IEA Bioenergy

Task 38

Greenhouse
Gas Balances
of Biomass and
Bioenergy Systems

The role of Soil Carbon in the GHG balance of bioenergy systems

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Summary

Interest in bioenergy is growing across the Western world in response to mounting concerns about climate change. However, there are also concerns that bioenergy systems may deplete soil carbon (C) stocks because a higher proportion of the organic matter and nutrients are removed from the site, compared with conventional agricultural and forestry systems. Published observations and model results indicate that bioenergy systems are likely to enhance soil C where these replace conventional cropping, as intensively cropped soils are generally depleted in soil C. However, soil C losses may occur where soil C is initially high, such as where fertile pastures are converted to biomass production. Measures that enhance soil C include maintenance of productivity through application of fertilisers, inclusion of legumes, and retention of nutrient-rich foliage. Although there may be some decline in soil carbon associated with biomass production, this is negligible in comparison with the contribution of bioenergy systems towards greenhouse mitigation through avoided fossil fuel emissions.

Vertisol profile, a cracking clay soil.
Courtesy of Derry Thomas

Introduction

Interest in bioenergy based on agricultural and forestry systems is growing in response to mounting concerns about climate change due, in large part, to use of fossil fuels for energy. In most conventional crop and timber production systems a significant fraction of the biomass remains on site after harvest, whereas, bioenergy systems often remove the majority of above ground biomass at harvest, including residues that would normally remain in the field. The removal of residues in bioenergy systems may significantly reduce the addition of organic matter to the soil, which may cause soil carbon to decline, and this loss may reduce the greenhouse gas mitigation benefits of bioenergy. This paper summarises the study of Cowie et al. (2006). It reviews factors that influence soil carbon dynamics in bioenergy systems, and, through modelling, investigates the likely magnitude of soil carbon change where bioenergy systems replace conventional land uses, and the impact on greenhouse mitigation benefits of bioenergy systems.

Acrisol profile, common in the tropics.
Courtesy of Derry Thomas

Residues from thinning a sawlog eucalypt plantation could be used for bioenergy.
Courtesy of Annette Cowie

1. The soil carbon pool

Soil contains huge quantities of carbon, generally around 50 to 300 tonnes per hectare. In comparison, plant biomass of pastures and crops is usually 2–20 tonnes per hectare, while plantation forests can accumulate 250 tonnes per hectare . Globally, the soil carbon pool is estimated to hold 2 000 Gt of carbon, compared with 500 Gt carbon in vegetation.

Soil carbon is derived from plant inputs, especially leaves and fine roots, and plays a fundamental role in the carbon cycle. Soil carbon stock at any one time reflects the balance between the inputs from plant residues and losses due to decomposition, erosion and leaching. Factors that enhance plant growth, such as warm, moist climate and high soil fertility promote organic matter addition to the soil carbon pool. Decomposition of organic matter occurs through the actions of soil fauna and microorganisms. In the mineralisation process, soil microbes digest organic matter, respiring carbon to the atmosphere and simultaneously releasing plant nutrients.

Decomposition is favoured by warm, moist climates that promote microbial activity, and inhibited by low temperatures, limited moisture, acidic pH, or low oxygen due to waterlogging or soil compaction. Mineralisation rate is also influenced by decomposability or “quality” of the organic residues, which is lowest for residues that are low in nitrogen or high in recalcitrant components such as lignin and waxes.

Cycling of carbon is inherently linked with cycling of nutrients, particularly nitrogen, because nutrients are returned to the soil as organic matter decomposes. In many environments nitrogen availability is the factor limiting plant productivity and, therefore, carbon inputs to the soil.

Soil carbon tends to accumulate in cool temperate forests and wetlands where plant productivity is relatively high but activity of soil biota that decompose organic matter is inhibited by low temperature or lack of oxygen, respectively. Soil carbon stocks are lower in the wet tropics where organic matter is turned over rapidly in the warm, moist climate, and lowest in dry environments where plant growth is limited.

Soil carbon stocks are higher in clay soils than sandy soils, because clay protects organic matter from decomposition

The soil organic carbon pool comprises components with different turnover times:

- the labile pool which decomposes rapidly (microbial biomass, soluble carbon, light fraction and macroorganic matter), with a turnover time of 1– 5 years,
- the humified pool, with turnover time of decades,
- inert organic matter, such as charcoal, which is highly resistant to decomposition due to physical and / or chemical protection, that decays over thousands of years.

2. Land use affects soil carbon

In a managed forestry or agricultural system where land use practices have remained constant over long periods, inputs and losses to the soil carbon pool will approach equilibrium, so soil carbon stock is basically constant. If land use practices change so that the balance between inputs and decomposition is affected, soil carbon stock will change.

Intensively cropped soils have low organic matter content, due to disturbance, erosion and regular periods of minimal organic matter input during fallow and in early establishment; cropping decreases soil carbon through a combination of reduced input and enhanced loss. A change in land use from forest or grassland to cropping will generally lead to loss of soil carbon of 50 % or more. Conversely, conversion of cropland to pasture or forest is likely to increase soil carbon by around 20 %.

Conversion from pasture to forest may led to loss of soil C in soils that are high in labile carbon, such as where new plantations are established into high productivity heavily fertilised pastures where soil C has been raised above native levels. As the plantation grows, soil carbon is replenished from litter fall and root turnover, usually restoring soil C to the original stock within 30 years.

Recent reviews suggest that soil carbon does not change, or increases, when broadleaf tree species are planted, but reforestation with pine species causes soil carbon stock to fall by around 15 %. Research is under way to confirm this observation and investigate possible causes.

There has been very little research into the impacts of bioenergy production on soil carbon, but from knowledge of the factors influencing soil carbon gained from studies of forest and agricultural systems in Europe, America, Australia and New Zealand, we can predict the probable soil carbon dynamics under bioenergy systems.

3. Impacts of bioenergy systems on soil carbon

Removal from the field or forest of a higher proportion of biomass in bioenergy systems, compared with crop or timber production systems, reduces the addition of organic matter to the soil carbon pool, and, therefore, may result in a decline in soil carbon stock. Loss in soil carbon may reduce long term productivity, and should be accounted in assessing the net greenhouse gas balance of bioenergy systems. Some bioenergy systems have a higher risk of soil carbon loss than others.

3.1 Bioenergy systems that maintain current land use but increase biomass removal

Biomass for bioenergy production can be obtained by harvesting additional biomass from conventional crop and forest systems. For example, wheat or maize straw may be baled and removed during or after grain harvest; forestry residues such as crowns and bark, usually left in the forest during harvest of sawlogs, can be baled or chipped, and used for bioenergy. Converting from conventional grain or timber production to bioenergy systems where a greater proportion of biomass is removed may reduce soil carbon as a result of three impacts:

1. Increased removal of biomass will directly reduce organic matter input to the soil.

2. As soil carbon begins to fall, plant productivity will also decline, due to the role played by soil organic matter in maintaining soil fertility. Declining plant productivity will, in turn, further reduce soil carbon.

3. Removal of plant biomass exports nutrients from the site, which will also impact on plant productivity in the long term unless these nutrients are replaced. Bioenergy systems that remove foliage and bark, which are particularly high in N, P, K and Ca, are at high risk of nutrient depletion compared with grain and timber production systems. Loss of chemical fertility will limit plant growth, leading to reduced input to the soil carbon pool.

There is some experimental evidence of decline in productivity and/or soil carbon in systems where all above ground biomass is removed, particularly in infertile soils. But for several reasons this impact is not likely to be large:

1. In many conventional forest and crop management systems, residues are burnt after harvest. Conversion to bioenergy systems would therefore remove biomass that would have been lost through burning. Removal of biomass that would otherwise have been burned will not change the inputs of carbon, although non-volatile nutrients that would otherwise remain in ash will be removed.

2. In systems where residues are retained on the soil surface it is likely that much of the above-ground litter, especially coarse material, decays at the surface, rather than entering the soil carbon pool, particularly in systems with low soil faunal activity. Removal of biomass that would have decomposed on the soil surface will have limited impact on organic input to the soil.

3. The major input to soil carbon is fine roots and leaf litter. These inputs are added continually during the growth of a pasture or forest. Thus, the quantity of biomass removed at harvest represents only a fraction of the total biomass produced by plants.

Therefore, increased removal of biomass in bioenergy systems may cause some loss in soil carbon, but because a significant proportion of total biomass production is retained, including the root and leaf litter biomass that constitutes the major input to soil C, the impact on soil C of removal of biomass for bioenergy should generally be small.

3.2 Bioenergy systems entailing land use change

As an alternative to modifying current systems to produce biomass for bioenergy, discussed above, new bioenergy systems may be introduced, replacing the current land use. The impact on soil carbon of this land use change will depend on the features of the bioenergy system, and the system that is replaced. Options include:

1. Conversion of cropland to short rotation bioenergy crops, such as rhizomatous perennial grasses (e.g. Miscanthus, switchgrass) or short rotation woody crops (e.g. willow, poplar) that are mown/coppiced every few years and allowed to regrow from roots/stump, and replanted after several harvests. Soil carbon is likely to increase due to reduced frequency of harvest and soil disturbance.

2. Conversion of cropland to long rotation forest plantations for timber plus biomass. The limited evidence available suggests this will increase soil carbon due to reduced frequency of harvest.

3. Conversion of pasture to short rotation bioenergy crops. This change may lead to small losses or gains in soil C, depending on the relative balance of organic inputs and decomposition rate under the old and new land uses.

4. Conversion of pasture to long rotation forest plantation for timber plus biomass. As for option 3, small gains or losses in soil C may result.

4. Land Management to enhance soil carbon

Based on studies in agricultural and forestry systems around the world, the following management practices, that maximise organic matter inputs and/or minimise losses, are recommended to promote soil carbon accumulation.

Retain slash/crop residues on site

to increase organic matter input and protect against erosion of the carbon-rich surface soil. In particular, foliage and bark should be retained on site, as these are high in nutrients (The high nutrient levels also create high ash content, which is undesirable for most bioenergy applications). Retaining leaves is easiest to achieve with deciduous tree species, annual crops or perennial grasses with a dormant phase; for broadleaf species this can be achieved by windrowing or stacking branches in the field until the leaves drop, though this may pose an unacceptable fire risk in some climates.

Apply fertiliser to overcome nutrient deficiencies and maintain fertility

Fertiliser application, where it increases plant growth and therefore litter inputs, leads to soil C accumulation in forests and crops. Fertiliser rates and timing should be matched to the requirements of the crop/forest to maximise efficiency of fertiliser use and limit leaching and runoff.

Consider returning ash

Return of ash to the field or forest from which the biomass was harvested could aid in replacing nutrients removed at harvest (other than N, which is volatilised during combustion). However, efficient means of distribution and integration into the crop/forest fertiliser strategy must be found to ensure net positive returns, both financially, and in terms of greenhouse gas (GHG) balance, from this practice.

Apply additional organic matter

Recycled organics such as manures, biosolids, composts and char are more effective than fresh plant residues in raising soil C because the carbon is present as relatively more recalcitrant forms.

Consider planting mixed species to maximise site productivity

Each species has a different carbon allocation strategy that results in a different pattern, rate, quality and quantity of organic carbon input to the soil. Mixed species planting can maximize biomass production where species have facilitative rather than competitive interaction: mixtures including nitrogen-fixing species (e.g. acacia with eucalypts, lupin with pine, and clover with pasture grasses) commonly produce higher total biomass yields than monocultures of either species.

Minimise cultivation disturbance to reduce mineralisation and erosion losses

Minimising soil disturbance will conserve soil carbon, particularly on erodible soils. Reduced or zero tillage planting techniques increase soil carbon in many cropping systems, though in Australia, for example, positive impact of minimum tillage on soil carbon is restricted to wetter temperate regions. Site preparation for tree planting commonly involves ripping, often in conjunction with mounding. Ripping depth and size of mound can be minimised without jeopardising growth rate in some soil types but mounding is clearly essential for successful plantation establishment in some heavy soils or waterlogged positions. Longer rotations, or coppicing, reduce the frequency of soil disturbance in forest systems and so promote soil carbon.

The most significant factor for enhancing soil carbon is strong plant growth. Therefore, management practices for a bioenergy system should be designed to address site-specific growth limitations to the crop or forest so as to ensure successful establishment and maximum growth rate.

Application of biosolids increases soil carbon.
Courtesy of Georgina Kelly

5. Quantifying soil carbon changes

Soil C stock is notoriously difficult to quantify due to substantial spatial variability at fine and broad scale. Sampling protocols have been developed, but accurate measurement and monitoring of soil carbon, particularly to detect change in the short term (< 5–10 years), is prohibitively expensive for routine accounting of carbon sequestration in bioenergy projects, as hundreds of samples are required to obtain acceptable accuracy.

Modelling could be a cost-effective alternative for estimating soil carbon change. As indicated above, soil carbon change is determined by the balance between plant inputs and soil C turnover rate, influenced by initial soil C status, soil type and climate; models based on these interactions can predict soil C change.

For example, the RothC model of soil C dynamics is well proven in many environments. Linked with a model to estimate plant inputs, RothC can be utilised to estimate soil carbon change, as demonstrated below using the FullCAM model. In order to simulate soil C dynamics of a bioenergy project, baseline soil C and environmental data are required. In addition to total soil organic carbon, the proportion of carbon in labile and recalcitrant pools must be known to run the RothC model. A fractionation procedure based on wet sieving to determine particulate organic carbon and charcoal measurement by photo-oxidation and 13 C NMR allows quantification of soil C pools equivalent to the conceptual pools of the RothC model. With suitable calibration, mid-infra red analysis can provide a simple, cost-effective approximation of pool structure.

Estimation of soil carbon change in bioenergy projects may be undertaken through a combination of measurement, to establish the baseline C stocks in each of the soil C pools, and modelling to estimate carbon dynamics over time. Models of plant growth and soil C dynamics have been calibrated for many crop and forest systems, though further work is needed to parameterise models for a broader range of environments and management systems, and to improve the ability of models to predict impacts of complex soil processes over the long term.

6. Modelling the Impact of soil carbon change on greenhouse gas balance of bioenergy systems

The FullCAM model of carbon dynamics was used to simulate the long term GHG balance of bioenergy systems in comparison with three conventional forestry systems in Australia. FullCAM links the process-based model of forest growth 3-PG with the forest carbon accounting model CAMFor and the RothC model of soil organic matter turnover. Input data required are monthly climatic data, site specific soil data, and management events.

Three conventional forestry systems and associated bioenergy systems were modelled:

System 1 – Short rotation Eucalypt plantation producing pulplogs.
Reference: harvest residues decay on site, stems used for pulp.
Bioenergy Case: harvest residues used for bioenergy, stems used for pulp.

System 2 – Radiata pine sawlog plantation.
Reference: thinning and harvest residues decay on site, stems used for pulp and construction timber, excess mill residues burnt to waste.
Bioenergy Case: thinning, harvest and excess mill residues used for bioenergy, stems used for pulp and construction timber.

System 3 – Eucalyptus sawlog plantation.
Reference: thinning and harvest residues decay on site, stems used for construction timber, excess mill residues burnt to waste.
Bioenergy Case: thinning, harvest and excess mill residues used for bioenergy, stems used for construction timber.

Table 1 lists site and management details for each system. Further detail of the sites, model parameterisation and assumptions are given by Cowie et al. (2006). In each case where forest residues are recovered for bioenergy it was assumed that 70 % of the branch biomass is removed, leaving 30 % of branch biomass, 100 % leaf mass, and 2–3 % stem mass (representing the stump), as litter. Where sawn timber is produced, it was assumed that 3.5 % of the carbon from mill residues is utilised to dry the timber. The bioenergy and corresponding reference systems each produce the same mass of pulp and / or timber products. The bioenergy system is based on theoretical calculations for co-firing biomass in a 500 MW black coal power plant. The assumed displacement factor is 0.83 t C avoided fossil emission per t C in biofuel. Emissions from establishment and harvest are assumed to be, respectively, 1.1 t CO_2e ha^{-1} and 0.073 t CO_2e per t C in biomass harvested. Processing and transport emissions are assumed to be 0.40 t CO_2e per t C in biomass used for bioenergy.

Table 1
Site and management details for three conventional forestry systems and corresponding bioenergy systems.
Source: Cowie et al, 2006

System	Short rotation eucalypt		Pine		Sawlog eucalypt	
Species	*Eucalyptus globulus*		*Pinus radiata*		*Eucalyptus grandis*	
Location	Western Australia		South Australia		South-eastern Queensland	
Mean annual rainfall (mm)	1022		704		1138	
Mean annual air temperature (° C)	14.9		13.4		20.4	
Soil type	Sandy loam		Sand		Sandy loam	
Initial soil C (tC/ha, 0–30 cm)	49.8		43.9		67.7	
Rotation length (years)	10		35		28	
Thinning (age, % biomass removed)						
Thinning 1	NA		10 (50)		10 (50)	
Thinning 2			24 (25)		18 (50)	
Thinning 3			27 (10)		NA	
Assumed fate of aboveground biomass (%)						
Activity	Reference	Bioenergy	Reference	Bioenergy	Reference	Bioenergy
Thinning 1						
bioenergy	NA	NA	0	88	0	82
litter			100	12	100	18
Thinning 2						
pulp	NA	NA	24	24	0	0
sawn timber			16	16	0	0
bioenergy			1	48	0	0
mill residue			32	1	0	82
litter			27	11	100	18
Thinning 3						
pulp	NA	NA	24	24	NA	NA
construction			16	16		
timber			1	48		
bioenergy			32	1		
litter			27	11		
ClearFall						
pulp	50	50	3	3	0	0
sawn timber	0	0	29	29	10	10
bioenergy	0	31	1	58	0.4	75
mill residue	0	0	45	1	22	0.4
litter	50	19	22	9	68	15

6.1 Calculation of net Greenhouse Gas (GHG) balance

The net GHG balance for each system was determined from the carbon sequestration by the growing forest, plus the credit for avoided fossil fuel emissions, less the GHG emissions incurred in producing, processing and transporting the biomass, including indirect emissions from fertiliser manufacture and N_2O release after N fertiliser application. The GHG balance of the bioenergy system was compared with the GHG balance of the traditional (reference) system to determine the net benefits of the bioenergy system.

Model results indicate that each of the bioenergy systems has lower soil C after 100 years than the corresponding reference system (Figure 1). These differences are largely due to relative declines in the resistant plant matter and humified pools. The difference is greatest in the short rotation eucalypt system, which shows a 35 t ha^{-1} increase in soil C over 100 years under the reference system, and a 6 t ha^{-1} increase in the bioenergy case. The sawlog eucalypt reference system shows an initial decline followed by stabilisation of soil C. Under the bioenergy system, there is a continuing decline, and this system shows a loss of 35 t C ha^{-1} over 100 years. The soil C stock varies little over 100 years in the pine system, both in the reference and bioenergy cases.

Changes in the soil C pool are small compared with the accumulation of C in tree biomass over the first rotation, and the growing pools of products (Figure 2). Over several rotations displaced fossil fuel carbon becomes the dominant pool, particularly in the sawlog eucalypt system, which has the highest proportion of removed biomass allocated to bioenergy rather than wood products due to low mill recovery for this species.

The net GHG balance of the bioenergy systems in comparison with the corresponding reference systems shows a significant benefit in increased C stocks for all three forestry systems (Figure 3, Table 2). The displaced fossil fuel carbon is thirteen to twenty-two times greater than the relative decline in soil C stock.

Rendzic Leptosol from the province of Upper Austria.
Courtesy of Florian Winter, Federal Forest Research and Training Centre, Austria (BFW)

Table 2
Change in carbon stock of the forest and product pools, and displaced fossil fuel over 100 years. Positive values indicate a gain, negative values a decline.
Source: Cowie et al, 2006

	Short rotation Eucalypt (tC/ha)			Pine (tC/ha)			Sawlog Eucalypt (tC/ha)		
Pool	Reference	Bioenergy	Difference[4]	Reference	Bioenergy	Difference[4]	Reference	Bioenergy	Difference[4]
Soil[1]	35	6	-30	3	-5	-6	-9	-35	-19
Litter[2]	5	2	-2	2	1	0	5	2	-1
Trees[2]	76	76	0	62	62	0	96	96	0
Products in use[1]	18	20	0	38	39	0	26	30	0
Products in landfill[1]	228	228	0	41	41	0	21	21	0
Fossil fuel displaced bioenergy[3]	0	391	391	0	165	165	0	594	594
Fossil fuel spent	-16	-78	-62	-7	-29	-22	-17	-96	-79
Net GHG balance	345	644	296	139	274	136	123	612	494

1 Value at 100 years determined from fitted trend line, to overcome influence of fluctuating pool size.
2 Value at 100 years determined from average carbon stock of pool over the period.
3 Total carbon stock of pool at 100 years.
4 Difference between bioenergy and reference case at 100 years.

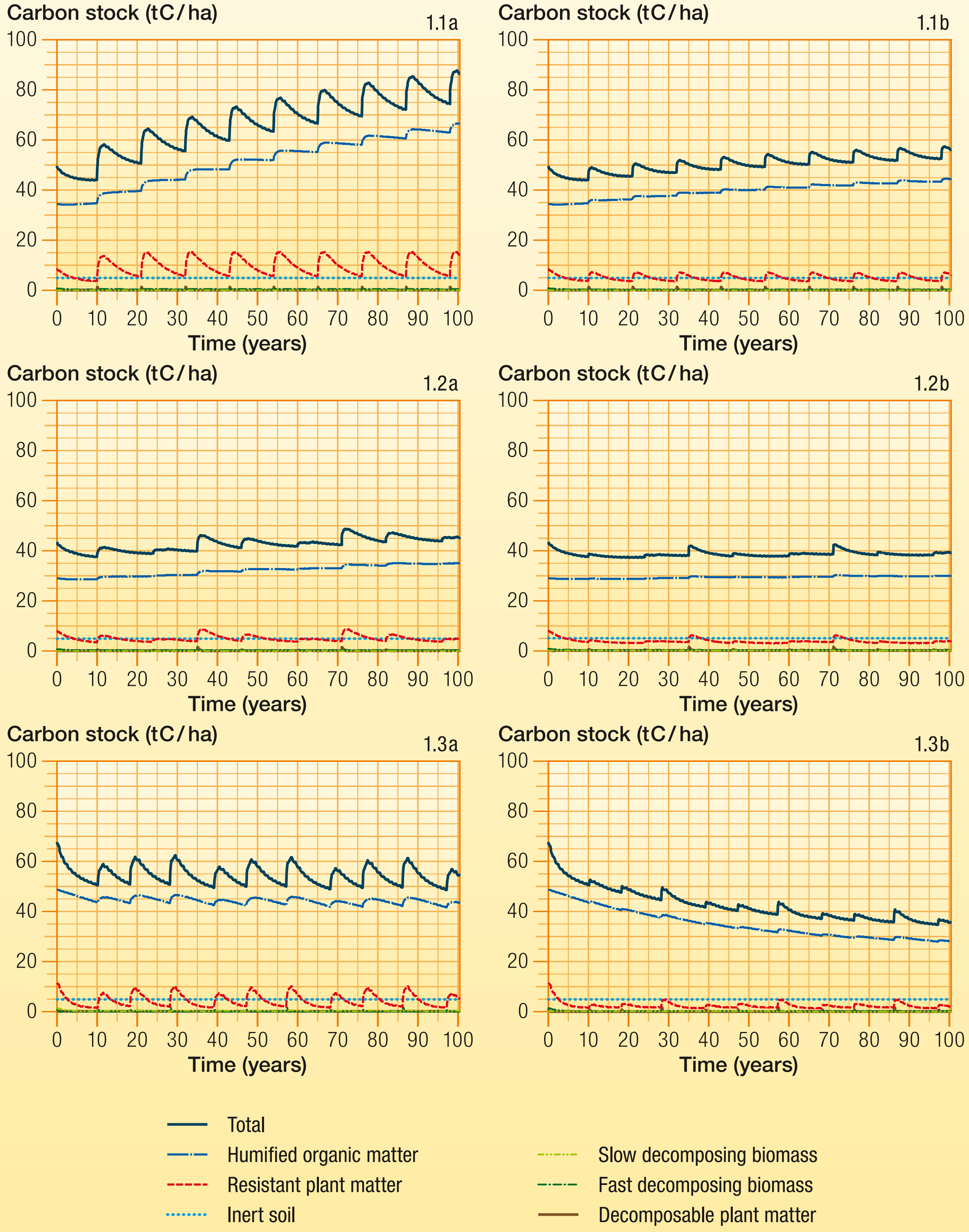

Figure 1

Soil carbon pools for short rotation eucalypt (1.1), pine (1.2) and sawlog eucalypt (1.3) conventional forestry systems (a) and bioenergy systems (b).

Source: Cowie et al, 2006

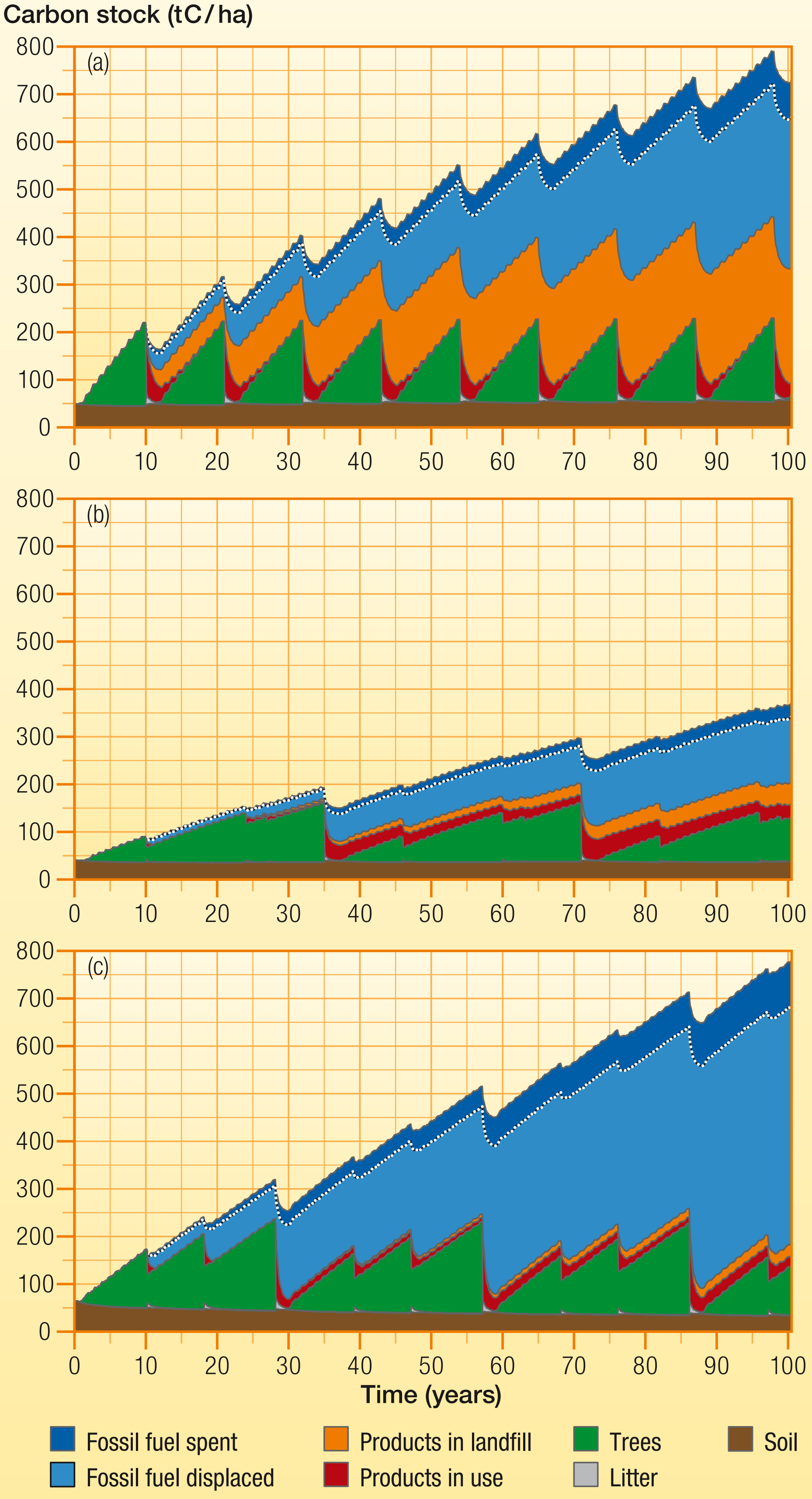

Figure 2

Carbon stock of all forest and product pools, avoided emissions, and fossil fuel spent for each bioenergy system for

(a) short rotation eucalypt,

(b) pine and

(c) sawlog eucalypt.

Fossil fuel spent is a negative value. The net carbon stock is indicated by the dotted line.

Source: Cowie et al, 2006

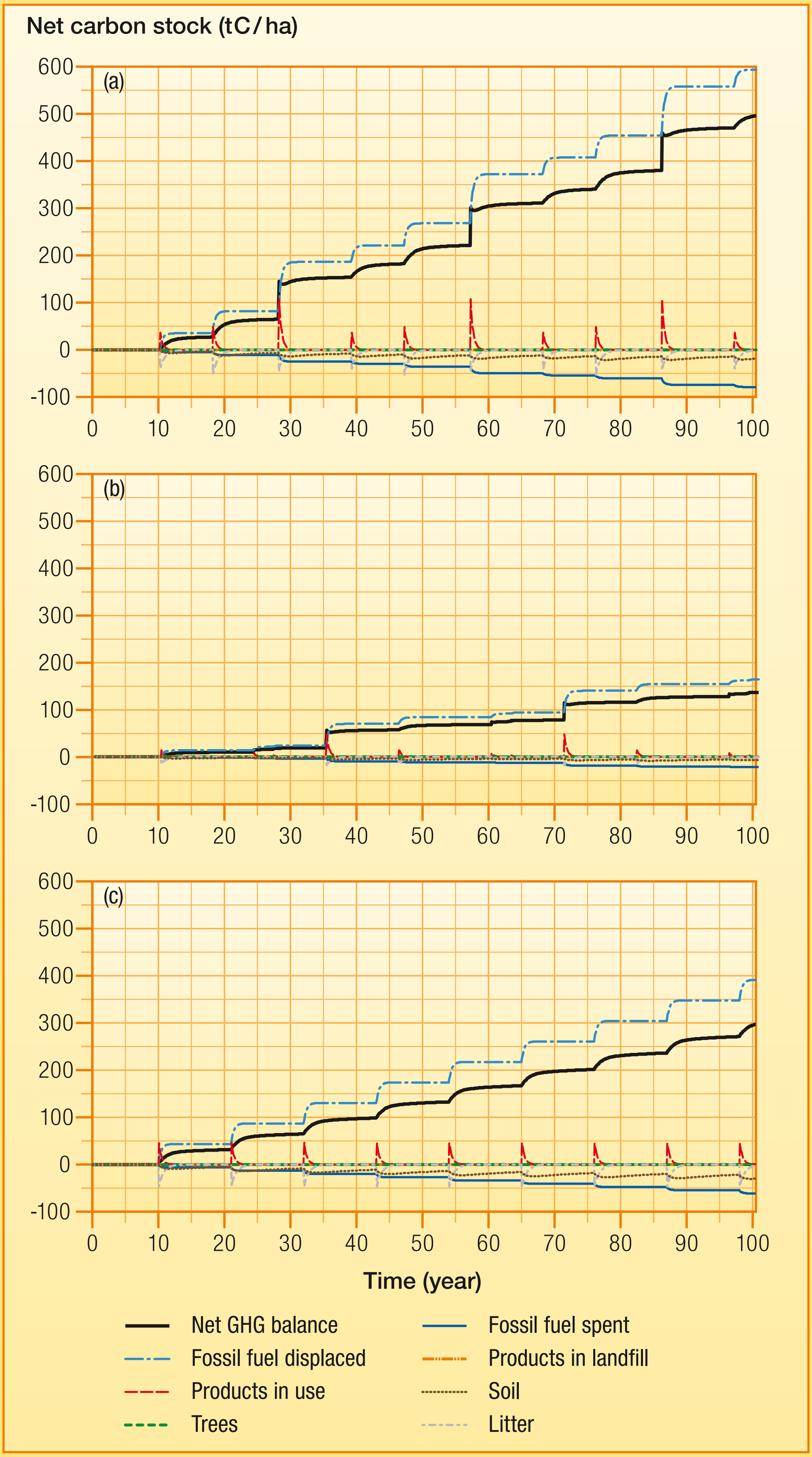

Figure 3

Difference between the bioenergy and reference cases in carbon stock of each pool in

(a) short rotation eucalypt,

(b) pine and

(c) sawlog eucalypt.

For soil and litter pools negative values indicate a relative decline in carbon stock; for fossil fuel spent, negative values indicate greater emissions.

Source: Cowie et al, 2006

7. Summary and Conclusion

Replacing current agricultural and forestry systems with systems that produce biomass for bioenergy is likely to affect soil carbon stocks, because it will alter the balance between organic matter inputs and losses from the soil carbon pool. There is a risk of depletion of soil carbon stocks in biomass production systems, because a higher proportion of the organic matter and nutrients are removed from the site, compared with conventional grain and timber production systems. Environmental and management factors will govern the magnitude and direction of change. Initial soil carbon content has a major influence: losses are most likely where soil C is initially high. Bioenergy systems such as coppiced willow, switchgrass, or long-rotation timber + biomass plantations, are likely to enhance soil carbon where these replace conventional cropping, as intensively cropped soils are generally depleted in soil C. Soil C losses are most likely where soil C is initially high, such as where improved pasture is converted to biomass production short-term loss of soil C is likely, and the equilibrium soil C stock under bioenergy systems may be lower than that of the previous pasture. Intensively managed bioenergy systems, such as perennial grasses and short rotation woody crops, are likely to have lower equilibrium soil C than long rotation forests, due to more frequent site disturbance and high rate of biomass removal. Measures that enhance soil C include maintenance of soil fertility through application of organic chemical fertilisers or inclusion of legumes to promote plant growth, and retention of nutrient-rich foliage on-site.

Modelling results for Australian forest systems show that, although there may be a small decline in soil C in bioenergy systems in comparison with conventional forest systems, the loss is insignificant in comparison with the mitigation benefits of bioenergy. Studies of forest and agricultural systems in other countries, including Norway spruce and Scots pine in Sweden, support this conclusion. Removal of additional biomass for bioenergy has little impact on soil carbon because this biomass makes a minor contribution to the soil carbon pool compared with the organic matter inputs throughout the growth of the crop or forest. The small loss in soil carbon is negligible compared with the contribution of bioenergy systems towards climate change mitigation through displacement of fossil fuel emissions.


Young maize crop.
Courtesy of Annette Cowie


Coppiced willow, a short-rotation bioenergy crop.
Courtesy of Bernhard Schlamadinger


Direct drilling into maize stubble.
Zero tillage conserves soil carbon.
Courtesy of Annette Cowie

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IEA Bioenergy
Task 38

IEA Bioenergy (www.ieabioenergy.com) is an international collaborative agreement, set up in 1978 by the International Energy Agency (IEA) to improve international cooperation and information exchange between national bioenergy research, development and demonstration (RD&D) programs. IEA Bioenergy aims to realize the use of environmentally sound and cost-competitive bioenergy on a sustainable basis, thereby providing a substantial contribution to meeting future energy demands.

IEA Bioenergy Task 38 (www.ieabioenergy-task38.org) integrates analyses and disseminates information on greenhouse gases (GHGs), bioenergy, agriculture and forestry from national programs of all participating countries. Besides the development of state-of-the-art methodologies for assessing GHG balances, emphasis is placed on demonstrating the application of established methods and on supporting decision-makers in implementing effective GHG mitigation strategies.

Work of the task includes case studies and special projects undertaken by individual task members, in which the standard methodology developed by Task 38 for assessing GHG balance of bioenergy and carbon sequestration activities is applied to particular projects or topics. This study on the impacts of bioenergy on soil carbon is an example of a special project supported by the Task.

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