Assessing the short rotation woody biomass production on marginal post-mining areas

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ABSTRACT: The Lusatian lignite-mining district (Eastern Germany) is characterized by a high share of marginal post-mining areas. At these sites, crop yield is generally low, and hence, conventional land use systems often fail in terms of reliable and efficient crop production. In this paper the attempt is made to evaluate the production of woody biomass for bioenergy in short rotation coppices (SRC) and alley cropping systems (ACS) with black locust (*Robinia pseudoacacia* L.) and lucerne (*Medicago sativa* L.) from the aspect of possible ecological and economic benefits compared to the conventional agricultural recultivation practice. The results show that, due to both high establishment and harvesting costs and comparatively low prices of energy wood, land use systems such as SRC or ACS are currently hardly profitable compared to conventional agriculture. However, the cultivation of black locust resulted in a higher humus accumulation and in a lower harvest-related nutrient export than the cultivation of lucerne as a typical recultivation crop in this region. Therefore, it can be concluded that for an improvement of soil fertility woody biomass production is more beneficial than the conventional agricultural recultivation practice.

Keywords: agroforestry; black locust; carbon accumulation; short rotation coppice; woody biomass

Lignite mining and the reclamation of post-mining areas have a long tradition in the Lusatian region in Eastern Germany. Nowadays, the active opencast mines extend over a total area of more than 34,000 ha (Statistik der Kohlenwirtschaft 2007). The opencast mines move continually through the landscape leaving exploited dump areas behind. Therefore, in this low-precipitation region there is a high share of young recultivation areas that are characterized by an extensive, low-structured and partly vegetated landscape, and hence, by frequently strong winds and distinct dry periods (compared to average weather conditions in Germany). Furthermore, due to the unfavourable soil physical and soil chemical properties of the overburden materials, most of the mine soils are of low fertility (low water retention capacity, low humus and nutrient contents) – even after costly amelioration efforts (Häge 1996). Usually, these areas are recultivated by turning them into forests or agricultural lands. However, due to these unfavourable growth conditions crop yield and yield stability are comparably low, and hence, conventional land use systems often fail in terms of the reliable and efficient crop production. The establishment of an economically reasonable land use system on such marginal sites is a challenge for farmers and foresters.

In this context, the production of woody biomass for the generation of bioenergy may be a promising alternative to improve soil fertility (Quinkenstein et al. 2009) and to enhance the economic value (Grünewald et al. 2009) of these post-mining areas. In Germany, currently, biomass is one of the most important renewable energy sources and the governmental strategies for a further extension of renewable energies most likely will lead to a further increase in biomass demand and prices.

To produce sufficient amounts of woody biomass in an economic way, fast-growing trees are usually planted in short rotation coppices (SRC). These

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are wood plantations where fast-growing trees are planted at high densities and harvested in short rotation periods of three to six years. Because the trees are able to resprout after cutting, such plantations can be utilized for more than 20 years. Alley cropping systems (ACS) are an alternative when crops are cultivated between hedgerows of trees or shrubs managed as short rotation coppices. ACS allows the combination of crop and woody biomass production in the same field and can have positive effects on biodiversity and microclimate (Quinkenstein et al. 2009). The latter even can result in higher crop yields compared with conventional agriculture (Pretzschel et al. 1991).

However, the typical fast-growing trees used in short rotation coppices like poplar (*Populus* sp.) or willow (*Salix* sp.) are not suitable because of comparably low biomass productivity in this dry region (Grünewald et al. 2007). By contrast, the leguminous tree species black locust (*Robinia pseudoacacia* L.) is known for its tolerance to water stress and its ability to fix nitrogen. For that reason noteworthy yields are obtainable with this tree species on marginal sites as well (Böhm et al. 2009).

In this context, the present paper evaluates the production of short rotation woody biomass for bioenergy generation from the aspect of possible ecological and economic benefits in a post-mining area of the Lower Lusatian region. The study presented here aims to address the following specific questions: (I) will ACS with short rotation coppice hedgerows of black locust result in a higher crop yield compared to conventional agriculture?; (II) is it possible to improve soil fertility by using black locust in SRC or ACS?; and (III) which of both land use systems SRC and ACS has a higher economic output compared to the conventional agricultural recultivation practice?

MATERIAL AND METHODS

Site description

The study sites are situated in the recultivation area of the lignite opencast mining "Welzow-Süd" which is located in the State of Brandenburg in Germany (Fig. 1). The study area is characterized by an average annual precipitation amount of 560 mm and mean annual temperature of 9.3°C (1951 to 2003). The substrate (mainly sands and loamy sands) at the study site was dumped and ameliorated in 2004. Soil formation is in an initial stage and the soil structure is still instable. Furthermore, there is no groundwater influence due to the lowering of the groundwater level because of the ongoing mining activities. Substrates are characterized by a very low content of total organic carbon (< 0.3% at 0–30 cm soil depth), low sorption capacity and deficient nutrient supply. More details about soil characteristics were given by Grünewald et al. (2009).

Data collection was carried out in an ACS established in 2007 and in an adjacent SRC of black locust established in 2005. The ACS comprises an area of 7 ha and is composed of 24 m wide alleys (corresponds to 68.6% of the total area), which are cultivated with lucerne (*Medicago sativa* L.), and 11 m wide tree hedgerows (31.4%). Each hedgerow consists of four double rows of black locust with a plant density of 9,200 trees·ha^{-1} (distance between double rows = 1.80 m; distance between two single rows within a double row = 0.75 m; distance between two trees within the row = 0.85 m). The same planting layout and plant density are present in the SRC that has a size of 12 ha. The hedgerows are aligned in north-south orientation, across to the prevailing wind direction (west to east).

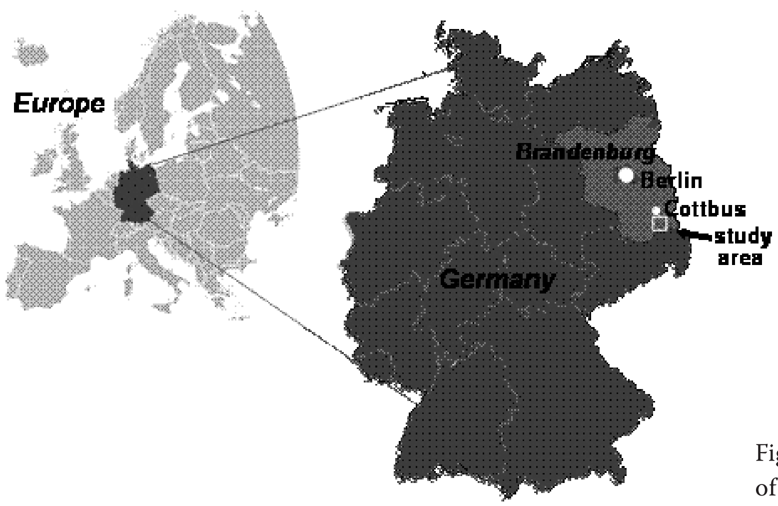

Fig. 1. Location of the study area in the State of Brandenburg (Germany)

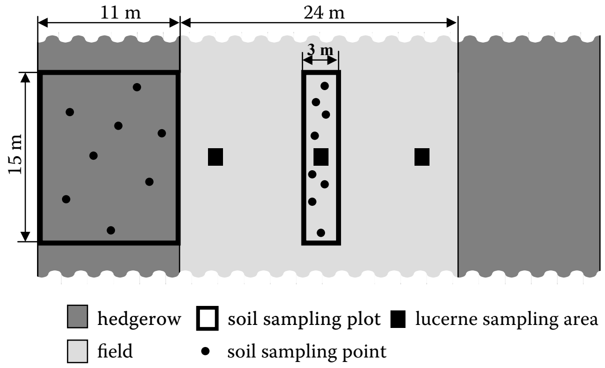

Fig. 2. Sampling scheme used at the study site of alley cropping (samples were taken at eight sampling areas distributed at the study site of alley cropping)

Soil and plant samplings

Soil samples were taken in spring 2008 and 2009 on 3 m × 15 m plots located in the centre of the alleys as well as on 11 m × 15 m plots within the hedgerows (each $n = 8$). On each plot, at least eight soil cores were taken from a depth of 0–30 cm using a manual soil sampler (inner diameter = 2 cm) and pooled to one composite soil sample (Fig. 2). The aboveground biomass of lucerne was sampled completely on three times eight plots of 1 m × 1 m in summer 2008 and 2009. These plots were arranged at different distances from the hedgerows (3 m away from the hedgerow on the leeward side, at the centre of the alley and 3 m away from the opposite hedgerow on the windward side; Fig. 2). Woody biomass was sampled at SRC in winter 2009 after four years of growth. For this purpose, eight randomly distributed representative trees were cut and shredded completely.

Soil, plant and data analyses

For the determination of hot water extractable organic carbon (HWC) and hot water extractable nitrogen (HWN) 10 g of air-dried fine soil (< 2 mm) was boiled in 50 ml of deionized water for 60 min. After the extracts had cooled down at room temperature, 2 ml of a 2N Mg_2SO_4 solution were added and the extracts were centrifuged at 4,000 rev·min^{-1} for 10 min. The concentrations of HWC and HWN were measured in the decanted extracts by a CN analyzer (Shimadzu). Macronutrients were analyzed in dried (60°C) and ground aliquots of shredded herbaceous and woody biomass. Nitrogen (N) was determined by dry combustion using a CNS analyzer (Foss-Heraeus). The determination of the elements phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca) was carried out by HNO_3 digestion under pressure, according to Schramel et al. (1993). All four elements were analyzed with an ICP-OES spectrometer (Thermo Scientific). Aboveground biomass was estimated by drying the shredded plant material at 103°C till weight constancy. Statistical analyses were performed using the software STATISTICA® (StatSoft, Vers. 7). The differences between means were tested for significance by the Mann-Whitney *U* test (independent samples) or by the Wilcoxon test (related samples).

Economic assessment

The profitability of the production of woody biomass in SRC and ACS with black locust was compared to the conventional agricultural recultivation practice (conventional agriculture) using the discounted cash flow method (Grünewald et al. 2009). Costs and revenues were discounted over a period of 24 years as an approximation of the productive lifetime of black locust SRC. The annual values of these three land use systems (SRC, ACS and agriculture) were calculated as annuities in Euro (€) per hectare and per year based on the discounted costs and revenues (Bemmann et al. 2007). For the annual crops, average annual costs and revenues were calculated. By doing so, it was possible to compare the economic return of annual crops with that of SRC and ACS. According to Hartmann (2002) a discount rate of 5% was applied.

The economic assessment is based on the following assumptions for SRC and ACS: the rotation period of black locust is 4 years; short rotation areas were cleared after 24 years; NPK fertilizer was added at the beginning, P and K were added after each harvest; short rotation areas were limed after 12 years. For conventional agriculture and ACS the same crop rotation was assumed that starts with twice 3 years lucerne, then 1 year winter rye (*Secale cereale* L.), followed by twice 3 years lucerne and 1 year winter rye, then 1 year winter rape (*Brassica napus* L.), 1 year winter triticale (*Triticosecale*), 1 year winter rye, 3 years lucerne, 1 year winter rye, 1 year winter rape and 1 year winter triticale. This crop rotation is adapted for the established recultivation practice and contains an above-average share of lucerne in the first 10–15 years. During the first 3 years, lucerne was only mulched and remained on site to improve the soil quality. Crop areas were limed after 8 and 16 years. Crop residues remained in the field.

An overview of costs and revenues is given in Table 1. For ACS, 10% higher tillage costs were assumed because of the field fragmentation by hedgerows. Otherwise, based on our own data, higher yields by 6% in total were supposed for crops growing in ACS. In this approach, however, neither subsidies nor costs of rent, transport or drying were considered.

RESULTS AND DISCUSSION

Biomass yield

After the first rotation period (4 years of growth), the average woody biomass yield of the black locust SRC investigated in this study amounted to 3 t·ha^{-1}·year^{-1} (Böhm et al. 2009). According to investigations by Grünewald et al. (2007, 2009) in post-mining areas a significant increase of biomass productivity can be expected for the following rotations. These authors reported a comparable yield after the rotation time of 3 years, however, after the third rotation period they determined an annual yield of more than 7 t·ha^{-1}. Hence, related to 24 years (6 rotations) an average woody biomass yield of 6 t·ha^{-1}·year^{-1} can be expected for black locust at post-mining sites described. For the investigated ACS, which has an area share of black locust only 31.2%, a long-term average yield of nearly 2 t·ha^{-1} ACS·year^{-1} can be assumed. These estimated or expected woody biomass yields are relatively low compared to other sites. For example Vetter et al. (2002) reported yields of more than 14 t·ha^{-1}·year^{-1} for a SRC of black locust with the rotation time of 5 years. Anyway, yields of black locust obtainable at the study site are high compared with those of poplars and willows. Due to unfavourable growth conditions, especially due to distinct periods of drought stress in spring and early sum-

Table 1. Production costs and revenues used to assess the economic viability of the three land use systems: short rotation coppice, alley cropping and conventional agriculture

Costs	Value	Reference
Black locust (€·seedling^{-1})	0.18	local tree nursery
Planting (€·ha^{-1})	311.50	Hofmann (2009)
Seed (lucerne/rye/triticale/rape) (€·ha^{-1})	100.00/38.42/82.32/42.56	Hanff et al. (2008)
Seed (lucerne/cereals and rape) (€·ha^{-1})	51.44/33.29	Hanff et al. (2008)
Plough/harrow/roll/surface cultivator (€·ha^{-1})	68.49/27.08/24.34/17.93	Hanff et al. (2008)
Fertilizer/application of pesticides (€·ha^{-1})	8.00/8.00	Hanff et al. (2008)
Fertilizer NPK (lucerne/rye/triticale/rape) (€·ha^{-1})	96.24/105.19/219.40/167.26	Hanff et al. (2008)
Fertilizer (N)PK (1st rotation/2nd–6th rotation) (€·ha^{-1})	38.83/58.44	own data
Lime (€·ha^{-1})	16.00	Hanff et al. (2008)
Pesticides (rye/triticale/rape) (€·ha^{-1})	20.00/58.00/66.00	Hanff et al. (2008)
Harvest of black locust (€·t dry matter^{-1})	15.00	Hofmann (2009)
Harvest of lucerne (€·ha^{-1})	34.04	Hanff et al. (2008)
Harvest of cereals and rape (€·ha^{-1})	62.71	Hanff et al. (2008)
Land clearing (€·ha^{-1})	1,000.00	Hofmann (2009)
Revenues		
Yield of black locust (1st rotation/2nd–6th rotation) (t dry matter·ha^{-1})	3/6	Böhm et al. (2009), Grünewald et al. (2009)
Yield of lucerne (2 harvests·year^{-1}) (t dry matter·ha^{-1})	6.6	own data
Yields of rye/triticale/rape (t corns·ha^{-1})	3.5/3.6/2.2	Hanff et al. (2008)
Price of black locust wood chips (€·t dry matter^{-1})	75.00/110.00	Hanff et al. (2008), C.A.R.M.E.N. (2010)
Price of lucerne/rye/triticale rape (€·t dry matter/corns^{-1})	92.00/180.00/175.00/360.00	LA Sömmerda (2006), Hanff et al. (2008)

mer, the biomass yields of these tree species range only between < 1 t·ha^{-1}·year^{-1} and 4 t·ha^{-1}·year^{-1} at these post-mining sites (Grünewald et al. 2009).

Additionally, crop yields are low at these marginal sites. Fig. 2 represents dry matter (DM) yields of lucerne harvested at different distances from the hedgerows of the ACS. The biomass yield of lucerne varied between 1.8 t DM·ha^{-1} and 2.5 t DM·ha^{-1} at each harvest (two harvests per year can be expected). These values correspond to yields of lucerne at comparable marginal sites published by Grünewald et al. (2007). On average, two harvests a year are possible at the study site. Hence, an annually yield of up to 5 t DM·ha^{-1} can be expected in the first years. However, a yield increase with time is likely due to improved soil fertility. This could also be noted in adjacent fields. According to these unpublished observations an annual lucerne yield of 6.6 t DM·ha^{-1} was assumed for the economic assessment presented in this study. Generally, crop yields varied depending on the location within the alley. Higher yields were determined on the leeward side as well as on the windward side than at the centre of the field (Fig. 3). These differences in biomass yield are not significant; however, a positive effect of hedgerows on the crop yield is visible. According to Quinkenstein et al. (2009) it is most likely that hedgerows improved the microclimate for crops and resulted in higher water availability to the plants, especially at the peripheries of alleys. Apparently, the positive effect of improved microclimate, especially reduced evapotranspiration due to the decreased wind velocity (Brandle et al. 2004), prevails over a possible competition effect between the trees and the crop. An increase of the negative competition effect with time, such as reported by Jose et al. (2000), cannot be excluded because of the expansion of the tree roots. Currently, however, the crop yield in ACS is higher than on conventionally managed agricultural land.

Hot water extractable carbon and nitrogen

HWC and HWN represent easily decomposable parts within soil organic carbon (TOC) and soil nitrogen (TN) and hence can be regarded as short-term to medium-term available fractions of TOC and TN (Körschens et al. 1990; Böhm et al. 2010). Generally, an increase of these C and N fractions indicates a humus accumulation process in soil.

Fig. 4 shows HWC and HWN contents one and two years after the establishment of the ACS. During these years, the HWN content increased significantly ($P \leq 0.05$) under hedgerow as well as under field. By contrast, the HWC content increased significantly ($P \leq 0.05$) only under black locust. Within the years the differences in HWC and HWN contents in soil were not significant between hedgerows and field alleys. However, the increase of HWC as well as of HWN was more distinct under trees than in the soil of alleys although lucerne remained on site during the first three years (Fig. 4). This indicates that the cultivation of black locust leads to a faster and potentially higher humus accumulation in soil compared to lucerne as a typical recultivation crop. This corresponds to results published by Nii-Annang et al. (2009), who also found a higher C accumulation rate under short rotation trees than under crops. Higher additions of aboveground and belowground organic matter may be an important reason for the higher build-up of soil organic carbon (Grünewald et al. 2007). Furthermore, lucerne litter has a lower potential to generate recalcitrant humic material and hence a higher turnover rate in soil than that of black locust (Bross et al. 1995). The higher lignin content in the litter of black locust could also be an explanation for different HWN increases under these both N fixing plants. Litter with a comparatively high content of lignin such as black locust may contribute to

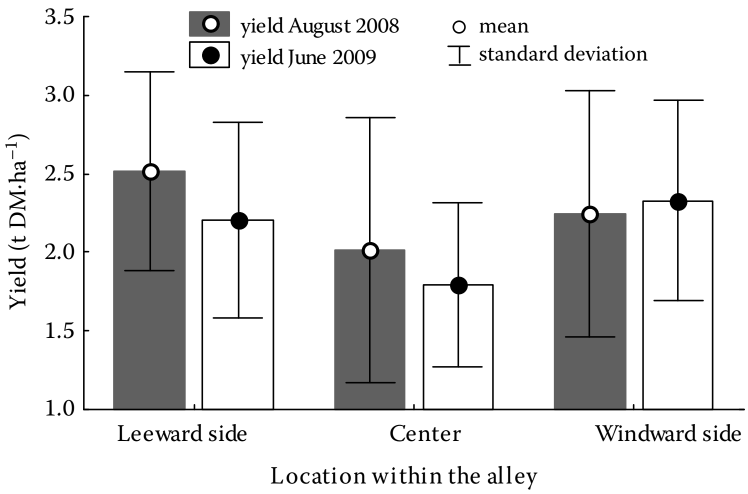

Fig. 3. Dry biomass yields of lucerne (*Medicago sativa* L.) at the study site of alley cropping on the leeward and windward side of the black locust (*Robinia pseudoacacia* L.) hedgerows (each at 3 m distance from the hedgerows) and at the centre of the 24 m wide alleys (n = 8)

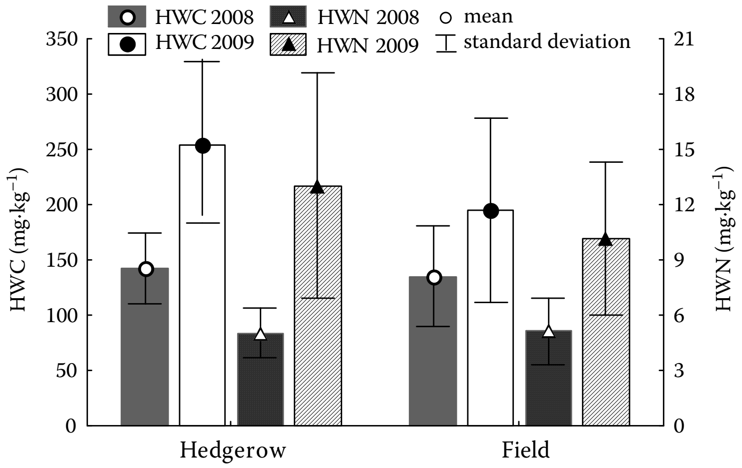

Fig. 4. Contents of hot water extractable organic carbon (HWC) and hot water extractable nitrogen (HWN) in the soil of the study site of alley cropping at a depth of 0–30 cm, differentiated in hedgerows and in the field (n = 8)

a higher build-up of soil organic N and thus provide a low but continual supply of N (Bross et al. 1995).

Nutrient export

Generally, the nutrient export that occurs at each harvest must be assessed separately for each land use system. Annual nutrient exports are common for the conventional agriculture. By contrast, however, harvest-related nutrient losses occur in SRC only once per rotation period. Moreover, the leaves of short rotation trees remain on site and the nutrient content of woody biomass is lower than that of harvested crop (LVL 2002; Quinkenstein et al. 2009). The results presented in this study confirm the lower nutrient export in SRC compared to conventional crops. Fig. 5 represents the nutrient export of black locust and lucerne related to the average biomass yield of one year (6.0 t·ha^{-1}·year^{-1} for black locust; 6.6 t·ha^{-1}·year^{-1} for lucerne). All analyzed nutrients were significantly lower ($P \leq 0.05$) in woody biomass of black locust than in lucerne. The lowest difference between lucerne and black locust was found for Ca. The export of the other elements was more than twice higher (for K even more than five times higher) for lucerne than for black locust (Fig. 5). Hence, conventional agriculture leads to a higher nutrient export than SRC. ACS takes up an intermediate position depending on the share of hedgerows. The higher the export of nutrients, the more fertilizers have to be applied on the site to maintain soil productivity. Furthermore, the need of liming increases due to the enhanced soil acidification that is related to the higher loss of cations. Therefore, SRC, and to a lesser extent also ACS, result in lower running costs than conventional agriculture. This effect increases with increasing rotation periods, because the content of nutrients bound in one weight unit of woody biomass decreases relatively with the increasing wood to bark ratio and thus with the increasing rotation time.

Economic assessment

The economic value of SRC and ACS generally increases with each rotation period due to the high investment costs of tree seedlings and tree

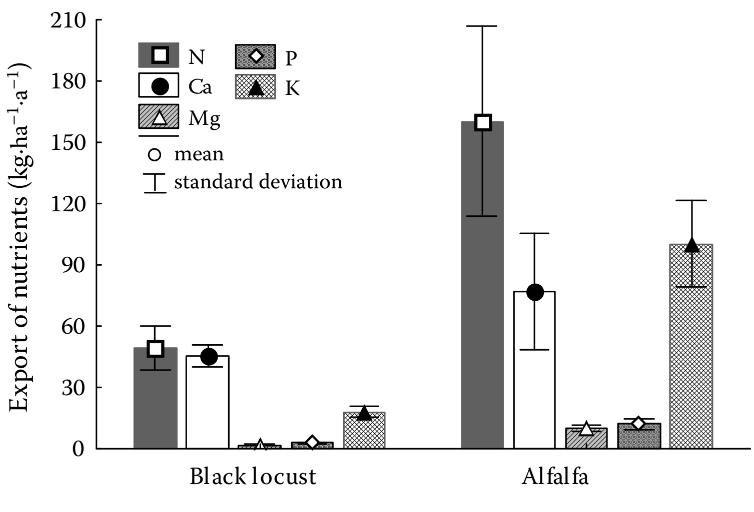

Fig. 5. Contents of nitrogen (N), calcium (Ca), magnesium (Mg), phosphorus (P) and potassium (K) in herbaceous biomass of lucerne (alley cropping system) and woody biomass of black locust (short rotation coppice) related to 1 ha monoculture (n = 8)

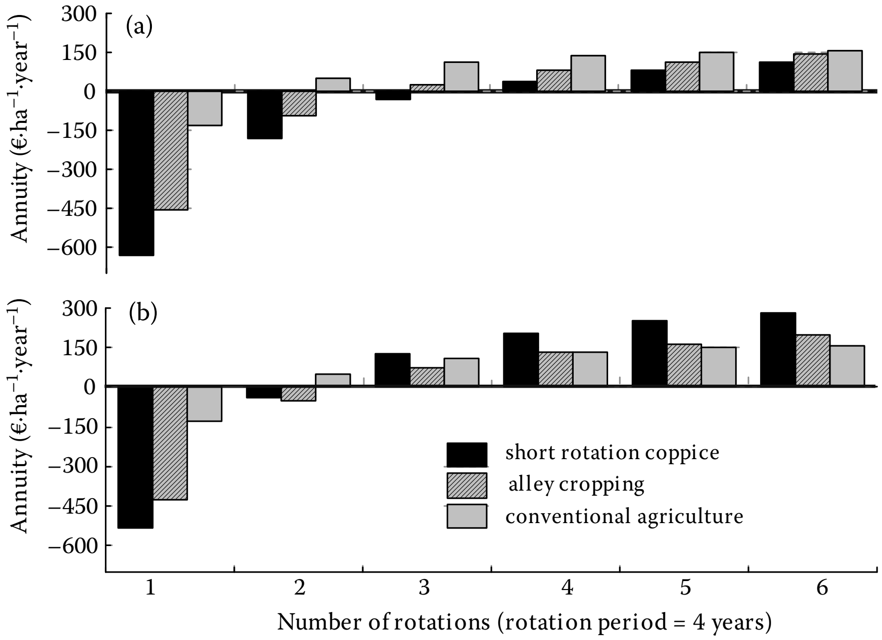

Fig. 6. Annuities of short rotation coppice, alley cropping and conventional agriculture calculated for the post-mining area of the opencast mining "Welzow-Süd"; (a) price of wood chips = 75 €·t DM^{-1} [average of the Brandenburg State; Hanff et al. (2008)] and (b) price of wood chips = 110 €·t DM^{-1} [average of Germany; C.A.R.M.E.N. (2010)]; annuities for each rotation period were calculated for the case of a complete failure of black locust, i.e. clearing costs were considered at the end of each rotation period

planting. Additionally, high one-time costs of land clearing are incurred at the end of the production period. Therefore, the objective should be to use a SRC for 20 years at least. Comparatively high harvesting expenses additionally raise the production costs. This factor plays a decisive role especially in regions with a small share of SRC or ACS because of the lacking and thus expensive harvest technology (Pallast et al. 2005). Fig. 6a shows the profitability of SRC and ACS in the study area compared to conventional agriculture over a time period of 24 years using the regional average price of wood chips. According to these calculations at least 3 rotation periods are required for the positive annuity of ACS. Even 4 rotation periods are needed for the profitable cultivation of SRC. However, due to the comparatively low investment costs the conventional agriculture creates an income already in the fourth year. One main determinant for the small economic value of SRC and ACS is the low regional price of wood chips probably due to a high wood supply in the local market caused by the mining activities. Across Germany, the price of wood chips is on average about 45% higher (Hanff et al. 2008; C.A.R.M.E.N. 2010). If this higher price is used for the calculations, then ACS and especially SRC are more profitable than conventional agriculture (Fig. 6b). In this case the annuity of SRC is higher than that of conventional agriculture already after 3 rotation periods and nearly twice as high after 24 years (Fig. 6b). According to Grünewald et al. (2009) these findings suggest that a positive economic impact may be achieved from the cultivation of SRC or ACS if a strategy of cultivation and marketing is found that includes the reduction of investment and harvesting costs and especially the payment of appropriate prices. This seems to be somewhat a question of time because the expansion of bioenergy is planned and politically intended in Germany.

CONCLUSION

The production of woody biomass at agricultural sites is not yet widespread in Germany. Due to the high initial investment and high harvesting costs as well as comparatively low prices of energy wood, the land use systems such as SRC or ACS are currently hardly profitable compared to conventional agriculture at marginal post-mining sites in Lower Lusatia. However, a moderate increase of the regional wood price would turn the combination of crop and woody biomass production in ACS into an economically advantageous land use system in the study area despite the unfavourable growth conditions. This is supported by the fact that the hedgerows result in higher crop yields compared with conventional agriculture. Regardless of the economic assessment of the production of short rotation biomass the cultivation of fast-growing trees such as black locust results in higher C and N accumulation rates in soil. Furthermore, the low content of nutrients in woody biomass is responsible for a low nutrient export in the course of harvest compared to the arable crop. Hence, more nutrients remain *in situ* in the soil, which has resultant beneficial effects on the soil formation processes of the overburden substrate. For the marginal post-mining areas of Lower Lusatia it can be concluded that black locust cultivated in short rotation coppices contributes more to an improvement of soil fertility than the conventional crop rotation.

Generally, the obvious benefits of woody biomass production at marginal post-mining sites, such as faster and higher humus accumulation, lower applications of fertilizers and pesticides, and also a decrease in greenhouse gas emissions or increased security of energy supply should be economically valued. Otherwise, the production of woody biomass need not currently be competitive with conventional agriculture within the study area.

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