

Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec

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Abstract

The conversion of relatively undisturbed ecosystems such as forests and grasslands to intensively managed agroecosystems has had major impacts on global carbon (C) cycling largely as a result of land clearing, cultivation, and replacement of perennial vegetation by annual crops. Numerous studies have demonstrated the ability of fast-growing perennial plant species dedicated to bioenergy production to sequester substantial amounts of C. Thus, the conversion of conventionally managed agricultural land to perennial bioenergy crops can be expected to increase C stored in above- and belowground biomass and in soil organic matter because of their perennial nature and greater root biomass. In this study, C storage was compared among five ecosystems in southwestern Quebec including two perennial crops, switchgrass (*Panicum virgatum* L.), and willow (*Salix alba* × *glauca* L.), and an annual corn (*Zea mays* L.) crop at two sites of differing soil fertility, a 20-year-old abandoned field, and a mature hardwood forest. After 4 years of production, corn had significantly higher levels of aboveground C than willow at the less fertile site, but no significant differences were detected at the more fertile site. Both perennial systems had significantly higher root C than the corn system but switchgrass had significantly higher root C levels below 30 cm compared with willow and corn. Soil organic C under willow at the more fertile site was higher than under the other managed or unmanaged systems, including willow at the less fertile site. The results of this study suggest that perennial energy crops grown on relatively fertile soils, have the potential to increase substantially soil C levels compared with conventional agricultural systems or unmanaged systems. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Global concern over increasing carbon dioxide (CO₂) concentrations in the atmosphere possibly modifying climate patterns, has prompted Canada to agree to reduce its greenhouse gas emissions to

at least 5% less than 1990 levels by 2008–2012 (UNFCCC, 1997). This has encouraged research into the specific role that terrestrial ecosystems may play in global carbon (C) cycling. Hence, strategies to reduce CO₂ emissions into the atmosphere, such as the replacement of fossil fuels with renewable biomass energy sources and the storing of additional C in terrestrial C sinks need to be more fully assessed.

Perennial crops such as switchgrass (*Panicum virgatum* L.) and short-rotation willow (*Salix* sp.) can

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be used for renewable energy production. Switchgrass is a warm-season (C_4), perennial grass, native to eastern Canada, the southern Canadian Prairies (Samson and Omelian, 1994), and much of US. The relatively deep root system and high aboveground production of this grass make it a potentially valuable bioenergy crop. Not surprisingly, switchgrass has already been identified as an ideal herbaceous energy crop species in US (McLaughlin et al., 1996).

Willows are grown under short harvesting cycles primarily as agricultural crops in energy plantations because they can achieve high biomass yields through short rotations of 4 years or less. Studies have demonstrated that willow grown as energy plantations can be more efficient at sequestering C on an annual basis than trees grown in native temperate forests, and that production per hectare (ha) can exceed that of traditional crops (Ranney et al., 1991).

Both bioenergy systems have the potential to increase organic C storage in soil and vegetation compared with present agricultural cropping systems by increasing above- and belowground biomass as well as soil organic matter levels. Through the process of photosynthesis, plants transform CO_2 , water, and solar energy into biomass and oxygen. When this biomass or biofuel is burned, the CO_2 released into the atmosphere is CO_2 recently trapped from the atmosphere. The only net CO_2 emissions come from the use of fossil fuels in the production and processing of the biomass because the C in the aboveground biomass is recycled.

The objective of this research was to compare C storage between two perennial bioenergy systems, switchgrass (*P. virgatum* L. var. 'Cave-In-Rock') and short-rotation willow (*Salix alba* × *glauca* L.) in their fourth year of production with an annual corn (*Zea mays* L.) crop, each at two adjacent sites with relatively high and low levels of soil fertility, in southwestern Quebec. Soil C and above- and belowground plant C were determined and compared between these systems. The data obtained were further compared with soil C data from a mature, steady-state forest and a 20-year-old abandoned field. The conventional corn cropping system, mature forest, and abandoned field were used as benchmarks against which potential losses or gains of soil organic C (SOC) from the perennial cultures could be compared.

2. Materials and methods

2.1. Site location, description, and history

The study area is located in the Emile A. Lods Agronomy Research Centre, and adjacent areas, on the Macdonald campus of McGill University on the West Island of Montreal, in southwestern Quebec, Canada ($42^{\circ}25'N$ latitude, $75^{\circ}56'W$ longitude). The mean annual air temperature and total precipitation at the sites were $6.5^{\circ}C$ and 1062 mm, respectively, in the year of sampling (1996). The growing season was characterized by a wet April and May, 140 and 35% above the 30-year normal, dry June and August, 20 and 77% below normal.

The study included a randomized complete block design comparison of switchgrass (S), willow (W), and corn (C), with plots at two sites, the Seedfarm (SF) and the Ecomuseum (ECO). In addition, there were four forested sampling locations in the nearby Morgan Arboretum (MA) and four locations in abandoned fields (AF) between the ECO and MA sites. The SF site was situated in an open field having a south-facing slope. The SF soil tended to be rockier and shallower than the soil of the ECO site which was located on relatively flat land protected by windbreaks to the east and west, and was considered to be a higher fertility site on the basis of previously observed productivity.

Before 1993, the ECO site was under continuous corn and received annual livestock manure applications of 20 t/ha, whereas SF was under a corn–alfalfa rotation and received no manure amendments. In 1993, 12 plots were established at each of the SF and ECO sites in a randomized complete block design with four blocks, each having one plot of switchgrass, willow, and fallow. The plots were large, ranging from 0.125 to 0.3 ha, to allow operational harvesting.

Fallow plots at ECO were sown to a cover crop (*Raphanus sativus* L.) and those at SF were colonized by pioneer weed species and later sprayed with a non-selective herbicide. These fallow plots were planted to willow in 1994 but growth was poor because of insect infestation in summer 1995. The willows were mowed, the regrowth sprayed with a non-selective herbicide, and the soil was ploughed that autumn. Corn (hybrid 'Pioneer 3921') was sown in these plots in May 1996. Row spacing and plant

population was 76 cm and 80,000 plants per hectare, respectively. Corn plots at SF were fertilized with 205, 104, and 62 kg/ha of N, P, and K, respectively, compared with 161, 104 and 62 kg/ha of N, P, and K at ECO. A combination of mechanical and chemical weed control was carried out at both sites.

Switchgrass plots at both sites were mechanically sown with a Brillion grass seeder at a rate of 6 kg/ha in May 1993, and fertilized with 45 kg/ha N in June 1996. Mechanical and chemical weed control was carried out in 1993 only. Plots were mechanically harvested at 10 cm above the ground each spring.

Willow plots were established using stem cuttings in May 1993 planted at an initial row spacing of 0.92 m and a plant population of 11,000 trees per hectare. The survival rate was approximately 90%. Willows were cut to 10 cm above the ground using thinning saws in January 1996 and the resulting biomass removed from the sites. In June 1996, the plantations were fertilized with 77 and 84 kg/ha of N and K, respectively. Chemical weed control was carried out at the SF site because of significant grass weed establishment.

The mature hardwood forest consisted of beech (*Fagus grandifolia* Ehrh.) and sugar maple (*Acer saccharum* Marshall), 100–130 years old, and had a long history of management as a woodlot using selection harvesting. The 20-year-old AF were located between the MA and ECO sites. The fields had been managed as pastures until the late 1970s and then abandoned. Two AF sampling points were dominated by *Bromus tectorum* L., comprising roughly 90% of the plant cover whereas the other two were dominated (99%) by *Festuca* sp. Four, arbitrarily selected soil profiles were sampled in each of the unmanaged ecosystem types.

The soil of the study area is a complex of several soil series and more than one soil series was often found within a single plot at the SF and ECO sites. To eliminate possible effects from differences between series, subplots (3.8 m × 14 m) were established on the same soil series in each of the 24 plots. The soil series was a Chicot fine sandy loam, characterized as having a moderate moisture-holding capacity with a pH ranging from 5.8 to 6.4 (Lajoie, 1960). All forest and abandoned field profiles sampled were also on the Chicot soil series.

2.2. Sampling of above and below ground plant components and soil

Above- and below-ground biomass, and soil samples were collected in early October with sampling methodology differing among the crop types as required by differences in physical characteristics of the crops. For corn, six sampling points were randomly chosen in each subplot and at each point, six consecutive corn plants were cut at ground level. The length of each row of six plants and the width between plant rows was measured so that the dry weight per hectare could be calculated. Cobs were counted and plants and cobs were weighed separately. A subsample of each was taken to determine dry weight. Two root crowns were collected at each sampling point, and the area occupied by these crowns was measured. Crowns were washed, weighed, placed in paper bags and transported to the laboratory for drying. Soil samples were excavated from each sampling point using cylindrical metal soil cores 15 cm long × 6 cm in diameter at a distance of 0.19 m from the original plant locations towards an adjacent row. Soil and roots within the soil cores were obtained from four depths (0–15, 15–30, 30–45, and 45–60 cm). Soil samples were placed in paper bags, transported to the laboratory, where fine roots and rocks were hand sorted and weighed. Total root weight included fine roots and root crowns.

Switchgrass samples were collected from four randomly located sampling points within each sub-plot. At each point, all switchgrass plants within a 1 m² quadrat were cut at soil level using a sickle, and weighed to determine fresh weight. This large sample was mixed, and a 200 g sub-sample was collected by hand and dried for chemical analysis, and to determine dry weight on a per hectare basis. Within each 1 m² quadrat, litter was removed from a 0.25 m² sub-quadrat, dried and weighed. At the Centre of each 0.25 m² sub-quadrat, soil and fine root samples were collected using the procedure described for corn. Switchgrass does not have root crowns, and therefore, total root weight equaled fine root weight.

Sampling for willow was based on six randomly selected trees within each sub-plot. All aboveground litter and weed tissue were cut at the soil surface within a 0.85 m² quadrat placed around each willow tree. The trees were uprooted and care was taken to excavate an equivalent radius around each tree so

that all roots severed would be of approximately the same length. A hand-saw was used to cut the trees at their base, and the length and width of the area occupied by each root crown recorded. Root crowns were treated as described for corn. Average root crown dry weight was multiplied by the number of trees in the subplot and root crown weight per hectare calculated. Aboveground components of each sampled tree were weighed in the field after cutting. From the 10–20 shoots cut from each willow tree, one shoot of average size served as a sub-sample. All leaves from the sub-sample were removed manually. Leaves and shoots were placed in separate paper bags, weighed, transported to the laboratory, and dried to determine dry weight for each component. Shoot, leaf and total tree dry weight were then calculated on an area basis. Soil and fine root samples were collected 0.23 m from the base of trees using the procedure described for corn.

Soil of the mature hardwood forest and abandoned fields was sampled in mid-September 1997, following the same procedure as described for corn.

All aboveground and belowground components and soil samples were dried at 65°C to constant weight. Plant material was ground using a Wiley mill. Soil was ground in a mechanized mortar and pestle to pass a 2 mm sieve, and all samples were ground manually with a mortar and pestle to pass a 100 mesh sieve. Samples were analyzed for organic carbon (OC) content using a modified Mebius procedure, involving digestion with an acidified dichromate solution (Yeomans and Bremner, 1988).

2.3. Calculations and statistical analyses

In order to compare C storage under different management systems, which may have altered soil bulk density as well as C content, total soil C mass in the profile was expressed on the basis of a total soil mass which was equivalent across the different management systems (Ellert and Bettany, 1995). The mass of C in individual layers was calculated from C concentration, bulk density and layer thickness (15 cm). The value selected for the equivalent soil mass was the average soil mass across all systems from 0–60 cm, which was 7090 t/ha. In order to convert the soil mass in an individual profile to the standard profile mass, the difference between the profile mass and 7090 t/ha

was calculated. This difference was added to or subtracted from the profile mass and the C concentration of the deepest layer (i.e. 45–60 cm) was used to calculate the soil C equivalent to be added/subtracted for this mass adjustment.

Initially the corn, switchgrass, and willow data were analyzed independent of the data from the unmanaged systems as a randomized complete block design with the three crops as fixed treatments, four random blocks, and two sites as main factors. Root data were natural log transformed to ensure homogeneity of variance. These initial analyses indicated a significant ($P = 0.006$ – 0.02) crop \times site interaction for all variables, requiring individual crop/site comparisons. Consequently, the data were analyzed as a one-way ANOVA comparing crops on individual sites, and expanded to include the forest and field data. Root data from corn, switchgrass and willow plots were also analyzed as repeated measures analyses of variance, using depth as the repeated factor. Following significant ANOVA results, means were compared using Tukey's test. In all analyses, a probability level of $P \leq 0.05$ was considered significant. Statistical analyses were performed using the SAS statistical package (SAS Institute, 1994).

3. Results

The two-way ANOVA of living (shoot) aboveground biomass C indicated significant crop ($P < 0.001$) and site ($P < 0.003$) effects with no interaction ($P < 0.09$), whereas living plus dead (total) aboveground biomass C showed similar effects but with a significant interaction term ($P < 0.004$). Across both sites, corn had the highest shoot C, 7150 kg/ha, compared with 5800 and 5150 kg/ha for switchgrass and willow, respectively. Across crops, the ECO site had higher shoot C (6500 kg/ha) than the SF site (5500 kg/ha). The interaction arose from higher total and shoot C in corn and switchgrass than in willow at the SF site, and the lack of difference among crops at the ECO site (Fig. 1). Willow aboveground C was significantly higher at the ECO than at the SF site whereas the other crops showed no difference between sites. Total aboveground C of switchgrass at the SF site was 83% shoots and 17% litter, and was significantly different from the 90 and 10%, respectively,

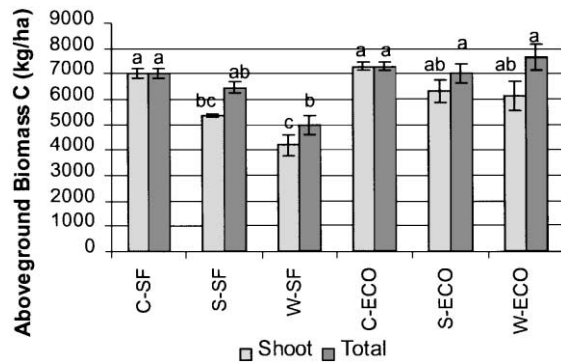


Fig. 1. Mean shoot (stalk + cob + grain) and total (shoot + litter + weed) aboveground biomass carbon of corn (C), switchgrass (S), and willow (W) at the SF and ECO sites. Within variables, means with the same letters do not differ significantly at the 0.05 level. Error bars represent S.E. ($n = 4$).

observed at the ECO site. The distribution of C among shoot, leaf, litter and weed components in the willow aboveground material was approximately 74, 8, 10 and 8%, respectively, at both sites.

The two-way ANOVA for fine root biomass C of the three crops indicated only a significant crop effect ($P < 0.001$), with corn significantly lower than the other crops (Fig. 2). Fine roots represented about 60% of total root C in willow and about 20% in corn. At depths of 30–45 and 45–60 cm, switchgrass roots had a significantly higher C accumulation than willow or corn at both sites. Both site and species effects on fine root C:shoot C ratio were significant (Fig. 3) with

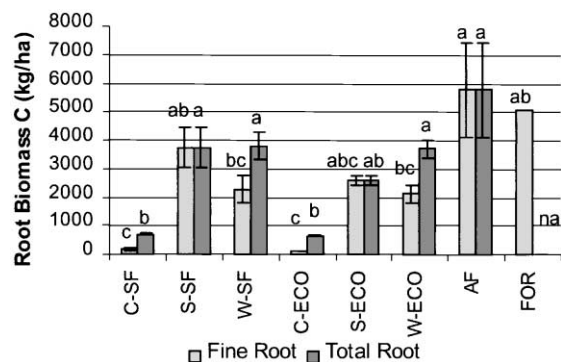


Fig. 2. Mean fine and total (fine + root crown) root C for corn, switchgrass, and willow at the SF and ECO sites. Within variables, means with the same letters do not differ significantly at the 0.05 level. Error bars represent S.E. ($n = 4$).

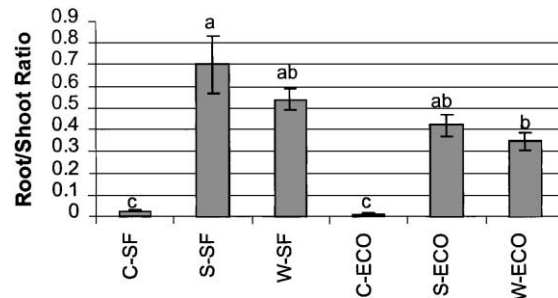


Fig. 3. Mean fine root:shoot ratio for corn, switchgrass, and willow at the SF and ECO sites. Means with the same letters do not differ significantly at the 0.05 level. Error bars represent S.E. ($n = 4$).

corn having a lower ratio than the other crops, and the ECO site having lower mean ratios than the SF site (0.26 versus 0.42; $P < 0.007$). Comparison across all systems showed that the unmanaged systems and perennial crops stored similar amounts of C in fine root biomass (Fig. 2).

When all living biomass components, or all living and dead biomass components in managed systems were summed to give total biomass C storage (Fig. 4), the two-way ANOVA indicated significant crop effects ($P < 0.02$ and 0.001 , respectively) but no site effect. Across sites, total crop biomass C and total living + dead biomass C were lower in corn systems than in switchgrass or willow. The interaction term was significant ($P < 0.02$) for the total living + dead biomass C because willow differed from corn at the ECO site only.

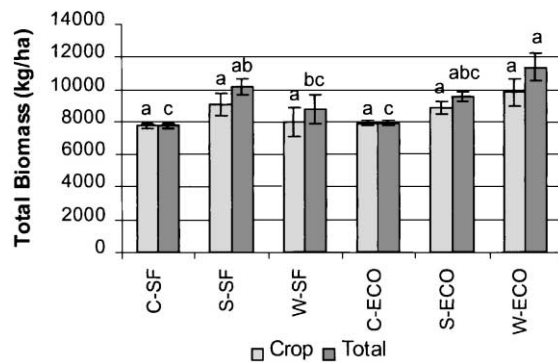


Fig. 4. Mean crop and total biomass C, above- and belowground for corn, switchgrass and willow at the SF and ECO sites. Within variables, means with the same letters do not differ significantly at the 0.05 level. Error bars represent S.E. ($n = 4$).

Overall, the crops exhibited distinct patterns of C allocation and storage. Corn was characterized by high aboveground and low belowground C storage, which together resulted in generally lower total biomass C storage than in the other crops. C storage in corn appeared to be unresponsive to differences between sites, possibly because fertilization mitigated site differences. Switchgrass had high aboveground, belowground and total biomass C and did not respond strongly to differences between sites. Willow was characterized by relatively high above and belowground biomass C and the highest contribution of 'non-crop' biomass C. In addition, however, willow was the most responsive of the three crops to differences between sites, resulting in significant differences in total biomass C between the two locations.

Comparing soil C across the managed systems, the two-way ANOVA indicated significant crop ($P < 0.05$), site ($P < 0.003$) and interaction ($P < 0.03$) effects. Across sites, willow had higher soil C (130 t/ha) than corn and switchgrass (both 110 t/ha), whereas across crops the ECO site had higher soil C than the SF site (130 t/ha versus 110 t/ha, respectively). Examining the interaction and including the unmanaged systems in the one-way ANOVA indicated that significantly more SOC was stored under willow at the ECO site than in most other systems, including the abandoned field and the forest, with the exception of switchgrass at the ECO site (Fig. 5). The proportion of the total system C (above- and belowground plant plus soil C)

represented by soil C ranged from 90–94% and did not differ among systems.

Using corn as the benchmark value to which soil C accumulation or loss beneath switchgrass and willow could be compared, and assuming that soil C levels from the 4 years of production (1993–1996) remained constant in the corn plots at both sites, willow soil C was calculated to increase by 9 t/ha per year compared to corn at ECO site. Switchgrass also increased soil C levels by 3 t/ha per year compared to the corn benchmark value. Similarly, using forest and the abandoned field soil C levels as benchmark values, willow and switchgrass at ECO also increased soil C levels by 9.5 and 3.5 t/ha per year, respectively. In contrast to the ECO site, there was no significant soil C accumulation or loss at the SF site using corn, the forest system or the abandoned field system as a benchmark level.

4. Discussion

4.1. Comparisons between managed sites

One of the main objectives of this research was to compare different crops in terms of their capacity to store C in different system components. Comparisons between the managed sites became important during the analysis, however, because significant crop \times site interactions observed with many variables indicate that crops allocate and store C differently on sites differing in soil and environmental conditions. Hence, consideration of the differences between study sites provides insight into species behavior and C storage processes. The ECO site was considered to have a higher fertility status, because of its management history involved annual manure applications, and the site may have been cooler and moister in the spring as a result of its sheltered location. In comparison, the SF site was considered to be less fertile and perhaps warmer and drier because of its southern exposure. These expectations are consistent with the results showing higher soil C storage, higher aboveground plant C and lower root:shoot ratio at the ECO site relative to the SF site.

Interpretation of differences in soil C storage between sites and crops is complicated by the lack of pre-experiment data in this study. Crop effects have been observed by comparing perennial crops with

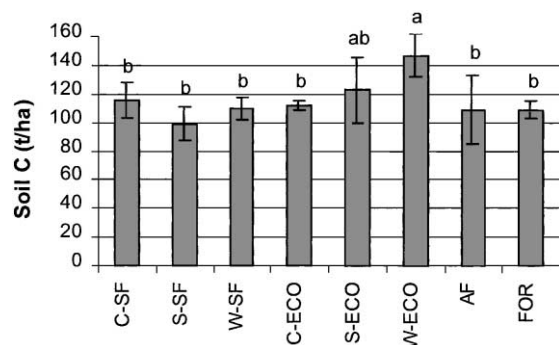


Fig. 5. Mass of soil organic carbon, in an equivalent soil mass of 7090 t/ha, under corn, switchgrass, willow, abandoned field (AF), and forest (FOR). Means with the same letters do not differ significantly at the 0.05 level. Error bars represent S.E. ($n = 4$).

corn, and cropped systems with unmanaged systems as ‘benchmarks’. This approach depends on relative differences between treatments, and the data available do not allow testing of the assumption that soil C levels are constant over time. This is particularly relevant in considering the ECO site, because historical manure additions may have elevated soil C levels in this location and levels may have declined once manure additions stopped just before the study. Interpretations of crop effects, for instance higher C under willow than under corn at the ECO site, is similar regardless of whether the effect is increased soil C relative to a constant benchmark or maintenance of soil C relative to a declining benchmark.

The generally higher soil C levels at the ECO site could also have arisen from inherent site conditions, irrespective of management. Cooler, moister soil climate at this location may result in higher soil C storage whereas warmer, drier soil conditions at SF may stimulate microbial activity, thus accelerating soil organic matter decomposition. Several studies have shown that increases in soil temperature, coupled with decreases in soil moisture, can increase microbial activity, leading to increased decomposition rates, and therefore, a decrease in soil C (Stevenson, 1986; Carter, 1996; Carter et al., 1997).

The higher aboveground biomass C at the ECO site is consistent with the idea of high fertility in this location. The observation that aboveground biomass C in corn, the production of which was supported by high fertilizer input, did not differ between the sites, whereas aboveground C in the perennial crops, which received less fertilizer, was lower at the SF site, supports the involvement of soil nutrients in causing the differences between sites. It is also relevant that corn at the ECO site received less fertilizer N than corn at the SF site because this difference would have further minimized inherent site differences.

The lower root:shoot ratios observed at the ECO site than at the SF site are consistent with a response of plant C allocation to nutrient and water availability. It has been well documented that plants growing in nutrient-poor environments increase their root growth in response to low concentrations of nutrients (e.g. Evans, 1977; Mouat, 1983; Eissenstat and Caldwell, 1988). It is likely that roots did not develop as extensively at the ECO site, because of the higher fertility, as at the SF site, where relatively nutrient-poor soils

would favor the allocation of a greater portion of resources into roots to ensure adequate resource capture. Similarly, drier conditions at the south-facing SF site may have stimulated the development of a larger, more extensive root system in order to allow plants to attain moisture at deeper levels.

4.2. Comparisons among crops

The results of this study demonstrate that the three crop species exhibit distinct behaviors with respect to C allocation and storage. Given the differences in growth form between the species, differences in plant biomass allocation patterns were to be expected. In addition, however, the crops appeared to differ in the relationship between belowground allocation and the resultant level of soil organic matter. Despite similarly high root biomass C in switchgrass and willow, soil C accumulation was higher under willow. Native grasses have been shown to undergo complete root turnover only once every 4 years (Dahlman and Kucera, 1965) compared with at least once per year for fine roots of deciduous tree species (Dewar and Cannell, 1992). In the switchgrass system where the plantations were only well-established during the 1996 sampling year, a root turnover every 4 years suggests that the contribution of roots to soil organic matter may not yet be fully evident. This may be particularly true in the deeper soil horizons where switchgrass root biomass C was substantially higher than under that of other crops. In contrast to switchgrass, willow roots, turning over once per year (Nadelhoffer et al., 1985), may have made greater contributions to soil organic matter, especially because the trees were pruned 1 year before sampling. It is also possible that, because willow was allowed to grow undisturbed for three consecutive years and then pruned (January 1996), part of its extensive root system died off and may have contributed large amounts of C to the soil. In a study by Ford-Robertson (1997), roots of recently dead or harvested trees were shown to release substantial amounts of C and some of this root-derived C was shown to be incorporated into the soil fraction. It is possible that some proportion of soil C measured in the willow system in 1996 represented a transient pulse related to coppicing, which will be returned to the atmosphere over a period of years.

The quality of inputs to the soil for the three systems may also have affected soil C storage. For example,

willow inputs into soil were in the form of roots, litter, leaves, and weeds. When willow is harvested in the winter, as is typically the case, the presence of senesced leaves on the soil surface should contribute substantially to soil C storage (Bransby et al., 1998). Lal et al. (1998) indicated that the rate of litterfall in agroforestry plantations helped maintain high soil C levels in these systems. In contrast, when switchgrass is harvested, all standing biomass is removed with the exception of some biomass losses during the harvest process. Therefore, only roots and litter contribute to soil C in this system (Bransby et al., 1998). Willow leaves have a higher N content (2.4–3.0%) in the autumn (Nilsson and Ericsson, 1985; Christersson, 1987) than switchgrass leaves (0.50–0.64%) (Thomas and Lucey, 1987; Wright, 1990; Goel et al., 1998). Therefore, incorporation of a greater amount of willow residues as well as their higher nutrient content may also explain the greater soil C levels found in willow systems compared with switchgrass systems.

Although no earthworm-related data were collected in the present study, informal observations of numerous earthworm burrows under willow but not under switchgrass or corn support the observation of Rehfuss et al. (1990) that the conversion of agricultural land to short-rotation forests significantly increases earthworm (Lumbricidae) populations. Earthworms mix plant residues and mineral soil, thus, promoting aggregate stability. Such stable aggregates may provide a protective environment for the organic matter enclosed in them, therefore leading to long-term C storage in the system (Marinissen and Didden, 1997). A study conducted by Linden and Clapp (1998) also demonstrated that considerable C was sequestered by the ingestion and deposition process of earthworms.

4.3. Comparison of managed and unmanaged systems

The unmanaged forest and abandoned field systems were included in this study as benchmarks against which the managed systems could be compared. The forest was viewed as a particularly important benchmark given that the managed fields had once supported similar forests. It had been expected that the managed sites would have had reduced soil C contents relative to the forest as has been observed in other studies

(Janzen et al., 1998). The present results show that this was not necessarily the case and that the mass of soil C under willow at the ECO site was significantly higher than that in either unmanaged system despite the high fine root biomass found in the unmanaged sites. Thus, switchgrass and willow, under favorable soil conditions such as found at the ECO site, may actually have total soil C levels superior to those of more stable, long-established ecosystems such as the forest and abandoned field. Under more nutrient-limited soil conditions such as those found at the SF site, perennial crops may not, however, increase soil C levels.

4.4. Carbon accumulation

The results showing increased C storage under switchgrass are consistent with the observations of Lal et al. (1998) which showed an increase in soil C concentration of 18%, equivalent to approximately 3 t/ha per year, over 6 years under perennial tall fescue relative to annual corn. The soil organic C gains observed at the ECO site in this study are large enough to warrant consideration in the context of C accounting associated with evaluation of agricultural management for biofuels. The results suggest that adoption of biofuel production systems will not only reduce the use of fossil fuels but will offset other fuel use by converting atmospheric CO₂ to unharvested perennial biomass and soil organic matter. It should be recognized, however, that biofuel cropping systems will reach a new C equilibrium, at which gains are offset by respiratory C losses, and thus increased storage is limited in magnitude and duration. Literature reviewed by Janzen et al. (1998) suggests that the duration of net storage may be less than a decade. Observations of C levels under willow suggest that management of these ecosystems may cause them to reach an equilibrium that would not be attained in natural forests and indicates that more research on the conditions required to maximize C storage is warranted.

5. Conclusions

This study has shown that, in southern Quebec, perennial cropping systems have the potential to store significantly more C than annual corn systems,

particularly when non-crop biomass and soil C are considered. In addition, perennial crop management appears to be capable of raising soil C storage to levels higher than those in unmanaged and native ecosystems. The research also suggests, however, that the potential for increasing C storage can depend strongly on site conditions, with highest gains expected on more fertile sites. The effect of soil and site conditions on C storage involves controls on plant productivity, allocation of plant C above- and belowground, and proportion of plant C converted to soil organic matter. Because conversion from annual to perennial cropping is likely to occur more readily on marginal or less productive soils, the potential to realize increased C storage through the adoption of perennial systems must be evaluated at the landscape level and in the context of a broader accounting of C equivalents of management inputs such as fertilizer and fuel.

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