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Assessing long-term impacts of increased crop productivity on atmospheric CO_2

James Cavazzoni and Tyler Volk
Earth Systems Group, Department of Biology, 34 Stuyvesant Street, New York University, New York, NY 10003-7599, USA

A full assessment of the impacts of land clearance and crop production on atmospheric CO_2 requires a systems approach. By considering long-term soil carbon changes and fossil fuel energy inputs, we show that increased crop productivity will alleviate CO_2 release to the atmosphere primarily by preventing additional land cultivation. Each hectare of cropland undergoing a simulated threefold crop productivity increase here prevents a net release on the order of 150–200 Mg C to the atmosphere over 100 years by avoiding additional land cultivation which would otherwise be required. This effective carbon sink would slowly diminish with time due to fossil fuel energy input requirements. However, future self-containment of the energy needs of high-yield crop production may displace on the order of 1.0 Pg C per year of fossil fuel carbon, in addition to the carbon sink attributable to avoided land cultivation. By avoiding land cultivation, high yield crop systems also preserve natural ecosystems. Copyright © 1996 Elsevier Science Ltd.

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Land clearance for crop production releases CO_2 to the atmosphere, which results from both the clearing and subsequent oxidation of vegetation, and the decrease in the soil carbon (C) content of cultivated land to levels below those of forests and grasslands (Schlesinger, 1991; Houghton, 1986). As CO_2 is expected to account for the majority of the global warming potential attributable to greenhouse gases over the next 100 years (Houghton *et al*, 1990), a 'C debt' may be attributed to cultivation in the atmospheric CO_2 budget. The total amount of this 'C debt' thus far – that arising from both soil C loss and land clearance associated with present worldwide cropland – is estimated to be about 160 Pg C (1 Pg = 10^{15} g), while the annual atmospheric C flux due to land clearance for cultivation alone is currently estimated to be approximately 1 Pg C (Houghton, 1994, private communication). By comparison, fossil-fuel combustion released an estimated 6 Pg C in 1989 (Boden *et al*, 1990).

Counteraction of the above C debt may focus on directly increasing the carbon content of cultivated soils above present levels through crop yield increases and/or management efforts (Li *et al*, 1994; Environmental Protection Agency (EPA), 1994). If atmospheric CO_2 levels are of interest, however, and not soil C *per se*, then the entire crop system must be considered, and not soil C in isolation. For instance, one way to directly enhance C sequestration in cultivated soils would be through intensive farmyard manure amendments (Li *et al*, 1994; Lucas *et al*, 1977). Li *et al* (1994) consider soil C increases of field plots upon application of some 35 Mg of farmyard manure per hectare per year (1 Mg = 10^6 g). While organic soil amendments should be used efficiently whenever possible, such rates applied to present cropland in cereals alone would require some 5 billion head of cattle on average (assuming that 50% of all cattle manure is collectable).[1] By comparison, there are presently 1 billion or so head of cattle worldwide (Loomis and Connor, 1992). Other farm-system considerations – not to mention feed and land requirements for additional cattle – would include environmental risks due to manure overapplication, and the competing use of cattle manure for fuel in developing regions, which may comprise 50–60% of the cattle manure use in India and Pakistan (Gifford, 1984).

In contrast to enhanced manure amendments, increased crop productivity is a general consideration which may be applied to crop systems worldwide. Cereal production has increased approximately threefold in the last forty years or

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[1] This estimate is the authors', using cattle manure production figures as in Stout (1990).

so, and this increase has been attained on essentially the same amount of cultivated land, from about 602 million hectares in 1950 to 708 million hectares in 1990. The result is that perhaps 90% of increased cereal production from 1950 to the present is attributable to increased yields, and this trend of cereal yield increases is projected to continue more or less linearly through the year 2010 (Mitchell and Ingco, 1993). A similar pattern also exists for total cultivated land, which changed from about 1409 million hectares in 1960 to 1477 million hectares in 1989. More importantly, per capita cereal supply for developing regions as a whole has generally increased from 1950–60 to 1990. Caution must be used when interpreting average world cereal supply/production per capita figures because of such factors as population weighting, policies which intentionally suppress grain production in industrialized regions, and restructuring of the former USSR and centrally planned economies of Eastern Europe.[2]

Increased crop productivity will have a direct impact on atmospheric CO_2 through increased crop residue production and return to the soil, which will generally maintain or increase soil C content, and soil fertility in general (Rasmussen and Collins, 1991; Lucas *et al*, 1977). Indirectly, however, the crop system C accounting must now include any fossil fuel energy inputs necessary to increase crop productivity, as CO_2 is released to the atmosphere from fossil fuel combustion. For a given food production level, C accounting in this manner must also include the additional land cultivation and consequent CO_2 release to the atmosphere which would otherwise be required without crop productivity increases.

Here, a long-term threefold crop yield increase is simulated in order to capture the essential features of this crop system assessment. This scenario corresponds to a factor of three in land requirements for a given food production, which is approximately the ratio that exists between potential and present arable land in Africa, Latin America and Asia (Crosson and Anderson, 1992; Hall *et al*, 1993). The average annual cereal yield increases in the simulation are well below those of recent decades, as discussed subsequently. The range of crop yield increases yet achievable may be exemplified in Africa, where, in general, potential productivity per hectare increases by a factor of 12 as farm inputs progress from low to high over various soil and agroclimatic conditions (Dudal *et al*, 1983). As an example, maize yields in the Ivory Coast averaged 0.8 Mg per hectare per year in 1991, far below the yield potential of 7 Mg per hectare per year (Avery, 1994, personal communication). For reference, low farm input levels correspond to hand labour, no chemical fertilizer or pesticides, and no soil conservation measures with consequent productivity losses due to soil degradation. High farm inputs correspond to full use of agricultural mechanization and optimum genetic stock, use of necessary farm chemicals and soil conservation practices (USDA, 1995).

Also relevant to this discussion are the energy input requirements for high yield crop systems and long-term sustainability. If the time horizon for fossil fuel depletion, and therefore the sustainability of fossil fuel dependent high crop productivity, is a cause of concern, then alternative energy sources – in addition to energy adjustments outside the entire food production system, and improved crop system energy efficiencies – must be considered. In principle, the energy needs for crop production may be self-contained for high yield crop systems. This may be achieved either directly by using advanced biomass conversion technology and a fraction of crop residues, or indirectly should high yields free cropland for future conversion to energy crops. These topics are considered here.

Soil carbon dynamics

Agricultural advances which increase yields have the potential to increase soil C, as increased residue return generally increases soil organic matter content (soil C multiplied by a factor which may range from 1.6–3.3) (Rasmussen and Collins, 1991). This effect is simulated here using a simple soil C model adapted from Lucas *et al* (1977) and Holtman *et al* (1979), which is empirically based on yield/soil C data for unirrigated continuous maize production in the USA. Cereal grains will be used here as an overall indicator of crop production owing to their predominance as a staple crop, either directly or indirectly (livestock feed) throughout the world (Loomis and Connor, 1992). The model simulates soil C dynamics in the soil plough layer (upper 20 cm) based on initial soil C content, and the amount of residue returned in relation to residue decomposition and soil erosion.

Increased soil organic matter generally increases soil fertility because of such factors as increased cation exchange and water holding capacities, and improved soil structure (Loomis and Connor, 1992). By increasing crop residue production and soil organic matter, then, increased yields increase yield potential – the maximum yield which would be expected under typical weather conditions – as well. This soil C/yield potential feedback is described here (as in Lucas *et al*, 1977) by

$$y[n] = r(5541 + 1553\, c[n]) \tag{1}$$

where $y[n]$ is the grain yield in year n (kg per hectare), $c[n]$ is the soil C content (% solids by weight in the plough layer at the beginning of year n), and r is the ratio of yield to yield potential for specified N fertilization intensity (N applied/N in grain). For the long-term crop system transitions simulated here, cereal yields gradually increase to 98% of yield potential over 90 years, with r held constant (at 0.98) thereafter.

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[2] For discussion of per capita food supply/production in developing regions see, for instance, Mitchell and Ingco (1993) and Dyson (1994). Average per capita grain supply for developing countries increased between 1980 and 1990, as well as for the longer period from 1960 to 1990 (based on USDA data cited in Mitchell and Ingco (1993), Table 8.3). The population weighted per capita index of food production for developing countries also increased between 1980 and 1990 (based on FAO data cited in World Resources Institute (1992), Table 18.1; Dyson (1994), Table 3).

This transition corresponds to a threefold increase in crop yield, which may be interpreted as a long-term scenario where world average cereal yields increase from about 3 Mg per hectare per year (roughly the present average) to one of about 9 Mg per hectare per year in the long-term. This is similar to Revelle's (1985) estimate of crop production for the year 2100, where he assumes an average cereal yield equivalent of 10 Mg per hectare per year for crops well-supplied with water and nutrients by that time.[3] This corresponds to an average annual cereal yield increase of about 1.4% for the first 40 years, and less than 1% over the entire 150 years. By comparison, average world cereal yields increased annually by 2.24% over the last 40 years. This figure was 2.17% and 2.39% in developing and industrialized countries, respectively. With the exception of the decline in maize yield growth rates during the 1980–90 decade (which was primarily due to a severe US drought in 1988), annual cereal yield increases during this recent decade were comparable to those from 1950–80 (Mitchell and Ingco, 1993).[4] In contrast, Larson (1993) anticipates the need for a 40% increase in present cereal yields over ten years in sub-Sahara Africa.

For reference, the high end of yields for wheat, rice, and coarse grains all presently average about 6 Mg per hectare per year (in the EC-10, Japan and the USA, respectively) (Mitchell and Ingco, 1993). In the USA, the USDA expects advances in technology (unrelated to climate change) to double yields of feed grains, wheat and soyabeans in the next 40 years (Council for Agricultural Science and Technology (CAST), 1992). (Maize yields in the USA now average 7.5 Mg of grain per hectare per year – up threefold since the mid 1940s (Hall *et al*, 1993).) Such an increase would average 1.5% annually, which is less than the 1.8% achieved over the last 40 years, and is deemed plausible enough by the CAST (1992) report. As will be made clear, the threefold yield increase simulated here (which would apply, for instance, to a transition from 1 Mg per hectare per year to 3 Mg per hectare per year in sub-Saharan Africa) is more relevant than the hypothetical final yield.

Soil C changes corresponding to this threefold yield increase for 100% residue return to the soil are shown in Figure 1, line A. Eroded soil C (not included in Figure 1) should be included in the atmospheric C sink as eroded soil is likely to be deposited in other field areas, wetlands and waterbodies (EPA, 1994).[5] This eroded soil adds another 13 Mg C per hectare or so to the soil C increase of Figure 1, line A (about 17 Mg per hectare) after 150 years. These values may be compared with an estimated 40 Mg C per hectare released to the atmosphere from cultivated soil.[6] The additive effect of eroded soil C and the soil C increase of Figure 1, line A would be to counteract about 75% of this release over 150 years. Applying this estimate to present cropland in cereals results in the sequestering of approximately 20 Pg C, which is about 12% of the total present C debt of 160 Pg C due to cultivation, or about one-third of the 60 Pg C released from all cultivated soils thus far (Harrison *et al*, 1993).

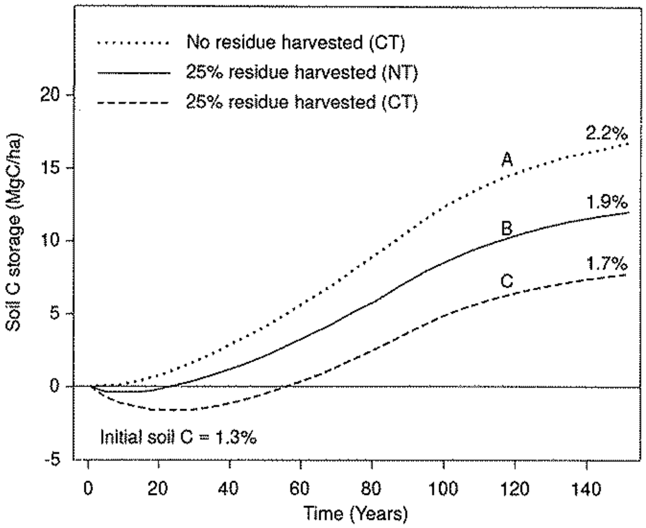

Figure 1 Soil C changes for increased cereal yields and residue harvest for bioenergy[a]

[a] The simulation in case A corresponds to a hypothetical crop system transition from an equilibrium soil C content of 1.3% to a soil C content of 2.2% as shown. For the soils in Lucas *et al* (1977) and conventional tillage (CT), this corresponds to a yield increase from about 3 to 9 Mg per hectare per year. Cases B and C simulate soil C changes for 25% residue removal using no-tillage technology (NT), which significantly reduces erosion, and CT.

Fossil fuel energy inputs for high yield crop production

In general, crop productivity will increase when farm inputs are increased from low to high (USDA, 1995; Dudal *et al*, 1983). Increased crop yields will depend on a combination

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[3] For a total biomass of about 22 Mg per hectare per year (Revelle, 1985) this yield would correspond to a net photosynthetic efficiency of about 1% (using an average insolation during a 5 month growing season in temperate regions (41º N latitude) of about 245 W/m^2, and an energy content of 15 GJ per Mg of biomass). By comparison, maximum net photosynthetic efficiencies for field production of C_3 crops (such as wheat and rice) at present atmospheric CO_2 levels is estimated to be about 3%, while that for C_4 crops (such as maize, millet, sorghum and sugarcane), which do not photo-respire and saturate at higher light levels, is perhaps twice this amount (Hall *et al*, 1993).

[4] According to USDA data total cereal yields worldwide increased by about 2.5% annually between 1980 and 1990 (Mitchell and Ingco, 1993, Table 7.3). Five-year averages based on FAO data show an annual increase of about 1.6% between 1981–86 and 1987–92 (Dyson, 1994, Table 2). FAO data also shows a 2% annual increase between 1978–80 and 1988–90 (World Resources Institute, 1992, Table 18.1).

[5] For the purposes here it is simply assumed that eroded soil C decomposes similarly to the soil in the plough layer. It should be emphasized that eroded soil is not necessarily lost to future crop production, but may be deposited in other field areas (Crosson, 1995, personal communication).

[6] This value is a rough estimate of average soil C release from the entire profile of newly cultivated soil, which may be inferred from Harrison *et al* (1993). An original soil C pool of 240 Pg C for 1400 million hectares of cultivated soil gives an average value of 170 Mg C per hectare. A 25% total C loss gives the estimated 40 Mg C per hectare.

of factors, however, including higher yielding seed varieties, somewhat more fertilizer use in developing countries, improved insect and weed control, as well as development of the necessary infrastructure and farm policies to support farming (Avery, 1991). While N fertilizer will play an important role in increasing yields in developing regions where N supply is a limiting factor (Larson, 1993; Loomis and Connor, 1992), any consequent environmental effects of modest chemical fertilizer increases (such as those necessary to increase crop yields in sub-Saharan Africa (Larson, 1993)), should be weighted against the damage that can occur from inappropriate cropland expansion when no fertilizer is used (Mellor and Reily, 1989). For industrialized regions, reductions in farm chemical inputs because of environmental effects (as in some parts of the USA and the European Community) should not adversely affect future yield increases, as the farm chemical inputs which would be eliminated are generally excessive and wasteful (Avery, 1994, personal communication). Improved management and advances in precision farming, which would ensure greater efficiencies in herbicide application and N uptake by plants, for instance, should increase crop system efficiency as well as yields in these regions.

Fossil fuel energy inputs associated with high crop productivity releases CO_2 to the atmosphere. For a given food production, this C release depends on the corresponding energy efficiency ratio (I/O ≡ commercial energy inputs for grain production: energy in grain output, as percent). For the purposes here, commercial energy is assumed equivalent to fossil fuel energy, ignoring hydro and nuclear power generation. The average I/O for cereal production in industrialized regions was approximately 30% in 1982, while that for North America was approximately 20% (Stout, 1990). High energy efficiencies will emit less C per unit of food output. For example, maize production in Indiana, USA, achieved an I/O of 16% in 1975, for a yield of about 9 Mg per hectare per year (Loomis and Connor, 1992), comparable to the final yield simulated in Figure 1, line A. For such yields this relatively low I/O would correspond to a release of about 0.4 Mg C per hectare per year (as petroleum, see below). As the annual soil C gains associated with Figure 1, line A average about 0.2 Mg C per hectare per year (including eroded soil C), it is already apparent how the C balance will shift when fossil fuel inputs are accounted for.

This effect is shown in Figure 2, line A, where a constant I/O of 20% is used for illustration. This I/O may be interpreted as an average value for the entire transition, and presumes future increases in crop system energy efficiencies worldwide. For this scenario the soil C gains due to increased cereal yields are negated after about 40 years due to fossil fuel inputs, and the net atmospheric C release in this case is some 30 Mg per hectare after 150 years. Higher I/Os would naturally release more C. However, where increased crop yields have prevented additional land cultivation, atmospheric CO_2 release has been prevented. This effect must be added to those considered thus far.

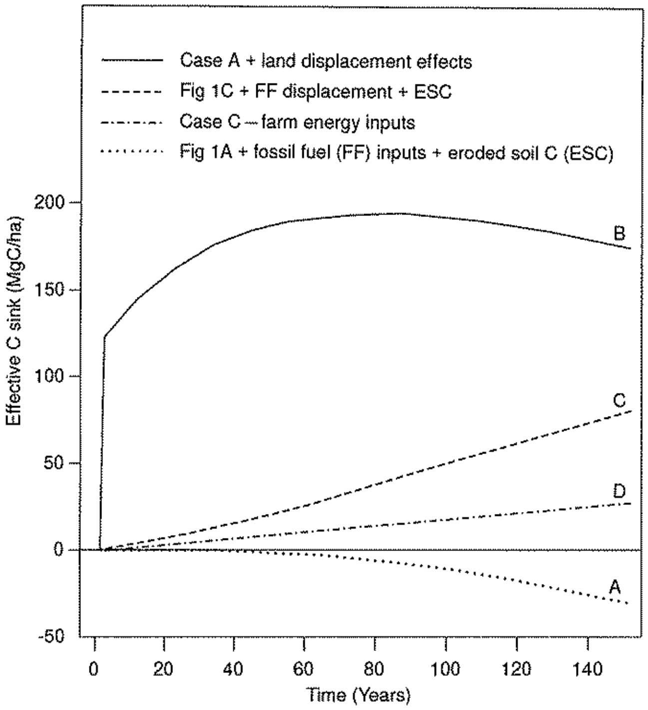

Figure 2 Net C balances for increased cereal yield scenarios[a]

[a]Case A: Adds to Line A in Figure 1 the atmospheric C release due to primary fossil fuel energy inputs (as petroleum), assuming a constant I/O of 20%, and the C sink due to eroded soil which is not included in Figure 1. Case B: Adds to case A the atmospheric C release prevented when one hectare of high yield farming prevents the additional cultivation of two hectares of low yield farming. Case C: Adds to the soil C increase of Figure 1, line C, the resultant effective C sink upon using the crop residue removed in that figure for bioenergy substituted for coal (provided farm energy demand is met or exceeded, ie up to an I/O of about 20%), and the corresponding eroded soil C. Case D: Subtracts from case C the energy needs for crop production, assuming an I/O of 15%. The effective C sink is that due to fossil fuel substitution outside the crop system only. The soil C difference between lines A and C in Figure 1 are accounted for as an effective atmospheric C source in cases C and D.

Land requirements for low yield farming

An estimated 110 Pg C released to the atmosphere as CO_2 has already been avoided due to land cultivation prevented because of increased cereal yields between 1950 and 1990, as show in Table 1. This effective substitution of yield for land applies across borders as well through food exports. Average cereal yields in Asia and Latin America in 1990 were about twice as high as in most African countries (1.2 Mg per hectare per year), while those for industrialized countries were about 3.5 times as high (Mitchell and Ingco, 1993).

Interpreting the avoided atmospheric CO_2 release in Table 1 as an effective C sink allows a comparison of the competing C debts of high and low yield farming, ie fossil fuel energy inputs versus extra land requirements. The general net C balance between these two effects is readily apparent. The estimated atmospheric CO_2 release avoided in Table 1 averages about 2.8 Pg C per year. By comparison,

Table 1 Atmospheric CO_2 release avoided due to increased yields between 1950 and 1990[a]

Row	Quantity	Value
1	Total world cereal production in 1990	1955 x 10^6 Mg
2	Cropland in cereals in 1990	708 million hectares
3	Average world cereal yield in 1990	2.76 Mg per hectare per year
4	Average world cereal yield in 1950	1.14 Mg per hectare per year
5	Area required for 1990 prouction at 1950 yield	1718 million hectares
6	Cultivated area difference (Row 5–Row 2)	1010 million hectares
7	Atmospheric C release avoided[b]	110 Pg C

[a] Rows 1–6 are adapted from Mitchell and Ingco (1993).
[b] Row 7 is based on the estimate that cultivation of the present 1450 million hectares of cropland has released 160 Pg C to the atmosphere due to changes in land vegetation and soil C.

average worldwide commercial energy inputs for cereal production in 1982 (8 GJ per hectare (Stout, 1990)) would have released approximately 0.1 Pg C as petroleum when applied to land presently in cereals, over an order of magnitude difference.

The ecosystem C release upon cultivation is simulated here as follows. Estimating that present cropland (about 1450 million hectares) has released 160 Pg C to the atmosphere, each cultivated hectare may be assigned an average C debt of approximately 100 Mg C. As an estimated 40 Mg C per hectare is released from the soil upon cultivation (gradually, with equilibrium achieved here after about 150 years), the remaining 60 Mg C per hectare is released from the clearing of vegetation, which may be assumed to be released more or less immediately to the atmosphere (as in the burning of forest or woodland). By undergoing the threefold increase in crop yields simulated here, each hectare prevents the cultivation of two additional hectares. This applies to an increase from 1 Mg of grain per hectare per year to 3 Mg per hectare per year just as well as for the transition here – the terms high and low yield are thus used comparatively.

Adding these considerations to the results of Figure 2, line A, results in the net C balance of Figure 2, line B (commercial energy inputs for low yield crop systems – about 1 GJ per hectare for the entire African continent in 1982 (Stout, 1990) – were neglected). For this scenario, a dramatic net effective C sink of about 190 Mg C per hectare is seen to result after 100 years, and 170 Mg C per hectare after 150 years, when each hectare of high yield farming prevents the additional cultivation of two hectares of low yield farming. Higher I/Os would decrease these effective C sinks. For comparison, an I/O of 35% would result in a C sink of about 170 Mg C per hectare after 100 years and 130 Mg C per hectare after 150 years, while the corresponding values for an I/O of 50% are 140 Mg C per hectare and 80 Mg C per hectare. Even for these higher I/Os the time horizon before which C released from fossil fuel inputs outweighs the C release prevented by avoiding additional land cultivation is advanced over 150 years, the time frame considered here.

Ultimately, these effective C sinks diminish with time because of fossil fuel energy inputs. Over the time horizon of hundreds of years, however, renewable energy sources must be considered. Crop production energy needs provided by any renewable energy source would cancel the fossil fuel C release of Figure 2, lines A and B. To close the discussion here, renewable energy derivable from high yield crop systems themselves are considered.

Crop residue utilization for bioenergy and fossil fuel displacement.

In general, high yield farming systems are sustainable as long as there are the necessary energy and inputs.[7] Industrialized societies use 10–15% of total commercial energy on food production, and 3–5% on the farming component. Most opportunities to adjust to the energy supply, then, lie outside the entire food production system (Loomis and Connor, 1992). Within the farm system, improved energy efficiency and advances in precision farming need to be considered. It also seems reasonable to suppose that farmers will employ the energy sources used by the rest of society, and need not be responsible for supplying their own energy needs. However, if the time horizon for fossil fuel depletion is of concern, then in principle a long-term consideration is the self-containment of the energy needs for crop production using advanced biomass conversion techniques and crop residues (Revelle, 1976).

The average primary commercial energy input for cereal production in industrialized regions in 1982 corresponded to about 13 GJ per hectare (Stout, 1990). This energy content is generally provided in one tonne of grain residue (10–15 GJ per Mg). Whether or not fossil fuel energy inputs for high yield crop production could be displaced by bioenergy derived from crop residues depends on the energy ratio (I/O) achieved, and the amount of residue that may be harvested without adversely affecting the entire farm system. This amount will depend on such factors as soil fertility, erosion control, and/or animal feed considerations (Hall *et al*, 1993).

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[7] In this sense, high yield organic farming, which generally requires large additions of organic material collected from outside the farm system, is no more autonomous than modern high-yield systems which require external energy inputs (Loomis and Connor, 1992). For instance, producing the 75 million tonnes of N used worldwide in 1991–92 as chemical N fertilizer (Food and Agriculture Organization, 1993) would require the manure N of some 4 billion head of cattle, neglecting manure N losses during storage and handling (see note 1).

Less C will be returned to the soil when residues are removed for bioenergy, although various methods of conservation tillage could mitigate soil C loss by reducing erosion. This effect is simulated in Figure 1, lines B and C, which compare no-tillage technology (NT) with conventional tillage (CT) for the transition of Figure 1, line A, but now with 25% residue harvest for bioenergy. For these figures, 25% residue removal results in soil C loss until increased yields and consequent residue production are sufficient to compensate for the removed residue. It takes about 20 years for this to occur for the NT case, and almost three times as long for CT. For this scenario the final soil C increase for the NT simulation is about 50% greater than that for CT because of significantly reduced eroded soil C losses. Many studies indicate that no-tillage agriculture reduces soil erosion to almost zero (Philips *et al*, 1980). It should be emphasized that doubling yields on good cropland effectively cuts erosion rates per tonne of food output by at least half when preventing cultivation of inferior cropland more susceptible to erosion (Avery, 1994, personal communication).

In general, the utilization of cereal residues for bioenergy is more viable for high yields as they produce more residue,[8] thus maintaining a higher soil C content and general soil fertility, than low yields. However, using residues for fuel which are not presently returned to the soil – because of burning for pest and disease control, removal for fodder, building material or thatching, inefficient fuel use and other non-fertilizer uses – would not further affect the soil, but may require trade offs in other areas (Barnard, 1990). (This is the case for sugarcane residues, discussed below.) In practice, only a detailed site specific analysis can tell what the impacts of a certain residue removal will be (Pasztor and Kristoferson, 1990). For the US corn belt, an estimated 35% of crop residues may be removed after erosion considerations with conventional tillage, and upwards of 50% using reduced tillage methods (Hall *et al*, 1993). In this particular case the amount of residue which may be harvested exceeds that required for the I/Os given above (ie 20–30% for industrialized regions, approximating the energy in the residues to be comparable to that in the grain, and a harvest index of 50%).

Bioenergy derived from crop residues in excess of crop production needs may be used to displace fossil fuels outside the crop production system. This C accounting is subject to two interpretations. The first is that all the bioenergy derived from crop residues acts as an effective C sink upon fossil fuel displacement, including the fossil fuel no longer required for crop production. Alternatively, as the C debt arises from cultivation for crop production specifically, only bioenergy derived in excess of crop production needs mitigates the C debt. These considerations are shown in Figure 2, lines C and D, respectively. For these lines it is assumed that 25% of cereal residues may be practicably harvested for bioenergy (Johansson *et al*, 1993), which would satisfy farm energy demand for an I/O up to about 20%.[9] The soil C changes for Figure 2, lines C and D are those of Figure 1, line C plus the associated eroded soil C. The difference between soil C levels for lines A and C in Figure 1 are accounted for as an effective C source in lines C and D in Figure 2.

As the world's remaining geological coal resources are vast – much greater than the remaining oil and natural gas supplies – containing perhaps over 6500 Pg C (Goldemberg *et al*, 1988), the crop residue bioenergy is assumed to displace coal (including liquid synfuel production), although it may also be considered to displace possible future CO_2 emissions from oil shale and tar sand as well. At equal energy conversion efficiencies (as through advanced bioenergy conversion technologies), each GJ of biomass substituted for fossil fuel would reduce the C released to the atmosphere as CO_2 by the C content of one GJ of fossil fuel displaced – 0.014 Mg C for natural gas, 0.019–0.020 Mg C for petroleum, and 0.023–0.025 Mg C for coal (Hall *et al*, 1991).

In line C, Figure 2, a long-term net C sink of about 80 Mg C per hectare, or an average of about 0.5 Mg C per hectare per year results upon 25% residue harvest for bioenergy (provided farm energy demand is met or exceeded). This effective C sink continues as long as bioenergy is substituted for fossil fuel – compared to the soil simulations here which reach C equilibrium – and potentially applies to all land in cereals. In line D, Figure 2, which uses an I/O of 15% for illustration, crop residue bioenergy in excess of crop production needs displaces about 0.20 Mg C per hectare per year when substituting for coal outside the crop production system.

Naturally, crop systems primarily exist to produce food, not to counteract their atmospheric C debt. Crop residue utilization for bioenergy may be viewed as a secondary consideration, while the C debt alleviation tertiary. The examples here do suggest that effective C sinks may be achieved by energy efficient high yield crop systems.

Sugarcane residues and energy crops on 'surplus' cropland for bioenergy

Two other factors relevant to the discussion here concern sugarcane residue utilization for bioenergy, and potential surplus cropland arising from yield increases which may be used for energy crops. In each case the effective C sinks per hectare are over an order of magnitude greater than those considered thus far – but involve much less land than for cereal production – so that soil C changes may be neglected.

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[8] In the transition of line C, Figure 1, harvest index increases from roughly 40% to 50%, and residue production by about 55% (after Holtman *et al*, 1979). Rasmussen and Collins (1991) note that wheat straw production has increased in the Pacific North-west, USA, despite higher harvest indices.

[9] The exact supply/demand energy balance depends on the fraction of residue harvested, crop system I/O, harvest index, and the different energy contents of cereal grains and residue, here taken as 15 GJ per Mg and 12 GJ per Mg respectively.

An additional consideration not discussed here is agroforestry on cultivated land, which involves the intercropping of trees with field crops, which could store C, and/or be used as part of a bioenergy programme (Houghton *et al*, 1993; Goldemberg *et al*, 1988).

In many sugarcane producing regions the tops and leaves of the sugarcane plant (or barbojo) are burned in the field to facilitate harvesting the cane stalks. Instead of burning, a portion of this residue may be returned to the field, and the remainder utilized for bioenergy (Williams and Larson, 1993). Fresh cane yields in developing regions range from 50–90 Mg per hectare annually (Goldemberg *et al*, 1988). Harvesting two-thirds of the barbojo and all the bagasse (the crushed cane) results in an energy equivalent of about 6 GJ per Mg of fresh cane (Johansson *et al*, 1993), so that the effective C sink as a coal substitute would be on the order of 10 Mg C per hectare per year. Fossil fuel inputs for cane production are ignored here.[10]

Increased crop yields may result in surplus cropland in industrialized countries – cropland no longer needed for domestic food production or food exports – which may potentially be used for bioenergy plantations (Hall *et al*, 1993; Revelle, 1985), thus displacing C released from fossil fuels. The CO_2 released due to the combustion of energy crops would be equal to the amount absorbed from the atmosphere in the previous growing season. One projection of this potential by 2025–2050 (Johansson *et al*, 1993) corresponds to an effective C sink of about 6 Mg C per hectare per year after subtracting estimated input energy requirements.[11]

Soil C sequestering upon conversion of food crops to energy crops is neglected here, but, for comparison, abandoned cropland which subsequently returns to natural forest (in the south-eastern USA) sequesters perhaps 0.34–0.79 Mg C per hectare per year on average until soil C equilibrium is reached (Huntington, 1995). Total ecosystem C sequestration (both in vegetation and soil) may total between 1.81–2.26 Mg C per hectare per year during a regenerative period of some 70 years. In contrast, total forest ecosystem C sequestering rates for a US tree planting system may average about 5 Mg C per hectare per year (Hall *et al*, 1991). In either case, these rates would apply only until forest maturity, while the value of 6 Mg C per hectare per year for energy crops continues year after year as a fossil fuel substitute. Additionally, energy plantations harvested rotationally will have some mean standing volume of biomass associated with them. For instance, forests managed for maximum sustained yield of biomass may achieve a mean lifetime carbon storage equivalent to about one-third that of forest maturity (Cooper, 1984).

Conclusions and discussion

After accounting for soil C changes due to increased crop productivity and the C released to the atmosphere via fossil fuel energy inputs for crop production, the assessment here indicates that increased crop productivity will alleviate CO_2 release to the atmosphere primarily by preventing additional land cultivation. Each hectare undergoing a simulated threefold crop yield increase here prevents an estimated net release of 150–200 Mg C to the atmosphere as CO_2 after the order of 100 years. From this perspective, studies which focus on crop yield increases and consequent soil C sequestering on cropland (EPA, 1994) are not generally rendered ineffective because of requisite fossil fuel inputs, as long as increased yields are presumed to prevent further land cultivation. Also, the assessment here effectively couples economics and practical aspects of crop production at the farm level (increased yields) to atmospheric CO_2 levels. This is pertinent, as attempts to increase the C content of cultivated soils may fail at the farm level if the emphasis is on increasing soil C *per se* (Holtman *et al*, 1979).

From a global perspective, the present C debt of approximately 160 Pg C due to land cultivation would have been perhaps 260 Pg C or more were it not for the higher cereal yields brought about by increasing fossil fuel inputs since 1950. Based on this result, farm policies should not generally discourage necessary fossil fuel inputs required for yield increases because of atmospheric CO_2 considerations. This conclusion is especially pertinent to developing regions. For Africa and Latin America, the ratio between potential and present arable land is between 4 and 5 (Crosson and Anderson, 1992; Hall *et al*, 1993). Much of the increase in cereal cropland by 2010 is projected to be in sub-Saharan Africa, where yields are yet low (Mitchell and Ingco, 1993).

Implicit in these results is consideration of the long-term energy inputs needed to sustain high yields, which was addressed here using the specific example of the self-containment of energy needs for crop production through crop residues. A major point inferred from line C, Figure 2 is that effective C sequestering may occur via cropland while simultaneously fulfilling the primary purpose of food production – a result which potentially applies to large areas of land – which may be contrasted with C sinks estimated upon abandonment of cropland and return to natural vegetation (Huntington, 1995; Schlesinger, 1990). Additionally, the effective C sink of 6 Mg per hectare per year for cropland converted to energy crops because of yield increases corresponds to about 240 GJ per hectare per year, which would provide renewable primary energy for roughly 20 hectares of cereal land at 13 GJ per hectare per year (the average 1982 commercial energy input for cereal production in industrialized regions). This implies that the average energy needs of increased crop productivity would be generally supplied if productivity increases are such as to allow about 5% of cropland to be freed and converted to energy crops (neglecting crop residue bioenergy utilization).

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[10] Average fossil fuel inputs for Brazilian cane production are perhaps 222 MJ per Mg fresh cane per year (Goldemberg *et al*, 1993, Table 1), which is about 4% of the estimated barbojo/bagasse energy harvest (6 GJ per Mg fresh cane per year).

[11] Net energy yields are estimated to be in the range of 10–15 times the energy inputs of these crops (Hall *et al*, 1993).

Globally, the effective C sinks per hectare estimated here for energy crops and crop residues may be applied to representative land areas to obtain a figure for potential atmospheric CO_2 mitigation. For industrialized regions an estimated 88 million hectares of cropland may be convertible to energy crops by 2025–2050 (Johansson *et al*, 1993). At 6 Mg C per hectare per year this value would result in an effective C sink of approximately 0.5 Pg C per year. Applying the potential C sinks for sugarcane (10 Mg C per hectare per year) and cereal residues (0.5 Mg C per hectare per year, the net C sink of line C in Figure 2) to the land presently devoted to these crops (17 million hectares and 700 million hectares in 1990 (Mitchell and Ingco, 1993)) results in effective C sinks of about 0.15 Pg C per year and 0.35 Pg C per year, respectively. The net result corresponds to a future C sink on the order of 1.0 Pg C per year, which is comparable to the C released due to present land clearance for crop production, and is roughly 15–20% of present fossil fuel C emissions.

A global figure for the potential C sink due to avoided land cultivation requires further analysis than may be considered here. In brief, the future dynamics of atmospheric CO_2 release due to land cultivation depends on long-term trends in crop yields, future global population and dietary habits. An adequate diet may be provided for a global population of approximately 10 billion people, using more, the same, or less cultivated land than today depending on long-term advances in high-yield crop systems (Waggoner, 1994).[12] Less total land would be ultimately cultivated if high-yield crop systems were adopted concurrently with population growth, as in sub-Sahara Africa. Alternatively, more total land could be initially cultivated under low yielding situations, with land conversion diminishing, and cropland possibly being gradually removed from production, as yields increase. In either scenario, the annual CO_2 release to the atmosphere as a result of newly cultivated land would eventually decrease, but the latter case would release more CO_2 to the atmosphere. Besides mitigating atmospheric CO_2 release, the former case would alleviate land conversion pressures, so that natural ecosystems may remain as they are.

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[12] See also, for instance, Smil (1994) and Revelle (1985). For a general discussion of human carrying capacity see Cohen (1995).

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