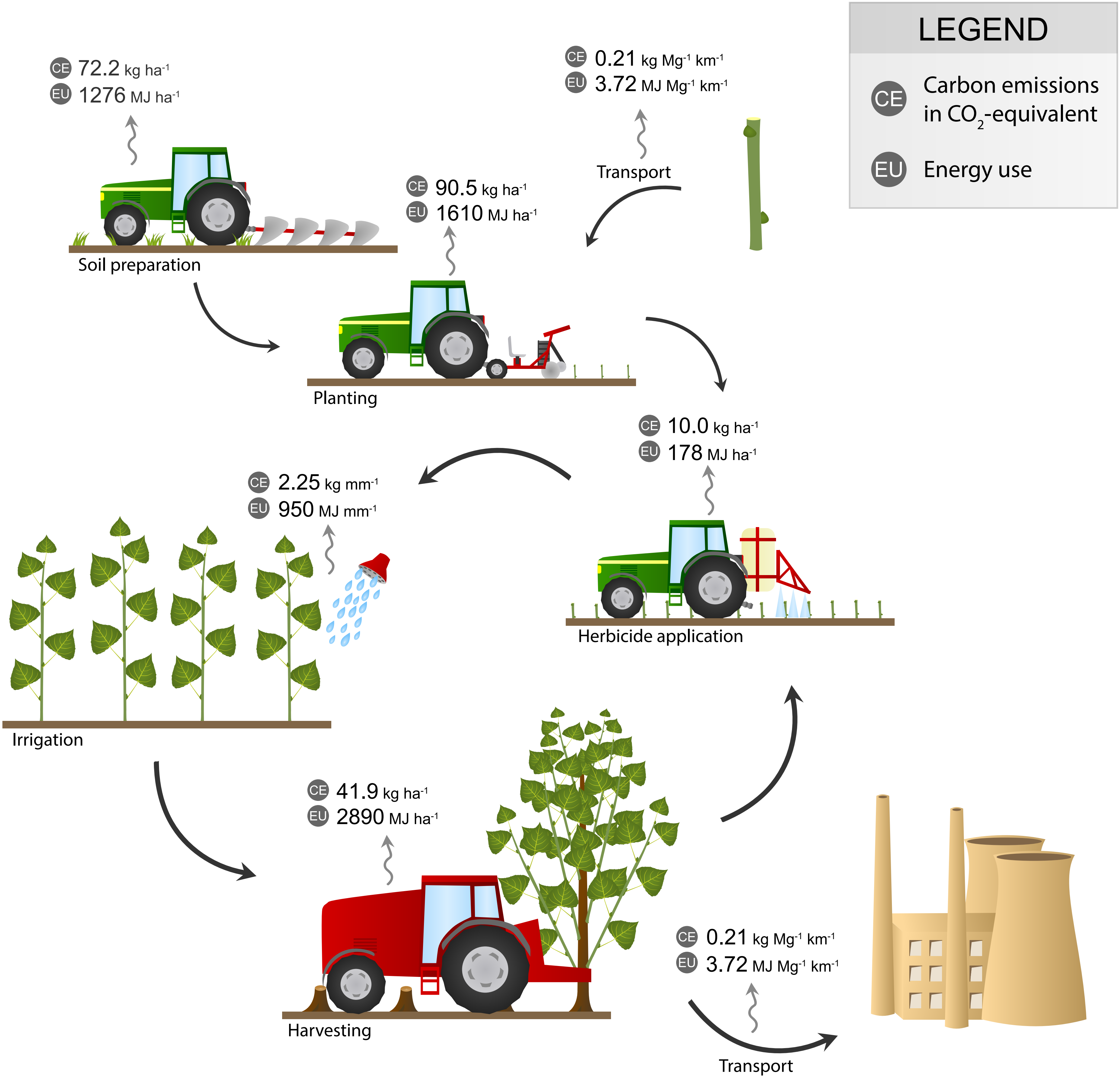
[89] P. Viebahn, J. Nitsch, M. Fischedick, A. Esken, D. Schüwer, N. Supersberger, U. Zuberbühler, O. Edenhofer, Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany, International Journal of Greenhouse Gas Control 1 (2007) 121-133.

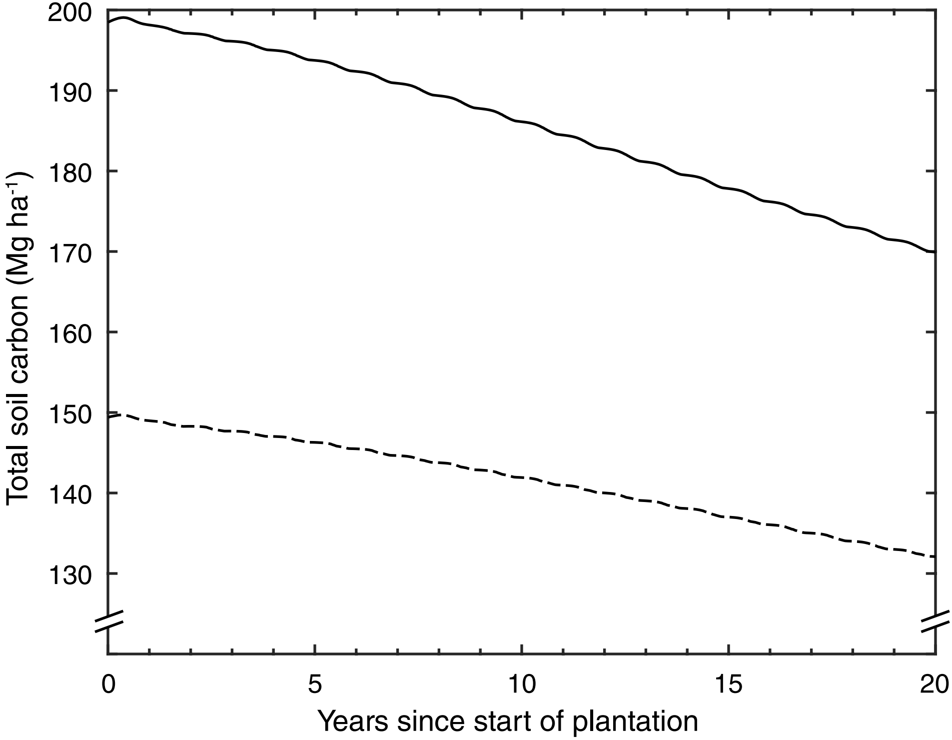
[90] M. Castaño-Díaz, M. Barrio-Anta, E. Afif-Khouri, A. Cámara-Obregón, Willow Short Rotation Coppice Trial in a Former Mining Area in Northern Spain: Effects of Clone, Fertilization and Planting Density on Yield after Five Years, Forests 9 (2018), 154.

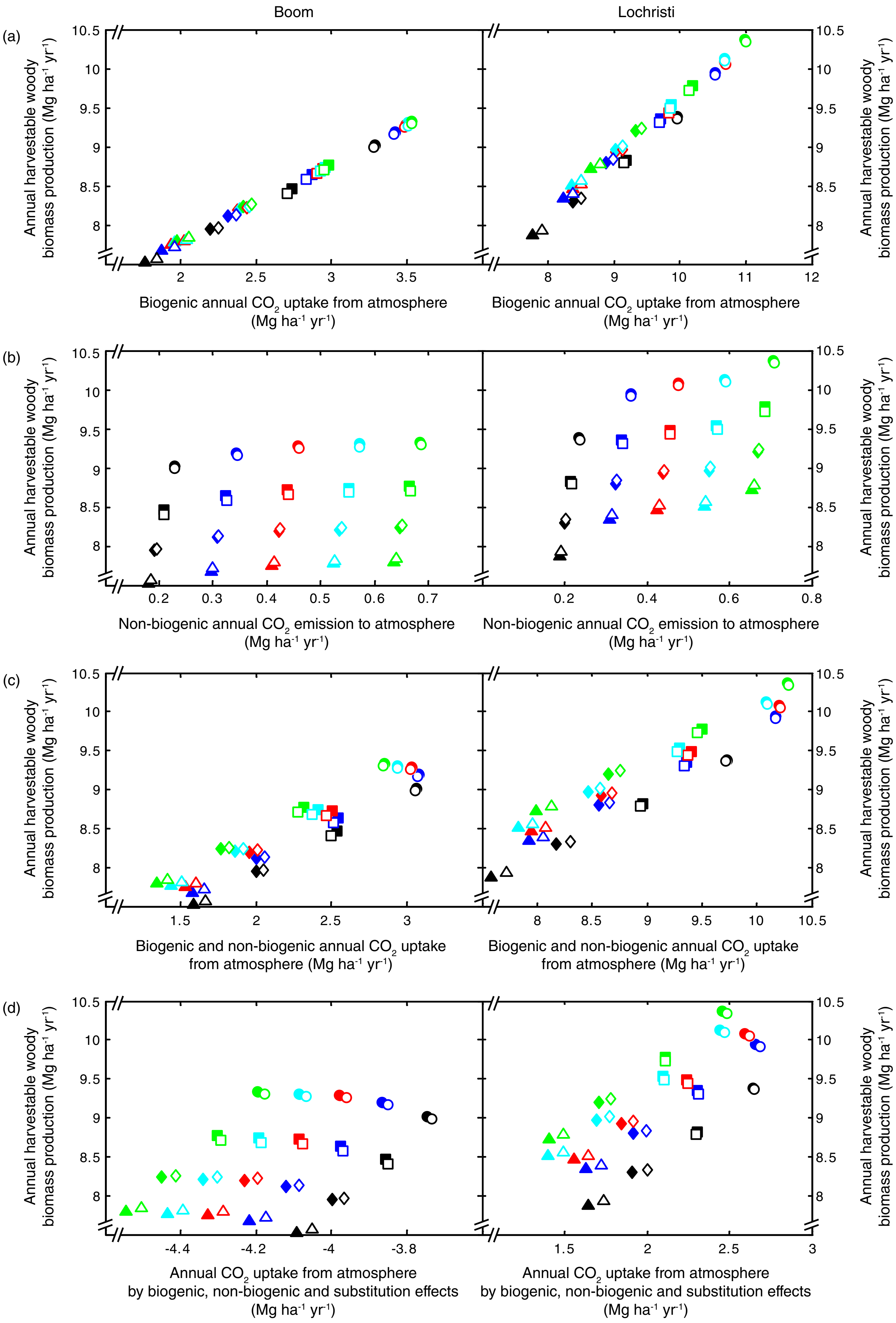
[91] S. Szczukowski, J. Tworkowski, A. Klasa, M. Stolarski, Productivity and chemical composition of wood tissues of short rotation willow coppice cultivated on arable land, Rostlinná Výroba 48 (2002) 413-417.

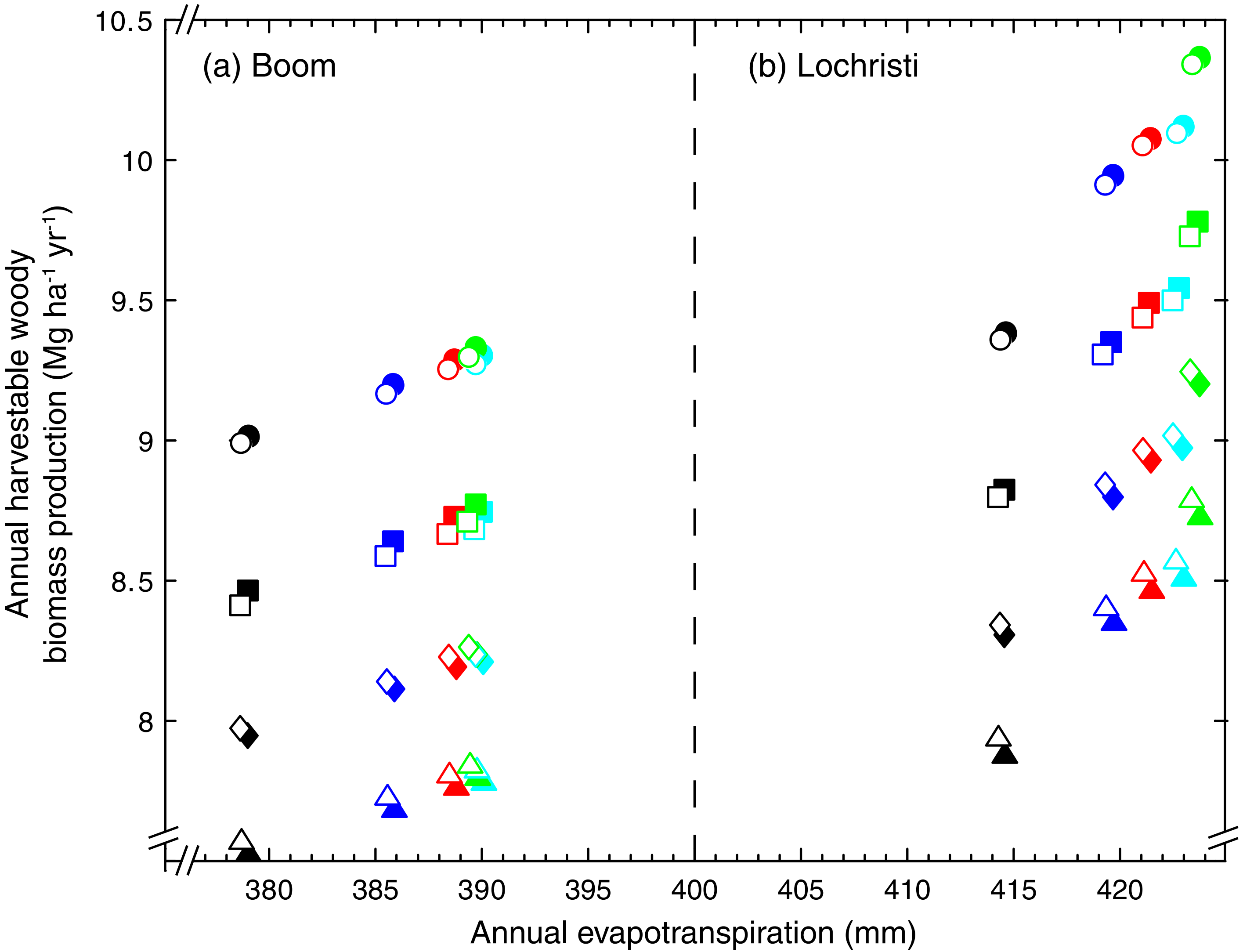
[92] D. Allen, D.W. McKenney, D. Yemshanov, S. Fraleigh, The economic attractiveness of Short Rotation Coppice biomass plantations for bioenergy in Northern Ontario, The Forestry Chronicle 89 (2013) 66-78.

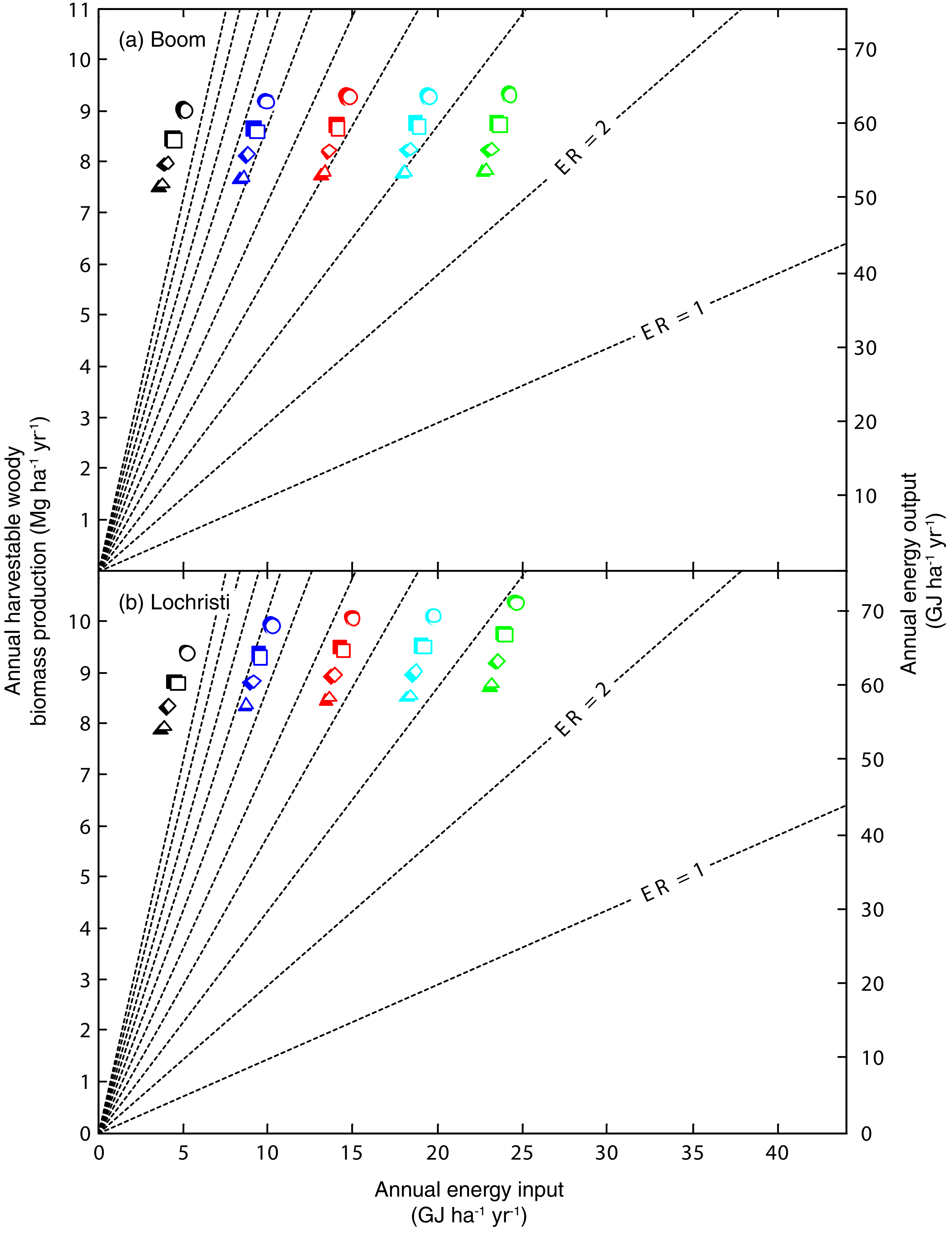

(a) Boom
(b) Lochristi
Precipitation (mm)
Temperature (°C)
140
120
100
80
60
40
20
0
30
25
20
15
10
5
0
-5
J
F
M
A
M
J
J
A
S
O
N
D

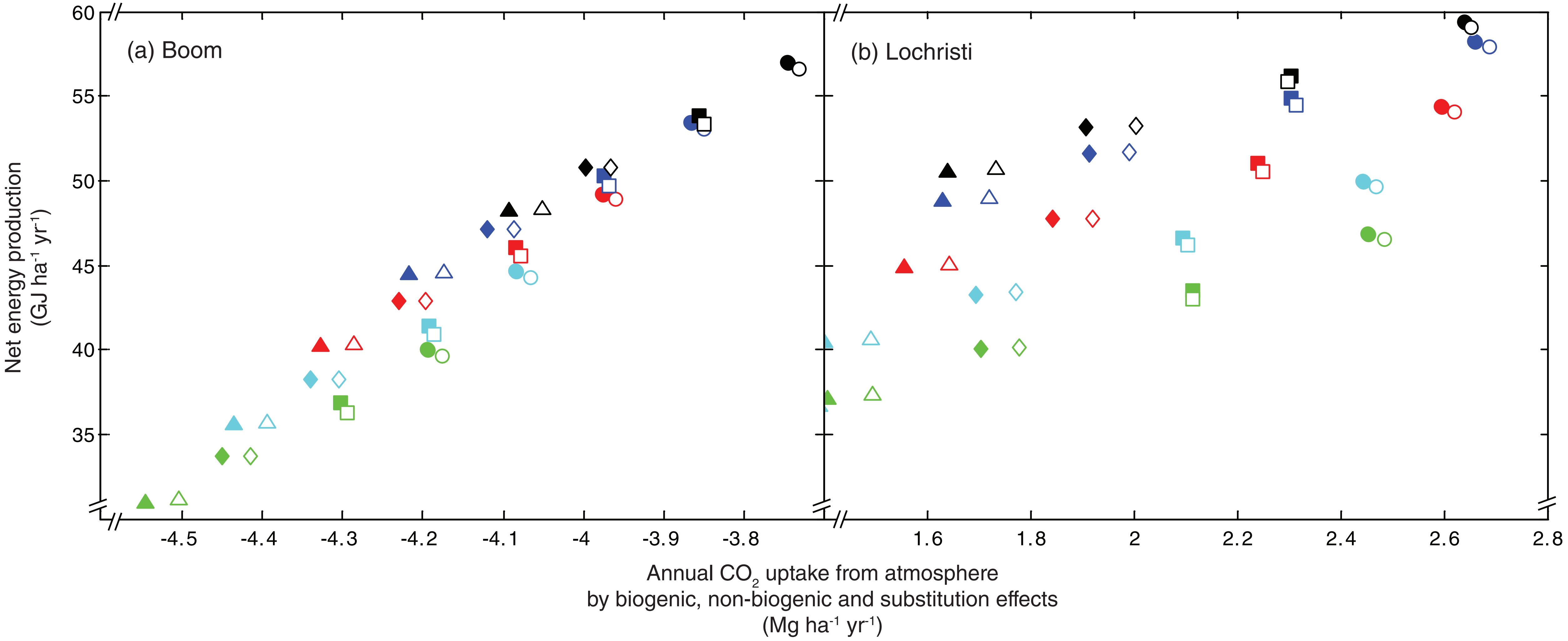

LEGEND
CE Carbon emissions in CO_2-equivalent
EU Energy use
CE 72.2 kg ha^{-1}
EU 1276 MJ ha^{-1}
Soil preparation
CE 0.21 kg Mg^{-1} km^{-1}
EU 3.72 MJ Mg^{-1} km^{-1}
Transport
CE 90.5 kg ha^{-1}
EU 1610 MJ ha^{-1}
Planting
CE 10.0 kg ha^{-1}
EU 178 MJ ha^{-1}
Herbicide application
CE 2.25 kg mm^{-1}
EU 950 MJ mm^{-1}
Irrigation
CE 41.9 kg ha^{-1}
EU 2890 MJ ha^{-1}
Harvesting
CE 0.21 kg Mg^{-1} km^{-1}
EU 3.72 MJ Mg^{-1} km^{-1}
Transport


200
190
180
170
160
150
140
130
Total soil carbon (Mg ha^{-1})
0
5
10
15
20
Years since start of plantation


Boom
Lochristi
(a)
(b)
(c)
(d)
Annual harvestable woody biomass production (Mg ha-1 yr-1)
10.5
10
9.5
9
8.5
8
2
2.5
3
3.5
8
9
10
11
12
Biogenic annual CO2 uptake from atmosphere (Mg ha-1 yr-1)
0.2
0.3
0.4
0.5
0.6
0.7
0.2
0.4
0.6
0.8
Non-biogenic annual CO2 emission to atmosphere (Mg ha-1 yr-1)
1.5
2
2.5
3
8
8.5
9
9.5
10
10.5
Biogenic and non-biogenic annual CO2 uptake from atmosphere (Mg ha-1 yr-1)
-4.4
-4.2
-4
-3.8
1.5
2
2.5
3
Annual CO2 uptake from atmosphere by biogenic, non-biogenic and substitution effects (Mg ha-1 yr-1)


(a) Boom
(b) Lochristi
10.5
10
9.5
9
8.5
8
380
385
390
395
400
405
410
415
420
Annual harvestable woody biomass production (Mg ha^{-1} yr^{-1})
Annual evapotranspiration (mm)


(a) Boom
(b) Lochristi
ER = 2
ER = 1
Annual harvestable woody biomass production (Mg ha^{-1} yr^{-1})
Annual energy output (GJ ha^{-1} yr^{-1})
Annual energy input (GJ ha^{-1} yr^{-1})
0
1
2
3
4
5
6
7
8
9
10
11
0
10
20
30
40
50
60
70
0
5
10
15
20
25
30
35
40



(a) Boom
(b) Lochristi
Net energy production (GJ ha^{-1} yr^{-1})
60
55
50
45
40
35
-4.5
-4.4
-4.3
-4.2
-4.1
-4
-3.9
-3.8
1.6
1.8
2
2.2
2.4
2.6
2.8
Annual CO$_2$ uptake from atmosphere by biogenic, non-biogenic and substitution effects (Mg ha^{-1} yr^{-1})

Figure 1: Climograph of (a) the Boom site and (b) the Lochristi site. The bars show the monthly averages precipitations, the solid lines represent the monthly averages temperatures while the dashed lines show the maximum and minimum monthly temperatures at both sites: Boom (1996-2007), Lochristi (2010-2012).

Figure 2: Visualization of the management actions and the specific energy use and CO_2 emissions of the different equipment used to carry out activities that were considered in the selection of the optimal management scenario.

Figure 3: Soil carbon stock of the SRC plantation at the Boom site (solid line) and the Lochristi site (solid line). The shown scenario has the following characteristics: density = 5000 cuttings ha^{-1}; rotation length = 2 years; no establishment cut; no irrigation.

Figure 4: 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.

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.

Figure 5: The annual evapotranspiration by the plantations: (a) Boom site, (b) Lochristi site. 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.

Figure 6: The annual energy input into the plantations and annual harvestable biomass at the Boom site (a) and the Lochristi site (b). 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.

Figure 7: A comparison of the annual net energy balance and the annual CO_2 uptake from the atmosphere, including biogenic, non-biogenic and substitution effects for the Boom site (a) and the Lochristi site (b). 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.

Table S1: Carbon balances for short rotation coppice at Boom and Lochristi sites: planting density 5000 cuttings ha^{-1}, no establishment year cut

	Boom Site			**Lochristi Site**		
Rotation length	2 yr			2 yr		
Irrigation	0 mm	100 mm	200 mm	0 mm	100 mm	200 mm
	CO_2 emissions (kg ha^{-1} yr^{-1})					
Transport cuttings	1	1	1	1	1	1
Soil preparation	4	4	4	4	4	4
Planting	5	5	5	5	5	5
Weeding	5	5	5	5	5	5
Irrigating	0	225	450	0	225	450
Harvesting	21	21	21	21	21	21
Tr. To power plant	192	198	199	200	215	221
BM conversion to el.	16527	17020	17102	17199	18480	19001
Total CO_2 emissions	**16754**	**17477**	**17786**	**17433**	**18955**	**19707**
	CO_2 uptake (kg ha^{-1} yr^{-1})					
Biogenic uptake	3289	3491	3534	9962	10684	10989
Substitution effects	9720	10009	10058	10114	10868	11175
Total CO_2 uptake	**13009**	**13500**	**13592**	**20076**	**21552**	**22163**
Total CO_2 balance	**-3745**	**-3977**	**-4194**	**2643**	**2598**	**2456**

Tr = transport, BM= biomass, el. = electricity, yr = year

Table S2: Energy inputs and outputs for short rotation coppice at Boom and Lochristi sites: planting density 5000 cuttings ha^{-1}, no establishment year cut

	Boom Site			**Lochristi Site**		
Rotation length	2 yr			2 yr		
Irrigation	0 mm	100 mm	200 mm	0 mm	100 mm	200 mm
Energy input (MJ ha^{-1} yr^{-1})						
Transport cuttings	1	1	1	1	1	1
Soil preparation	64	64	64	64	64	64
Planting	81	81	81	81	81	81
Weeding	89	89	89	89	89	89
Irrigating	0	9500	19000	0	9500	19000
Harvesting	1445	1445	1445	1445	1445	1445
Tr. To power plant	3352	3452	3469	3488	3748	3854
Total energy input	**5032**	**14632**	**24149**	**5168**	**14928**	**24534**
Energy output (MJ ha^{-1} yr^{-1})						
BM conversion to el.	61482	63314	63621	63979	68746	70685
Total energy output	**61482**	**63314**	**63621**	**63979**	**68746**	**70685**
Energy ratio	**12.2**	**4.3**	**2.6**	**12.4**	**4.6**	**4.7**
Net energy production	**56450**	**48682**	**39472**	**58811**	**53818**	**46151**

Tr = transport, BM= biomass, el. = electricity, yr = year