



Ethanol production from crop residues and soil organic carbon

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Abstract

In decision making about the use of residues from annual crops for ethanol production, alternative applications of these residues should be considered. Especially important is the use of such residues for stabilizing and increasing levels of soil organic carbon. Such alternative use leads to a limited scope for residue removal from the field. Scope for removal of residues from annual crops can however, *ceteris paribus*, be increased when such crops generate relatively large amounts of biomass. Also selecting residues that contain relatively high levels of available cellulose and hemicellulose for removal or returning suitable 'waste' from processing crop residues that is rich in refractory compounds such as lignin to the field may increase scope for removal of crop residues for ethanol production.

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1. Introduction

In industrialized countries crop residues, such as straw and stover, are increasingly under discussion regarding their potential contribution to energy supply. A much increased use of such residues to produce ethanol in Canada was advocated by Champagne (2007). Ethanol can be produced from cellulose and hemicellulose that are present in such residues. For instance, by dry weight, cellulose and hemicellulose may be 70–86% of wheat straw (Kabel et al., 2007). Cellulose and hemicellulose can be converted into glucose and xylose, and these sugars in turn can be converted into ethanol.

One of the benefits of producing ethanol from crop residues, according to Champagne (2007), is the reduc-

tion of the potential for air, water and soil contamination associated with the land application of organic residuals. In the USA (Fleming et al., 2006; Greer, 2006; Sticklen, 2006) and in the European Union (Swanston and Newton, 2005; European Commission, 2006), the use of agricultural residues for the production of ethanol is also advocated. There are in the European Union furthermore several projects for the generation of electricity from crop residues (Swanston and Newton, 2005). Energetic applications of crop residues in energy supply are argued to have advantages for security of supply and mitigating climate change (Swanston and Newton, 2005; European Commission, 2006; Fleming et al., 2006; Greer, 2006; Sticklen, 2006).

In promoting the use of crop residues for energy supply, one should be aware that there is competition with other uses of agricultural residues. First, use of agricultural residues for ethanol production competes with application to soil. This is not the only application of

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crop residues (see Section 3) but it is a very important one, as will be explained in Section 2.

2. Crop residues and soil organic carbon

Crop residues applied to soil are important for soil organic carbon. Adequate levels of soil organic carbon in turn are important for soil structure, limiting erosion, the provision of nutrients, counterbalancing acidification and water holding capacity of soils. Soil organic carbon is an important determinant of soil fertility and within limits crop productivity is positively related to the soil organic matter content (Syers et al., 1997; Recosky and Forcella, 1998; Wilhelm et al., 2004; Lal, 2005; Tarkalson et al., 2006).

Levels of soil organic carbon that are under long term cultivation with annual crops tend to be lower than under native vegetation. On average, soil carbon levels under arable soils with a long history of cultivation tend to be ~18% lower under temperate dry conditions, ~30% lower under temperate moist or tropical dry conditions, and ~42% lower in tropical moist climates if compared with soils under native vegetation (Ogle et al., 2005). These reductions of carbon levels in soils have contributed to increased levels of greenhouse gases in the atmosphere.

Current agricultural practice often leads to further losses of soil carbon from arable soils. In Europe, carbon loss from arable soils is on average $0.84 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ (Vleeshouwers and Verhagen, 2002). The average stock of soil carbon in non-organic soils in Europe is about 53 Mg ha^{-1} for 0–30 cm depth (Freibauer et al., 2004). Net losses of soil carbon from arable soils are also found elsewhere. In Eastern Canada, arable land on average loses $0.07 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ to the atmosphere (Gregorich et al., 2005). In China, the loss is on average $0.81 \text{ Mg C ha}^{-1} \text{ year}^{-1}$, with the average soil organic carbon stock up to a depth of 30 cm estimated at about 41 Mg C ha^{-1} (Tang et al., 2006). The loss of soil organic carbon in China parallels the yearly removal of ~300 million tons of straw (Wright, 2006). From Nepal losses of soil carbon have been noted in a variety of cropping systems, with for instance losses in maize/millet cropping systems ranging between 0.11 and $0.23 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ (Matthews and Pilbeam, 2005; Shrestha et al., 2006). In a set of 14 sampled annually cropped Brazilian soils losses of soil organic carbon were on average $0.15 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Zinn et al., 2005), whereas for soybean based crop rotation in the Brazilian Cerrado region losses were reported to be between 0.5 and $1.5 \text{ Mg C year}^{-1} \text{ ha}^{-1}$, with the original amount of soil organic carbon up to a depth of 30 cm estimated

to be somewhat over 90 Mg C (Jantalia et al., in press). In Africa, losses of carbon from soil are expected as little or no agricultural residues are returned to soils in many cropping systems (Syers et al., 1997). In case of semi-arid Sudan, a yearly loss from cropland during the 20th century of on average $0.29 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ has been found (Ardo and Olsson, 2003). Over shorter recent time spans C losses were found in the southern Ethiopian highlands of $\sim 0.85\text{--}1.75 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ (Lemenih and Itanna, 2004) and in Western Burkina Faso of $\sim 0.31 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ (Ouattara et al., 2007). From peaty arable soils losses may be especially high when there is deep drainage and intensive mechanical soil disturbance (Freibauer et al., 2004). Net carbon losses varying from 6 Mg in northern Norway up to $15 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ in the tropics have been reported (Gronlund et al., 2006; Reijnders and Huijbregts, 2007, in press).

It has emerged that low crop yields, low additions of crop residues, low additions of manure, mechanical tillage, high soil carbon contents and high temperatures enhance the loss of carbon from arable soils (Vleeshouwers and Verhagen, 2002; Freibauer et al., 2004; Lal and Pimentel, 2007). It has also been found that depending on the nature of soil, climate, crops and crop rotation, crop residues management and tillage system, a partial (20–40%) removal of crop residues from the field reduces the pool of soil organic carbon, can exacerbate soil erosion hazard and negatively impact future yields of crops (Wilhelm et al., 2004; Lal, 2005).

Soils to which crop residues are returned tend to store more soil organic carbon (and nitrogen) than plots where residues are taken away (Dolan et al., 2006). Vleeshouwers and Verhagen (2002) estimate that adding to arable soils the cereal straw that is currently taken away may on average increase European soil carbon levels by $0.15 \text{ Mg ha}^{-1} \text{ year}^{-1}$. Other studies have shown that full return of crop residues to arable soils may increase soil carbon levels by up to $0.7 \text{ Mg C h}^{-1} \text{ year}^{-1}$ (Webb et al., 2003; Smith, 2004; Freibauer et al., 2004; Rees et al., 2005).

Moreover it is probable that future warming of climate will, *ceteris paribus*, decrease soil carbon stocks. In the European context, Vleeshouwers and Verhagen (2002) estimated that an increase in average temperature of 1°C may, *ceteris paribus*, lead to an average net loss of soil organic carbon of about $0.04 \text{ Mg ha}^{-1} \text{ year}^{-1}$. This has been argued to necessitate increased inputs of agricultural residues to maintain steady state soil organic carbon levels (Jenkinson et al., 1990; Grace et al., 2006).

Thus, increased use of agricultural residues has been advocated in order to maintain or restore proper levels of

soil organic carbon and ensure agroecosystem sustainability (Lal, 1997; Duiker and Lal, 1999; Quedraogo et al., 2006; Chivenge et al., 2007). And Lal and Pimentel (2007) have argued in favour of a much increased application of crop residues to soils to boost food production.

Partly in view of the phenomenon that in many cases levels of organic carbon in arable soils are now well below their original levels under native vegetation, it has furthermore been proposed to increase the application of crop residues to soil to increase levels of refractory soil organic carbon, thus mitigating the increase in atmospheric CO₂ concentrations (Lal, 1997, 2001). Lignocellulose is more useful in this respect than more easily degradable carbon compounds such as for instance sugars or starches (Sartori et al., 2006). Available evidence is limited but suggests 14–24% of carbon contained in residues of crops can be converted to refractory soil organic carbon (Lal, 1997; Follett et al., 2005; Razafimbelo et al., 2005).

Against this background it may be argued that there is limited scope for residue removal from the field. Crops that generate relatively large amounts of below- and aboveground biomass, such as sugarcane and corn would, *ceteris paribus*, seem to offer more scope for residue removal, than crops that generate relatively low amounts thereof, such as oil seed crops and a variety of cereal crops (e.g. soybean, rapeseed, sunflower, rice, barley, oat, sorghum and wheat) (Wright et al., 2001; Wilhelm et al., 2004). This would seem applicable to all energetic uses of crop residues. In Section 3, the possibility will be considered that the scope of residue removal for ethanol production can be widened somewhat by selecting residues on the basis of their (hemi)cellulose content. Also, as will be pointed out in Section 4, it may be possible to return to the field ‘wastes’ rich in relatively refractory compounds such as lignin originating in crop residue processing after removal from the field.

3. The application of crop residues in ethanol production

To the extent that crop residues are removed from the field, a case can be made for resource cascading. In resource cascading applications in which the resource is used a higher level of quality are preferred over lower quality applications (Reijnders, 2000). For an agricultural residue such as straw for instance, one should first consider application in building materials such as strawboard (Sekhon et al., 2005) and straw bales for load bearing walls (Swanston and Newton, 2005), with lower quality applications such as use as a fuel being more appropriate for wastes from a strawboard manufactur-

ing facility or building products after disposal. Measures supporting the use of crop residues for energetic purposes should furthermore be designed in such a way that they have no negative impact on such high quality applications.

Regarding crop residues that have proper application in energy supply, efficient use in the generation of useful energy is a matter for consideration. Studies done so far suggest that, when transport distances are similar, the most efficient energetic use of lignocellulosic materials such as agricultural residues is the application for the generation of electricity. Applied in this way, crop residues are most efficient in replacing fossil fuels, much more so than when crop residues are converted to ethanol for use in cars (Wright and Hughes, 1993; Patzek and Pimentel, 2005; Reijnders and Huijbregts, 2007). However, when road transport distances to power generating plants are very large, it may be that energetic uses that require a much lower input of transport fuel become energetically more attractive (cf. Bernesson et al., 2006).

To the extent that the production of ethanol is considered to be the proper application of crop residues, the constituents thereof contribute in different ways to ethanol production and soil organic carbon. Crop residues contain cellulose in a matrix of lignin and hemicellulose. Lignin does not contribute to ethanol generation, but cellulose and hemicellulose do. Lignin is, together with compounds such as cutins, suberins and tannins, largely responsible for humus formation (Kirk, 1971; Rasse et al., 2005) and is a major contributor to refractory soil organic carbon (Loveland and Webb, 2003; Chapman and McCartney, 2005). There is evidence that in arable soils among the components of lignocellulose (lignin, hemicellulose and cellulose), lignin is by far the most refractory component (Melillo et al., 1989; Spaccini et al., 2000; Quénéa et al., 2006).

Thus, lignin is more suitable for carbon sequestration in soils than (hemi)cellulose. Still the presence of carbon compounds which are more easily degraded than lignin (with a half-life <1 year) in the soil is also important for soil fertility and stability (Spaccini et al., 2000; Loveland and Webb, 2003). The carbohydrates hemicellulose and cellulose in harvest residue belong to this category (Spaccini et al., 2000). On the other hand, using residues that have relatively high levels of available hemicellulose and cellulose in ethanol production is conducive to the efficiency thereof.

Against this background there is a case for selecting crop residues for the production of ethanol that have relatively high concentrations of hemicellulose and cellulose susceptible to conversion into ethanol. In the case

of corn stover, this fraction consists of cobs, leaves and husks (Crofccheck and Montross, 2004). The crop residue fraction that is relatively rich in lignin may be expected to be a relatively efficient contributor to refractory carbon in soils, but also contains a substantial amount of carbohydrates that are more easily degradable and contribute to soil fertility and stability.

Thus, it may be that the scope for residue removal may be widened by selecting residues on the basis of their relative suitability for ethanol production and for the formation of refractory soil carbon, respectively. Another option is to consider return processing 'waste' of crop residues that are relatively rich in lignin.

4. Application of processing residue

In generating ethanol from crop residues, a residue emerges that is rich in lignin and also contains unreacted cellulose and hemicellulose (Mosier et al., 2005). It would seem worthwhile to consider applying this residue to soils. Such an application would serve the presence of refractory carbon in soil, while also contributing to the presence of more rapidly degradable carbohydrates.

In doing so, one should limit or prevent undesirable side effects of adding this processing residue. A matter to consider in this respect is the accumulation potential of the residue for phenolic carbon compounds. Such accumulation may occur under anaerobic conditions and this may have a negative effect on soil fertility (Olk et al., 2006). Ionic composition and pH of the processing residue are subject to limitation, when use of the residue is to be sustainable (Mahmoudkhani et al., 2007). Also one should be aware that lignin binds heavy metals such as cadmium much better than cellulose does (Basso et al., 2004). Thus, provisions should be in place to limit the flow of heavy metals to soils, when the fraction that is rich in lignin is applied. If the processing residue has acceptable quality, it may well be that the amount of crop residue that can be removed from the field without a negative impact on soil characteristics can be increased.

The quantitative and qualitative aspects of applying processing residues to arable soils would seem to merit further research.

5. Conclusion

In decision making about the use of crop residues for ethanol production, alternative application of these residues should be considered. This can be argued to lead to limited scope for residue removal from the field. Scope

for removal can however, *ceteris paribus*, be increased when crops generate relatively large amount of biomass and when suitable lignin-rich residues can be returned to the field.

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