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Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years☆

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ABSTRACT

Although poplar short-rotation coppice (SRC) systems as an alternative to fossil fuels have been intensively studied, little is known about their biomass potential during several consecutive harvest cycles. For the very first time, this study reports on aboveground biomass yield and energy balance of a 16-year-old poplar SRC with a mixture of 17 pure species and hybrid *Populus* spp. clones. The plantation established on degraded land in Boom, Belgium, was maintained as a low-energy input system, i.e. no irrigation, no fertilizers and no fungicides were applied. The average dry biomass yield during the fourth rotation was 4.3 ± 3.4 ton ha^{-1} year^{-1} across all clones, but the most productive clones yielded up to 10.5 ton ha^{-1} year^{-1}. After 16 years, stool survival ranged from 6 to 91% among clones. Our results demonstrated the sustained biomass potential and resprouting capacity after a severe leaf rust attack and after several harvests of the studied *Populus nigra* and *Populus trichocarpa* clones as opposed to hybrids between *Populus deltoides* and *P. trichocarpa* which hardly survived the fourth rotation. These findings suggest that pure species might perform better than hybrids under suboptimal conditions, e.g. on degraded lands, throughout several harvest cycles and/or after leaf rust infestations. Despite the relatively low yields, the investigated system on degraded land had a positive energy balance producing 7.9 times more energy than it consumed from cradle to plant gate.

1. Introduction

Poplars (*Populus* spp.) grown under a short-rotation coppice (SRC) regime have been extensively studied in function of bioenergy production [1–6]. Decades-long research has led to a solid expertise in many countries and practical experience on growing poplar at high densities (i.e. ≥5000 cuttings per hectare) has been translated in best practice guidelines. Yet, the environmental impacts and economical viability of SRC as an alternative energy source to fossil fuels are still under debate [7–10]. The environmental impacts and energy balance of dense poplar plantations are evaluated through life cycle assessment (LCA), although a widely accepted and uniform methodological approach is lacking thus far [11]. The economic viability is assessed by means of life cycle cost and by financial models considering

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the costs and benefits over the entire lifetime of the plantation.

To avoid carbon emissions from land use change and to limit the loss of biodiversity, several authors suggested the use of degraded lands for bioenergy crops over agricultural lands [8,12,13]. About 15%, i.e. 5404 km^2, of Belgium's total area was considered to be degraded land in 2003 [14]. Growing poplar on degraded lands may help in recultivating degraded lands or in preventing further degradation of such lands. Rental or purchase price of degraded lands is cheaper in comparison with agricultural lands. However, in many cases, the extra work needed to bring in amendments or to prepare the site for growing SRC or other energy crops make them more expensive. Also, productivity and yields of SRC on degraded lands may be lower. This raises the question whether the productivity on degraded lands is so low that electricity generation from a poplar SRC system on such lands becomes inefficient, i.e. the system's energy ratio is less than unity. Although energy balances of SRC-based electricity systems have been extensively researched, no studies of energy balances on degraded lands were reported [11]. Further, field experiments covering the complete life span of poplar SRC on agricultural lands are scarce and even inexistent on degraded lands. The life expectancy is believed to be 20–25 years (including 7–8 harvests for 3-year harvest cycles) without significant yield losses, but it can be markedly affected by plant material, by plantation maintenance, by the presence of pathogens and by the planting density in relation to the harvest frequency [15].

Shorter rotation cycles allow higher planting densities and thus, higher biomass yields per unit land area. Coppicing usually stimulates spring re-growth and apparently avoids replanting costs. When rotation lengths are too short for a given species or genotype, re-growth may be hindered by depletion of the carbohydrate reserves primarily stored in the root system [5]. A recent study covering 12 years of poplar SRC in North Italy investigated the effect of 1-, 2- and 3-year harvest cycles on biomass potential of the commonly used *Populus deltoides* Bartr. clone Lux [16]. Under the annual harvesting scheme, most poplar stools were soon exhausted and did not survive the seventh year. On the other hand, highest survival rates and maximum productivity were ascertained in plots with a 3-year harvest cycle. For many years, poplars have been in the first place selected for single-stem growth and straight stem form in traditional breeding and selection programmes [17]. As a result, several commercially available poplar clones may not withstand frequent harvesting or short-rotation cycles without a decrease in productivity or in resprout capacity.

In this study, we document the biomass yield of a 16-year-old poplar SRC with multiple clones on degraded land, more specifically a former waste disposal site moderately polluted with heavy metals [18]. As far as we are aware, this is the longest running SRC plantation with poplar on degraded land. The plantation was maintained as a low-energy input system (no fertilization, no irrigation and no fungicides). We built on earlier work and compared actual yields with those from earlier rotations [6]. To study the dynamics of biomass yield of a poplar SRC over 16 years, we estimated effects of clone and rotation year as well as their mutual interactions on stool survival, number of shoots and biomass yield. We also estimated the energy ratio of the investigated SRC-based electricity system.

2. Material and methods

2.1. Site and experimental design

The SRC plantation was established on a former waste disposal site covered with a mixture of sand, clay and rubble from nearby areas in Boom, Flanders, Belgium (51°05′N, 04°22′E; 5 m above sea level). The site was moderately polluted with heavy metals and nutrient as well as mineral reserves were moderate in comparison with agricultural soils [3]. The 0.55 ha field site was plowed and harrowed before planting in April 1996. Hardwood cuttings (25-cm long) from selected poplar (*Populus*) clones were planted at a planting density of 10,000 trees per hectare according to a double-row plant design with alternating inter-row distances of 0.75 and 1.5 m and a spacing of 0.9 m between cuttings within rows. The 17 clones were distributed using a randomized block design with three replicate plots per clone. Each plot consisted of 100 trees or 10 rows by 10 columns, but only a core of 6 rows by 6 columns, i.e. 36 assessment trees, was sampled or studied to avoid border effects. A more detailed description of the plantation and of the soil characteristics and conditions has been provided earlier [3]. Monthly mean values of temperature and precipitation over the course of the experiment (1997–2011) are reported in Fig. 1. The meteorological data were obtained from the Royal Meteorological Institute of Belgium.

2.2. Plant material

The planted clones were a mixture of pure species and hybrids: one *Populus nigra* L. clone (N) Wolterson; three *Populus trichocarpa* Torr. & Gray clones (T) Columbia River, Fritzi Pauley and Trichobel; six *P. trichocarpa* × *P. deltoides* Bartr. clones (T × D) Beaupré, Boelare, Hazendans, Hoogvorst, Raspalje and Unal; three *P. deltoides* × *P. trichocarpa* (D × T) clones IBW1, IBW2 and IBW3; three *P. deltoides* × *P. nigra* clones (D × N) Gaver, Gibecq and Primo; and one *P. trichocarpa* × *Populus balsamifera* L. clone

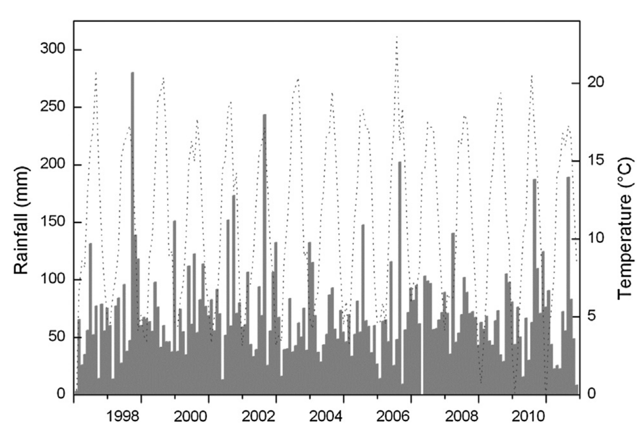

Fig. 1 – Average monthly rainfall (mm) and temperature (°C) measured at a meteorological station near the study site, from January 1997 till December 2011.

(T × B) Balsam Spire. Place of origin and clonal code numbers have been described by Laureysens et al. [3].

2.3. Management regime

After the establishment year, shoots were manually cut at 5 cm above the ground level in December 1996 to obtain a multi-stem coppice culture. The plantation was harvested in January 2001, in January 2004, in February 2008 and in November 2011. Thus, rotation length was 4 years, except for the second rotation which was only 3 years. Plantation management included mechanical weeding: twice during the establishment year and at the onset of the first rotation, and once at the onset of the three following rotations. Herbicides (glyphosate 3.2 kg ha^{-1} and oxadiazon 9.0 kg ha^{-1}) were applied six times throughout the full life span: twice during the establishment year and once at the onset of each rotation. No irrigation, fertilizers or fungicides were applied. After four rotations, in November 2011, stumps and coarse roots were mechanically removed by an excavator.

2.4. Biomass estimation

Survival of stools (%), number of shoots and shoot diameter were assessed for the 36 assessment trees at the end of the growing season of years 1997–2003, 2005, 2006, 2010 and 2011 [6,19–21]. Shoot diameter (*D*) was measured at 22 cm above ground level using a digital caliper (Mitutoyo, type CD-15DC, UK). When *D* exceeded 3 cm, the average of two perpendicular *D* measurements was further used in the calculations [22]. At regular intervals, a selection of shoots representative of the shoot diameter frequency distribution was randomly harvested from stumps, i.e. 5–30 shoots per clone [19–21]. The removal of the shoots was not accounted for in the larger destructive harvests or in the diameter distribution during the next years, since we believe it did not significantly affect the estimations of productivity or total biomass yield. Allometric relationships between shoot dry mass and shoot diameter ($M = aD^b$, with a and b as regression coefficients, and M as shoot dry mass; [22]) were retrieved from a previous study on the same plantation [6]. A previous study at this site demonstrated that one general allometric equation was sufficient for estimating aboveground biomass yield of all clones irrespective of year, except for clone Hazendans and during 2001, a year with severe leaf rust infestation [6]. After each harvest, the total aboveground biomass yield was chipped and transported to the power plant where these chips were gasified for electricity production.

2.5. Statistical analyses

Analyses were performed in the R Statistical Computing Environment (Language Environment Version 2.12.1). Clonal and rotation effects on survival, number of shoots and biomass yield were tested using a repeated measures analysis of variance (ANOVA). The following model was used:

$$z = \mu + cl + y < rt > + rt + cl \times rt + cl \times y < rt > + \varepsilon$$

where z is stool survival, number of shoots or biomass yield; μ is the general mean; clone (*cl*), rotation (*rt*) and year (*y*; nested within rotation) were treated as fixed effects; ε is the residual error. Post-hoc evaluation was done by Tukey's HSD test. All differences were considered significant at $P \leq 0.05$. Pearson correlation coefficients (*r*) among traits and Spearman rank coefficients (ρ) among years were calculated from clonal means.

2.6. Energy analysis

For the studied poplar SRC system, a full chain energy analysis was performed for two situations: (i) from cradle to farm gate and (ii) from cradle to plant gate (Fig. 2). For the latter, the system boundary includes the production of herbicides and tractors, soil cultivation (plowing and harrowing), biomass production, harvest, chipping, storage at the farm, stump removal, transport, natural drying of woody chips and their conversion to electricity (see Fig. 2 for systems boundaries of both situations).

The functional unit was 1 ha land. All direct and indirect energy inputs to the SRC system under study were considered in the inventory up to the production of electricity. Prior to plowing, some works were required to remove rubble from the site, but the energy cost of rubble removal was insignificant and therefore excluded from this analysis. Further, given that the biomass chips were naturally dried, the energy inputs for drying were also excluded from the analysis. Solar energy which initiates the build-up of the poplar trees was not considered in the energy balance. Likewise, an evaluation of environmental impacts was not undertaken.

The direct energy consumption within the system includes the use of diesel or electricity. The indirect energy use involves energy associated with the production of farm machineries and agricultural inputs, such as herbicides and poplar cuttings. Data on material use, diesel consumption, human labor, and machinery used to carry out each agricultural activity were collected onsite (Table 1). To calculate the direct energy costs, we multiplied the amount of diesel consumed during each farming activity by the low heating value of diesel, assumed to be 35.9 MJ l^{-1} [23]. The human energy cost was estimated by multiplying the amount of person-hour of labor for manual planting by the energy expended by a male worker to carry out a farm operation (1.9 MJ h^{-1} [24]). The indirect energy costs of materials were estimated by multiplying the input rate of each material by its energy intensity (Table 1). The assumed energy intensities were 371.1 MJ kg^{-1} for glyphosate [24], 211.2 MJ kg^{-1} for oxadiazon [23], and 0.3 MJ p^{-1} for the cuttings [24]. These values included energy costs for manufacture and transport of the materials to the farm. The indirect energy costs for agricultural machinery production were calculated by multiplying the embodied energy coefficient by the weights of the machine, taking into account the operating rates and life span of the machines (Table 1). For machinery, an embodied energy coefficient of 125 MJ kg^{-1} was assumed [24].

To estimate the direct energy costs for the transport of the harvested poplar chips to the conversion site, an energy coefficient of 0.8 MJ ton^{-1} km^{-1} was assumed [24]. We further assumed that the poplar chips were transported by truck over a distance of 50 km, a reasonable distance for a small country like Belgium. The direct energy input for the conversion process itself was estimated at 3% of the energy stored in the

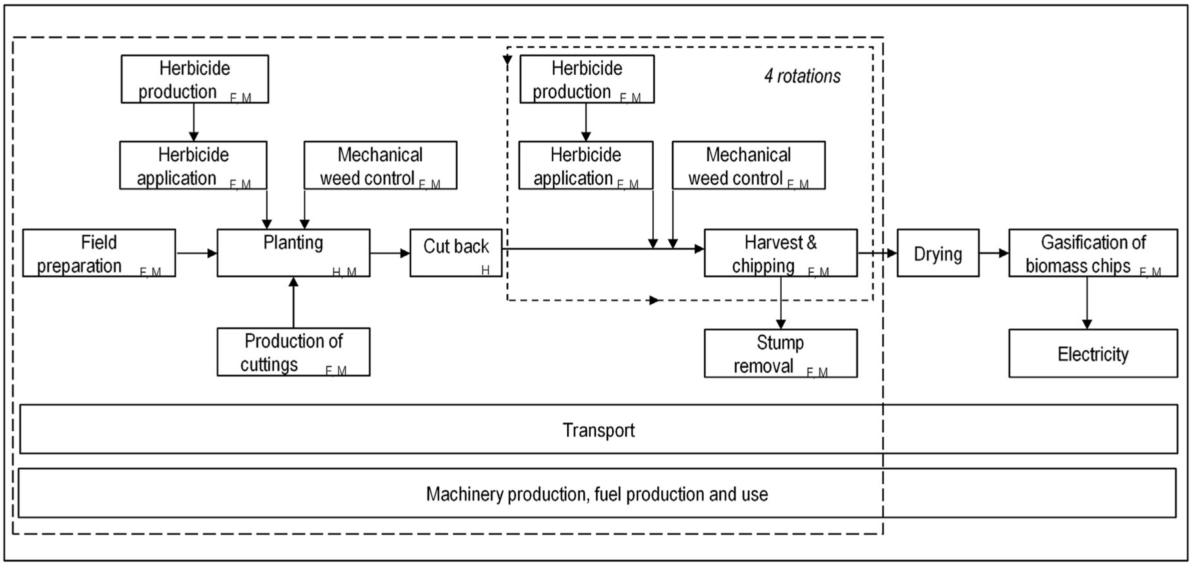

Fig. 2 – Schematic representation of the production chain of the studied poplar short-rotation coppice system. All operations are represented by boxes and energy flows by arrows. Inputs of fossil fuel (F), materials (M) and human labor (H) are indicated. Two system boundaries were considered (i) from cradle to farm gate (frame indicated by the dashed lines) and (ii) from cradle to plant gate (frame indicated by the full line). The rotation length was four years, except for the second rotation which was only three years long.

woody biomass [25]. The selected conversion technology for this study was a biomass gasification plant with an electrical efficiency of 37.2% [26].

To calculate the total energy input for biomass production we summed up all direct and indirect energy inputs till farm gate. The total energy input at the power plant gate was calculated by adding the energy inputs in conversion plant to the total energy input to produce the biomass. The total energy output at the farm gate was estimated by multiplying the total biomass yield over four rotations by the energy density of wood, i.e. 18.5 MJ kg^{-1} (HHV or higher heating value of poplar wood) [16]. The biomass loss due to natural drying at the farm gate was estimated to be 6% [27–30]. We further assumed that no losses occurred during transport and storage of biomass at the gasification plant. At the power plant gate, the total energy output was calculated by multiplying the

Table 1 – Farm activities, material and fuel inputs for the short-rotation coppice system over 16 years.

Activity	Implement used and lifetime (h)	Tractor/Excavator		Total weight (kg)[a]	Operating rate (h ha^{-1})	Diesel consumed (l ha^{-1})[b]	Distance (km)	Person-hour of labor (h ha^{-1})	Number of coverage
		Power (kW)	Lifetime (h)						
Plowing	Moldboard plow (2825)	94	7000	7390	0.86	33.2	–	–	1
Harrowing	Disk tiller (2967)	94	7000	7310	0.82	11.8	–	–	1
Application glyphosate (3.2 kg ha^{-1})	Boom sprayer (2154)	48	4000	4600	0.37	2.8	–	–	6
Application oxadiazon (9.0 kg ha^{-1})	Boom sprayer (2154)	48	4000	4600	0.37	2.8	–	–	6
Manual planting (10,000 cuttings ha^{-1})	–	–		–	–	–	–	100	1
Mechanical weeding	Rotortiller (2538)	48	4000	4500	0.44	2.7	–	–	7
Harvest and chipping[c]	Trailer (3000)	94	7000	8200	16.9	74.9	–	–	4
Removal of stumps	Grab bucket crane (5000)	94	9000	22,000	9.5	40.4	–	–	1
Transport of chips to power plant	Truck	–		–	–	–	50	–	4

a The total weight includes weight of implement and weight of tractor.
b The value of diesel consumption refers to an average of all harvests.
c A trailer was used to move the chipping equipment to the field site. A chipper mounted on the trailer was used at the site for the chipping.

electrical efficiency by the total biomass energy produced by the SRC system. Finally, we calculated the cradle to farm gate energy ratio by dividing the harvested biomass energy at the farm gate by the total energy consumed in biomass production (ER_{farm}). In the same way, we calculated the cradle to plant energy ratio by dividing the total energy output at plant gate by the total energy consumed to produce electricity (ER_{plant}).

3. Results

3.1. Biomass yield

Large clonal variation was observed for stool survival, for number of shoots and for biomass yield (Fig. 3). Striking differences in biomass yields were recorded among the 17 pure and hybrid poplar clones, ranging from 0 to 10.5 ton ha^{-1} year^{-1} during the fourth rotation (2008–2011). While some clones did not survive earlier rotations, other clones displayed highest productivity levels over their entire lifetime (Fig. 3). The pure species clones Wolterson (N), Columbia River (T), Fritzi Pauley (T) and Trichobel (T) were most productive and yielded 8.5–10.5 ton ha^{-1} year^{-1} in the fourth rotation. However, these large yields were attained by fairly contrasting growth strategies. Wolterson produced numerous shoots after coppicing, while the T clones, in particular Fritzi Pauley, accommodated high apical dominance and produced few, but large shoots.

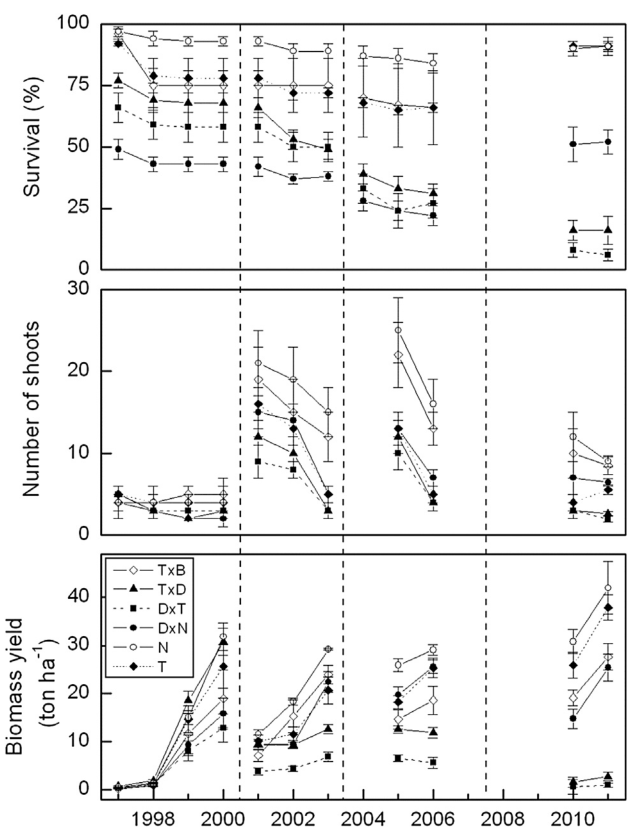

Fig. 3 – Time course of survival (%), number of shoots and aboveground dry biomass yield (ton ha^{-1}) during four rotation cycles of the short-rotation coppice culture with 17 poplar clones belonging to six parentages.
Means ± standard error are presented; the four rotations are separated by dashed lines. T = *Populus trichocarpa*; B = *P. balsamifera*; D = *P. deltoides*; N = *P. nigra*.

The performance of some clones varied substantially over different rotations and years. Significant clone × rotation interactions were observed for all studied productivity traits, and for biomass yield there were also significant clone × year<rotation> interactions (Table 2; Fig. 3). The T × D clones were characterized by fast juvenile growth rates and high biomass yield during the first years but due to high-mortality rates the T × D biomass yield dropped drastically from the second rotation onward (Fig. 3). Clone Hoogvorst (T × D) did even not survive the third rotation. As opposed to T × D clones, D × N clones slowly established and had low growth rates during the first growing season (Fig. 3). After the first rotation, biomass yield of the D × N clones steadily increased to intermediately and highly ranked biomass values compared to all other clones in the fourth and third rotations, respectively. Surprisingly, stool survival of some clones was higher in the fourth than in the third rotation (Fig. 3).

3.2. Correlations among traits

Highly significant correlations were found among traits in 2011, i.e. at the end of the fourth rotation. Obviously, high biomass yield was associated with high stool survival ($r = 0.96$ and $P \leq 0.001$). The number of shoots was also strongly and positively correlated with stool survival ($r = 0.86$ and $P \leq 0.001$). Overall, clones producing a higher number of shoots had higher biomass yield ($r = 0.85$ and $P \leq 0.001$). However, some exceptions were observed: few but larger shoots, resulted in large biomass yields for T clones. According to the Spearman rank coefficients across years (Table 3), clonal stability of biomass yield was generally highest within rotations. Across rotations, the first rotation was not representative for the subsequent rotations, i.e. the first rotation did not provide a proper prediction of the yield of subsequent rotations. Changes in clonal biomass rankings also occurred between the second and the fourth rotation, but Spearman rank coefficients suggested high clonal stability in the last two rotations (Table 3).

3.3. Energy inputs and outputs

The total energy input to produce the woody chips over 16 years was 49.3 GJ ha^{-1} while the total energy inputs to produce the usable energy, i.e. electricity was 68.8 GJ ha^{-1} (Fig. 4). Field preparation accounted for 4.6% of the total energy costs from cradle to plant gate. Weeding accounted for 30% of the total energy costs, primarily due to the large energy requirements of the herbicide production (Fig. 4). A similar energy cost was related to the operations of harvesting and chipping, 26.8% of the total energy costs. Biomass conversion into electricity was the largest energy cost of the SRC system under study, 23.8% of the total energy input. Relatively little energy was required for production and planting of cuttings, for transport over 50 km and for stump removal, all in the range of 4–5% of the total energy costs. The total biomass feedstock from the studied SRC system was 84.5 ton ha^{-1} of but was reduced to

Table 2 – Tests of fixed effects of the repeated measures three-way ANOVA model for stool survival, number of shoots and biomass yield. Year was treated as a nested factor within rotation. *P*-values are indicated in bold when non-significant. * = *P* ≤ 0.001.**

	Clone	Rotation	Year	Clone × year<rotation>	Clone × rotation
Stool survival	$F_{16,383} = 68.5^{***}$	$F_{3,383} = 116.9^{***}$	$F_{8,383} = 4.2^{***}$	$F_{127,383} = 0.17^{\mathbf{1.00}}$	$F_{48,383} = 8.5^{***}$
Number of shoots	$F_{16,346} = 26.1^{***}$	$F_{3,346} = 228.0^{***}$	$F_{7,346} = 56.4^{***}$	$F_{110,346} = 1.0^{\mathbf{0.45}}$	$F_{47,346} = 4.9^{***}$
Biomass yield	$F_{16,355} = 40.9^{***}$	$F_{3,355} = 29.8^{***}$	$F_{7,355} = 99.4^{***}$	$F_{110,355} = 2.0^{***}$	$F_{47,355} = 9.5^{***}$

79.4 after losses due to harvest and to natural drying. The energy yield at the farm gate was 1469.1 GJ ha^{-1}. After conversion of biomass into electricity, total usable energy produced by the studied SRC system was 546.5 GJ ha^{-1}. The ER_{farm} was 29.8 and was reduced to 7.9 when the biomass was converted into electricity, i.e. ER_{plant} (Fig. 4).

4. Discussion

4.1. Biomass yield

The average dry biomass yield of 5.3 ton ha^{-1} year^{-1} throughout four rotations is low compared to the frequently reported yields of 10–12 ton ha^{-1} year^{-1} [31]. Nevertheless, significant differences in biomass yields occurred among the planted clones, ranging from 0 to 10.4 ton ha^{-1} year^{-1} during the last rotation. Moreover, the performance of some clones varied substantially over different rotations and years highlighting the need of long-term experiments to identify most suitable poplar clones for SRC. The question whether poplars lose their resprout capacity and growth vigour after several harvests was only partly answered by this study. Clones as Wolterson (N), Fritzi Pauley, Columbia River and Trichobel (T) did not show any sign of stool exhaustion after four harvests and may even have tolerated one or two additional rotations. Indeed, the N and T clones reached peak biomass levels while biomass yields of T × D and D × T clones were lowest after 16 years. For clones of the T, D × N and T × B parentage, higher stool survival was observed in the fourth than in the third rotation. Likely, root sprouts from neighboring trees occupied some of the open areas in the field as new shoots could be distinguished from originally planted individuals indicating the vigorous sprouting capacity of these clones. Breeding and selection for SRC are complex; fast growth rates are not the only aim, but also sustained biomass yields during >20 years and good coppice ability or resprout capacity, i.e. vigorous spring re-growth after coppice [5]. Clones have good coppice ability when their growth is stimulated, or at least, not hampered by frequent harvesting. A large number of shoots after coppice might be considered as an indicator of good coppice ability or resprout capacity as observed for clone Wolterson (N) which produced 20–30 shoots after coppicing and displayed the highest yields during four rotations. Nevertheless, good coppice ability was also observed for

Table 3 – Spearman rank coefficients calculated from clonal means of biomass yield between the fourth and earlier rotations of the 16-year-old poplar short-rotation coppice system. Years without biomass assessments are put in italics. Significance levels are indicated as follows: * = *P* ≤ 0.001; ** = *P* ≤ 0.01; * = *P* ≤ 0.05; ns = non-significant.**

		4th rotation	
		2010	2011
1st rotation	1997	ns	ns
	1998	ns	ns
	1999	ns	0.52*
	2000	ns	0.56*
2nd rotation	2001	ns	ns
	2002	0.53*	0.87***
	2003	0.68**	0.85***
3rd rotation	*2004*		
	2005	0.74***	0.89***
	2006	0.88***	0.86***
	2007		
4th rotation	2010		0.97***

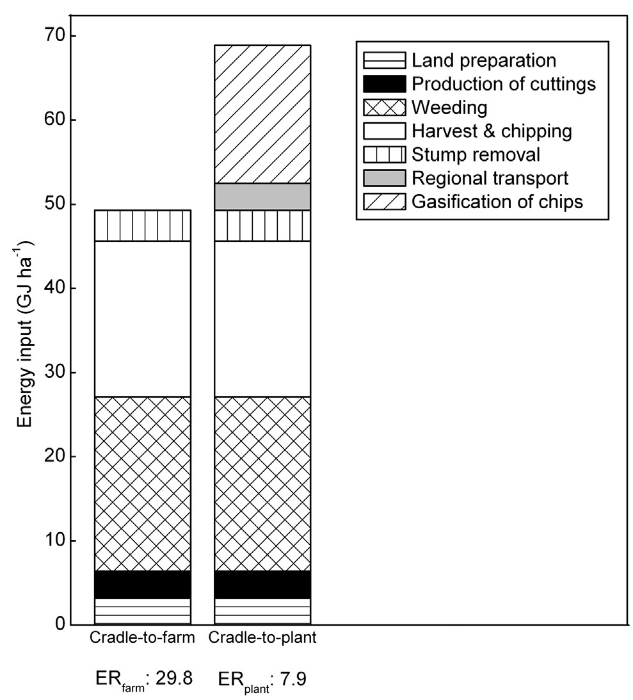

Fig. 4 – Breakdown of energy inputs (GJ ha^{-1}) for the poplar short-rotation coppice system during four rotations. Energy costs for each activity and energy ratios (*ER*) of two system boundaries are presented, i.e. from cradle to farm gate (ER_{farm}) and from cradle to plant gate (ER_{plant}). Calculations related to the energy balance are given in Material and Methods.

studied T clones, all characterized by contrasting growth strategy of few, large shoots.

The poor yields of the D × T and many of the T × D clones can be largely explained by their high susceptibility to leaf rust (*Melampsora larici-populina* Kleb.) and their intolerance to shade. As previously mentioned [6], a severe rust attack in combination with the bark-killing fungus *Discosporium populeum* (Sacc. Sutton) during the summer of 2001 reduced the overall yield and caused high mortality, mostly among the D × T and T × D clones. None of these clones completely recovered and their biomass yield continued to decrease, even several years after the major leaf rust infestation. Plots with high mortality as a result of the rust attack were overgrown with tall weeds since weed control was only applied at the onset of each rotation. In the high-mortality plots, the tall weeds likely reduced growth of the resprouting poplars by competing for light, water and/or nutrients. Hybrids usually outperform the pure species at early age and assure rapid establishment of the plantation, particularly hybrids between *P. deltoides* and *P. trichocarpa* [32,33]. Yet, there seems to be a trade-off between exceptional juvenile growth vigour and tolerance to environmental hazards [6,34,35]. Environmental hazards are most probable to occur throughout the lifetime of a poplar SRC, a period of >20 years. Hence, selection traits as coppice ability as well as tolerance to drought and diseases may be most important in breeding programmes focusing on suitable poplar SRC genotypes. Moreover, this study suggests waiting at least two rotations for poplar breeders to select the most suitable genotypes.

In contrast to monocultures, clonal mixtures tend to reduce yield losses caused by unpredictable environmental changes or hazards [36,37]. In the present trial, the clonal mixture appeared to be effective as a disease control strategy; the pure species partly compensated for the losses incurred by the rust infestation. Genetically diverse clones were planted in this (rather small) plantation, i.e. a wide range of pure clones and hybrids of European and North-American species. An intimate mixture of the 17 clones may have been more effective than the actual block design by facilitating a quick occupation of the spaces left by dead stools so that weeds cannot get the upper hand [38]. Although the large heterogeneity of the plantation due to the clonal mixture and block design did not affect harvesting and processing, it did affect plantation maintenance. Particularly weed control was hampered as the poorly yielding or high-mortality plots required more care than the low-mortality plots.

4.2. *Energy analysis*

The present SRC system yielded an ER_{farm} of 29.8, well within the range of 13–55 presented in a recent review on the energy ratios of poplar SRC [11]. Direct comparison of the present energy budget reported in this study with those from other studies remains complex due to differences in the type of SRC system investigated (low- versus high-input systems), the system boundaries, and the assumptions used. Consistent with previous studies, the use of herbicides as well as harvesting and chipping were the highest energy consumers among the agricultural operations [11]. Our study suggests that poplar SRC grown on degraded lands – in this case moderately polluted with heavy metals – may show very positive energy budgets. Apparently, the relatively low biomass yields throughout the four rotations were compensated for by the low-energy inputs of the system or, in other words, by the absence of irrigation, fertilization and fungicides. Since low inputs imply smaller environmental impacts and lower net carbon dioxide emissions, the studied poplar SRC may be characterized by low environmental impacts and a small contribution to greenhouse gas emissions [39]. However, this and other long-term SRC trials indicated that clonal failures due to diseases and frequent harvesting are likely [6,16,40,41] advising against the use of constantly high yields in the evaluation of the energy performance of poplar SRC.

Several biomass conversion technologies are readily available, each with their own advantages and disadvantages. In this study, we opted for a biomass gasification plant with an electrical efficiency of 37.2% [26]. Obviously, higher energy efficiencies would be obtained with co-generation of power and heat though this scenario requires a local demand for heat [27]. Like all types of woody biomass, SRC contain heavy metals to some degree, e.g. Pb, Cu and Zn. However, the heavy metal content of SRC from polluted sites may be higher than that of SRC from agricultural lands. Using contaminated enriched SRC for bioenergy purpose can reduce the conversion efficiency [42] or even corrode the boilers [43]. Such risks can be minimized by secondary emission reduction measures, e.g. using filters in boilers [44].

5. Conclusion

By growing poplar SRC on degraded lands and with a minimum of energy input (e.g. use of chemicals, irrigation and fertilization), environmental challenges and competition with food crops can be minimized [8]. From this study, we learnt that the SRC systems on degraded lands can payback the energy invested in their production. Carefully selected plant material and adjusted plantation maintenance may even further increase the energy ratio of poplar SRC on degraded lands. Particularly pure *P. nigra* and *P. trichocarpa* clones appeared to be most suitable for growth under suboptimal conditions, i.e. being planted on degraded land and coping with several harvest cycles and with diseases as leaf rust. The initially highly promising D × T and T × D hybrids hardly survived the fourth rotation. Therefore, more long-term research is needed to reveal significant shifts in clonal ranking over the entire lifetime of a poplar SRC and to identify most appropriate clones.

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REFERENCES

[1] Ceulemans R, Deraedt W. Production physiology and growth potential of poplars under short-rotation forestry culture. Forest Ecol Manag 1999;121:9.
[2] Kauter D, Lewandowski I, Claupein W. Quantity and quality of harvestable biomass from *Populus* short-rotation coppice for solid fuel use – a review of the physiological basis and management influences. Biomass Bioenerg 2003;24:411.
[3] Laureysens I, Bogaert J, Blust R, Ceulemans R. Biomass production of 17 poplar clones in a short-rotation coppice culture on a waste disposal site and its relation to soil characteristics. Forest Ecol Manag 2004;187:295.
[4] Dickmann DI. Silviculture and biology of short-rotation woody crops in temperate regions: then and now. Biomass Bioenerg 2006;30:696.
[5] Karp A, Shield I. Bioenergy from plants and the sustainable yield challenge. New Phytol 2008;179:15.
[6] Al Afas N, Marron N, Van Dongen S, Laureysens I, Ceulemans R. Dynamics of biomass production in a poplar coppice culture over three rotations (11 years). Forest Ecol Manag 2008;255:1883.
[7] Searchinger T, Heimlich R, Houghton RA, Dong FX, Elobeid A, Fabiosa J, et al. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 2008;319:1238.
[8] Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, et al. Beneficial biofuels – the food, energy, and environment trilemma. Science 2009;325:270.
[9] Gasol CM, Brun F, Mosso A, Rieradevall J, Gabarrell X. Economic assessment and comparison of acacia energy crop with annual traditional crops in Southern Europe. Energy Policy 2010;38:592.
[10] Whitaker J, Ludley KE, Rowe R, Taylor G, Howard DC. Sources of variability in greenhouse gas and energy balances for biofuel production: a systematic review. Glob Change Biol Bioenergy 2011;2:99.
[11] Djomo SN, El Kasmioui O, Ceulemans R. Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. Glob Change Biol Bioenergy 2011;3:181.
[12] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and the biofuel carbon debt. Science 2008;319:1235.
[13] Tilman D, Hill J, Lehman C. Carbon-negative biofuels from low-input high-diversity grassland biomass. Science 2006;314:1598.
[14] Bai ZG, Dent DL, Olsson L, Schaepman ME. Proxy global assessment of land degradation. Soil Use Manage 2008;24:223.
[15] Sims REH, Maiava TG, Bullock BT. Short-rotation coppice tree species selection for woody biomass production in New Zealand. Biomass Bioenerg 2001;20:329.
[16] Nassi o Di Nasso N, Guidi W, Ragaglini G, Tozzini C, Bonari E. Biomass production and energy balance of a 12-year-old short-rotation coppice poplar stand under different cutting cycles. Glob Change Biol Bioenergy 2010;2:89.
[17] Steenackers J, Steenackers M, Steenackers V, Stevens M. Poplar diseases: consequences on growth and wood quality. Biomass Bioenerg 1996;10:267.
[18] Laureysens I, Blust R, De Temmerman L, Lemmens C, Ceulemans R. Clonal variation in heavy metal accumulation and biomass production in a poplar coppice culture: I. Seasonal variation in leaf, wood and bark concentrations. Environ Pollut 2004;131:485.
[19] Pellis A, Laureysens I, Ceulemans R. Growth and production of a short-rotation coppice culture of poplar I. Clonal differences in leaf characteristics in relation to biomass production. Biomass Bioenerg 2004;27:9.
[20] Laureysens I, Pellis A, Willems J, Ceulemans R. Growth and production of a short-rotation coppice culture of poplar. III. Second-rotation results. Biomass Bioenerg 2005;29:10.
[21] Laureysens I, Deraedt W, Indeherberge T, Ceulemans R. 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 Bioenerg 2003;24:81.
[22] Pontailler JY, Ceulemans R, Guittet J, Mau F. Linear and non-linear functions of volume index to estimate woody biomass in high-density young poplar stands. Ann Forest Sci 1997;54:335.
[23] Dalgaard T, Halberg N, Porter JR. A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. Agric Ecosyst Environ 2001;87:51.
[24] Frischknecht R, Jungbluth N, Althaus HJ, Bauer C, Doka G, Dones R, et al. Overview and methodology. Ecoinvent report no. 1. Dübendorf, Switzerland: Swiss Centre for Life Cycle Inventory; 2007. p. 68.
[25] García Cidad V, Mathijs E, Nevens F, Reheul D. Energy crops in Flemish agricultural sector. Report no. 1. Gontrode, Belgium: Support Centre Sustainable Agriculture (Stedula); 2003. p. 94 (in Dutch).
[26] Mann MK, Spath PL. Life cycle assessment of a biomass gasification combined-cycle system. Golden, CO, USA: National Renewable Energy Laboratory; December 1997. p. 159.
[27] Dubuisson X, Sintzoff I. Energy and CO_2 balances in different power generation routes using wood fuel from short-rotation coppice. Biomass Bioenerg 1998;15:379.
[28] Sintzoff I, Martin J, Menu JF, Temmerman M, Thiry J, Tyteca D, et al. Woodsustain. Contributions of wood energy to sustainable development in Belgium. Groupe Energie Biomasse. http://www.term.ucl.ac.be/geb; 2001.
[29] Nellist ME. Storage and drying of arable coppice. Aspects Appl Biol 1997;49:349.
[30] Borjesson II P. Energy analysis of biomass production and transportation. Biomass Bioenerg 1996;11:305.
[31] Dillen SY, Rood SB, Ceulemans R, In. Growth and physiology. In: Jansson S, Bhalerao R, Groover A, editors. Genetics and genomics of *Populus*. New York, USA: Springer; 2010. p. 39.
[32] Hayes HK. Development of the heterosis concept. In: Gowen JW, editor. Heterosis. Ames, IA, USA: Iowa State College Press; 1952. p. 49.
[33] Stettler RF, Zsuffa L, Wu R. The role of hybridization in the genetic manipulation of *Populus*. In: Stettler RF, Bradshaw HD, Heilman PE, Hinckley TM, editors. Biology of *Populus* and its implications for management and conservation. Ottawa, ON, Canada: NRC Research Press, National Research Council of Canada; 1996.
[34] Wu R, Stettler RF. Quantitative genetics of growth and development in *Populus*. 2. The partitioning of

genotype × environment interaction in stem growth. Heredity 1997;78:124.
[35] Dillen SY, Storme V, Marron N, Bastien C, Neyrinck S, Steenackers M, et al. Genomic regions involved in productivity of two interspecific poplar families in Europe. 1. Stem height, circumference and volume. Tree Genet Genomes 2009;5:147.
[36] DeBell DS, Harrington CA. Deploying genotypes in short-rotation plantations – mixtures and pure cultures of clones and species. Forest Chron 1993;69:705.
[37] Begley D, McCracken AR, Dawson WM, Watson S. Interaction in short-rotation coppice willow, *Salix viminalis* genotype mixtures. Biomass Bioenerg 2009;33:163.
[38] McCracken AR, Dawson WM. Disease effects in mixed varietal plantations of willow. Aspects Appl Biol 2001;65:255.
[39] Njakou Djomo S, Blumberga D. Comparative life cycle assessment of three biohydrogen pathways. Bioresour Technol 2011;102:2684.
[40] Labrecque M, Teodorescu TI. Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern Quebec (Canada). Biomass Bioenerg 2005;29:1.
[41] Kopp RF, Abrahamson LP, White EH, Volk TA, Nowak CA, Fillhart RC. Willow biomass production during ten successive annual harvests. Biomass Bioenerg 2001;20:1.
[42] Witters N, Mendelsohn RO, Van Passel S, Van Slycken S, Weyens N, Schreurs E, et al. Phytoremediation, a sustainable remediation technology? II. Economic assessment of CO_2 abatement through the use of phytoremediation crops for renewable energy production. Biomass Bioenerg 2012;39:470.
[43] Yin C, Rosendahl LA, Kaer SK. Grate-firing of biomass for heat and power production. Progr Energy Combust 2008;34:725.
[44] Van Loo S, Koppejan J. Handbook of biomass combustion and co-firing. Twente, The Netherlands: Twente University Press; 2002.