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Review of the impact of crop residue management on soil organic carbon in Europe

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Introduction

Crop residues, including wheat straw and corn stover, are a feedstock for the production of cellulosic biofuel that could contribute to meeting advanced biofuel targets and decarbonization goals for the transport sector. Crop residues are an eligible pathway to compliance with the transport target and advanced biofuel subtarget laid out in the recast Renewable Energy Directive 2009/30/EC for the period 2021–2030 (REDII) (European Commission, 2016). Biofuel made from crop residues theoretically could contribute substantial volumes toward these goals (Searle & Malins, 2016b). However, the potential large-scale use of crop residues for biofuel raises concerns about environmental impacts. In particular, incentivizing the collection and use of crop residues that otherwise would have been retained in fields can affect soil carbon and soil quality. Policy measures regulating the use of crop residues could mitigate this risk.

This study reviews the evidence on the environmental impacts of crop residue harvest in the European Union (EU). Many studies on crop residue removal have focused on corn stover in the United States, however, the situation in the EU may be different. In the next section, we review existing EU legislation relevant to crop residues and discuss the effectiveness of these measures in preventing overharvesting of residues for biofuel. The following sections review literature on the role of crop residues in sustainable agricultural management, analyze available data on the impact of crop residue harvesting on soil organic carbon (SOC), and present guidelines for policy design to allow the use of crop residues for advanced biofuel production while ensuring sustainable management practices. In this study, we focus on sustainable management in the EU context, which may differ from the United States and other regions.

EU legislation on crop residues

The main legislation relevant to crop residues that applies at the EU level is the Common Agriculture Policy's (CAP) rules on cross-compliance according to Council Regulation 73/2009, Article 6 (1) (Council of the EU, 2009). CAP provides direct payments to farmers in the EU, and one of the requirements for receiving this aid is that farmers must comply with the Good Agriculture and Environment Conditions (GAEC) standards. Biofuels used for compliance with the current Renewable Energy Directive (RED) must also meet these standards, because the current RED that applies in the year 2020 requires cross-compliance with CAP (Council of the EU, 2009). In 2015, the Council Regulation 73/2009 was replaced with Council Regulation No 1307/2013, which includes revised environmental standards (Council of the EU, 2013). However, the current RED was not amended to reflect these changes.

CAP and GAEC do not address crop residues directly. Instead, GAEC sets minimum standards for the protection of broad environmental parameters, including wildlife habitat, water quality, and soil quality. The specific GAEC standards relating directly to soil quality include:

- Minimum soil cover and land management practices to prevent soil erosion
- Maintaining soil organic matter
- Maintaining soil structure

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Member states may choose how to implement these standards by setting more specific rules depending on the environmental context and agricultural practices of each country. Setting standards for crop residue management is one implementation option member states can use to meet the above GAEC standards. All member states prohibit the burning of stubble (the plant stalk below where the stalk is cut by harvesting equipment) as a measure to ensure soil organic matter maintenance. While all member states have some requirements on soil cover, in most countries' restrictions only apply during the winter or on agricultural land with significant slope. In most cases, member states allow leaving stubble, ploughing crop residues into the soil, planting winter crops or cover crops, or applying mulch as eligible methods of establishing soil cover. The retention of crop residues in the field is thus an option for GAEC compliance in some member states, but is not strictly required in any. No member state has rules on a minimum amount of residue that should be left in the field. Further details on implementation of relevant GAEC standards by member state are provided in Appendix A (European Commission, 2017).

Since 2015, farmers have been able to apply for greening payments that require specific measures to maintain permanent grassland (including a ban on ploughing and conversion of environmentally sensitive permanent grassland), crop diversification, and maintaining an "ecological focus area" of at least 5% of the arable area of the holding. However, the greening requirement is voluntary for farmers who apply for direct payments.

The CAP/GAEC requirements are general, and some assessments indicate that member states' implementing provisions fail to provide sufficient environmental protection (Hart, Baldock, & Buckwell, 2016). The European Court of Auditors (2016) reported that the information available from cross-compliance did not allow the European Commission to adequately assess the systems' effectiveness.

While cross-compliance with CAP/GAEC is one of the required sustainability criteria with which economic operators must comply in the current RED, economic operators do not have to show proof of compliance in order for biofuel produced from their crops to be eligible to contribute to the RED target. The RED implicitly assumes that farmers will comply with CAP/GAEC to receive direct payments, and therefore that checking compliance again in the context of RED is unnecessary. The majority of large scale crop producers receive these direct payments and thus should comply (Matthews, 2016). However, the European Court of Auditors (2015) noted a 27% noncompliance rate with cross-compliance. Member states are responsible for enforcing compliance through random checks.

Cross-compliance with CAP/GAEC is not included in the commission's RED II proposal. There is thus little assurance from existing requirements that harvesting crop residues for the production of advanced biofuel will not have negative impacts on soil carbon and soil quality. Even if CAP/GAEC compliance had been included in this proposal, it is not strictly required for all crop residue suppliers, is not adequately enforced, and is too general to ensure residue harvesting is sustainable (European Commission, 2006).

Environmental role of crop residues in the field

Crop residues provide a number of environmental services when left in the field, including contributing to the formation of SOC, preventing erosion, reducing evaporation from the soil surface, improving soil structure, supporting living organisms, contributing nutrients to the soil, and providing water filtration and retention capacity (Powlson, Glendining, Coleman, & Whitmore, 2011; Lal, 2014; SoCo Project Team , 2009; Nicholson et al., 2014; Johnston et al., 2009). Whether and how much crop residue can be harvested without significant negative impacts on these ecosystem services is a critical question in understanding the potential for producing sustainable, low-carbon biofuel from this type of feedstock. This section describes the environmental role of crop residues in the field, focusing on what is already understood on SOC impacts of residue retention versus removal. The following section presents a new quantitative assessment of SOC impacts of residue retention compared to removal.

SOC is important both for carbon storage to mitigate climate change and for contributing to healthy soils. SOC increases the water retention capacity of sandy soils (Rawls et al., 2003) and improves soil structure (Smith, 2016), and can thus theoretically improve crop yields (Nicholson et al., 2014). SOC is formed from biomass input to the soil from plant roots and dead above-ground biomass. It is distinct from soil inorganic carbon (SIC), which occurs in mineral forms, such as limestone, and does not have the same water retention properties nor support biota in the same way as SOC. In annual cropping systems, the main biomass inputs to the soil are decaying roots and crop residues. SOC is lost from soils through decomposition by microorganisms and erosion. The maintenance or change in SOC over time is the net balance between these inputs and outputs.

It is generally accepted that the retention of crop residues in the field contributes to greater SOC formation and higher SOC levels compared to complete residue removal (e.g., Powlson et al., 2011; Nicholson et al., 2014), but the degree of SOC benefit as well as the amount of residue necessary to provide SOC benefits have been unclear. In a review of long-term experiments from various regions around the world, Powlson et al. (2011) found that most studies reported greater SOC with residue application or retention compared to complete residue removal, but that this difference was statistically significant in a minority of studies.

The amount of residue needed to prevent additional SOC loss is not well understood or agreed upon. Earlier studies in the United States suggested 30% of corn stover could be sustainably removed (Andrews, 2006), while it has generally been believed in the EU that two-thirds of straw could be removed (Joint Research Center [JRC], 2009; Kretschmer, Allen, Kieve, & Smith, 2013). In a lifecycle assessment of biofuel produced from corn stover, Liska, Yang, Milner, Goddard, and Blanco-Canqui (2014) concluded that any residue removal would result in SOC loss compared to complete residue retention in fields, although this study did not specifically evaluate evidence of SOC impacts with varying levels of residue retention. Some studies have explicitly studied how varying amounts of residue affect SOC levels. In an experiment in Denmark, Thomsen and Christensen (2004) found a linear relationship between SOC and straw input with four varying levels of straw input ranging from zero to 12 t/ha/yr. Kenney (2011) also found increasing SOC with increasing stover input compared to complete stover removal in an experiment in Illinois, United States, but it is not clear from this study whether this relationship is linear. The results from Kenney are shown in Figure 1. Overall, there is a relative paucity of studies reporting on SOC impacts of varying amounts of residue application or retention at the same experimental site, so the relationship between amount of residue applied and SOC is not clearly understood.

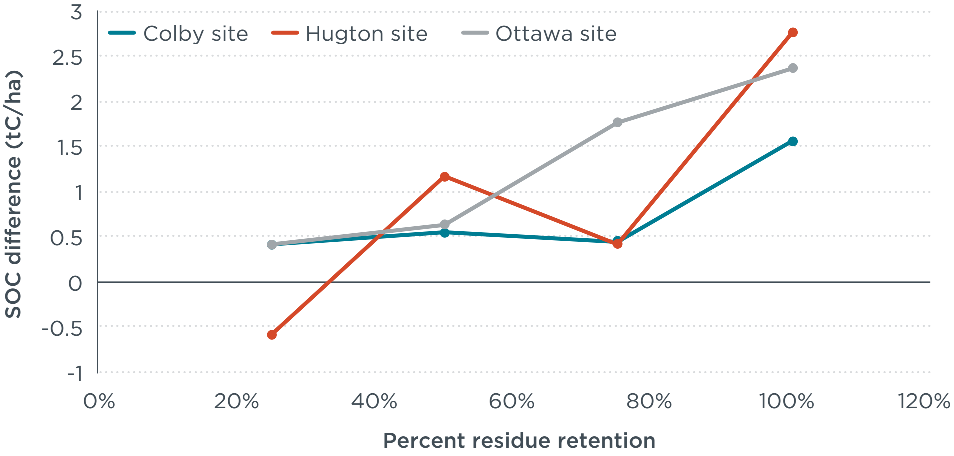

Figure 1. Difference in SOC between residue retention and removal by percentage of residue retained after 2 years. (Kenney, 2011)

Kenney (2011) and other studies report the amount of stover removed as a percentage of total stover production. However, yields of stover and other crop residues can vary considerably by location, so the percentage removed is not entirely informative. For example, removing 50% of stover from a field yielding 10 t/ha stover leaves twice as much stover on the ground as removing 50% from a field with a 5 t/ha stover yield. The latter depletes SOC to a much greater extent than the former. Understanding how crop residue removal or retention affects soil carbon and quality according to the absolute amount, rather than the percentage, is thus likely to be more meaningful. It may be possible to remove a larger fraction of very high-yielding residue crops without adverse environmental impacts.

Other agricultural practices may influence the relationship between residues and SOC. Soil texture may matter. Clays, which are mineral soils with small particle size, may theoretically support greater SOC accumulation than soils with larger particle size. Clay allows greater aggregation or bonding in soils, reducing erosion. In addition, clay can encase organic particles and prevent or slow decomposition (von Lutzow et al., 2006). The starting SOC content of soil may also affect further SOC accumulation if soils begin to reach SOC saturation (Six, Elliott, & Paustian, 1999).

Tillage or ploughing practices also may influence the impact of residue retention on SOC. Tillage mixes air into the soil and reduces soil aggregation, accelerating the decomposition of residues and organic matter (Stubbs, Kennedy, & Schillinger, 2004). Tillage could thus reduce the effectiveness of residue retention in building SOC. This effect is apparent in U.S. data on land used to grow continuous corn. Using data from Searle and Malins (2016a), we find statistically significantly greater SOC accumulation in no-till plots compared to conventional-till plots in the United States, with full stover retention on all plots (Figure 2; $p < 0.05$). At least in the United States, practicing no-till does seem to enhance the positive effect of residue retention on SOC. In the EU, however, no-till is far less common than in the United States (Horowitz, Ebel, & Ueda, 2010; Eurostat, 2015). Evidence is thus lacking on the combined effects of no-till or reduced-till and residue retention in that context. There is disagreement in the literature on the extent to which no-till can improve SOC globally (Luo, Wang, & Sun, 2010; Powlson et al., 2015).

There may be reason to expect that lower amounts of residue are necessary to achieve any particular level of SOC benefit in the EU compared to the United States, as conditions and management practices vary. For example, the EU overall tends to have lower erosion rates (e.g., Nearing, Xie, Liu, & Ye, 2017), which is one factor affecting soil carbon and quality. There is a fair amount of literature in the United States on SOC impacts of corn stover retention versus removal, but the findings of this body of research may not be fully applicable to the EU. Less research and analysis have been done on this topic in the EU context specifically. In the next section, we conduct a thorough review of relevant experiments that have been conducted in EU countries and present a meta-analysis of findings across these studies.

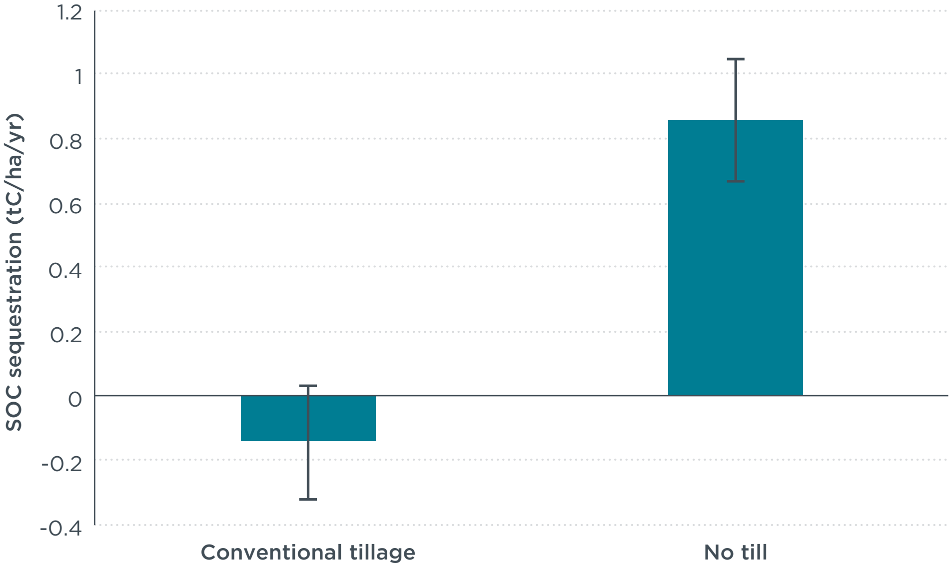

Figure 2. Effect of tillage on SOC sequestration on continuous corn plots with residue retention in the United States.

Meta-analysis of SOC impacts with residue management practices

In this section, we present a meta-analysis on SOC change with residue application or retention using data from experimental studies in the EU. Our goal is to understand how SOC changes with residue retention and whether and how this relationship depends on other management factors through a comprehensive analysis of the available data.

It is important to note that our analysis does not answer the question, "Does residue retention increase SOC over time?" because many studies included in our analysis did not measure SOC changes over time. Instead, they measure and compare SOC levels in plots that have experienced residue retention over several years compared to those with residue removal. Therefore, similarly to Powlson et al. (2011), we answer the question, "Does residue retention result in greater SOC levels compared to complete residue removal?" There is an important distinction between these questions, and we argue that the latter is more relevant to biofuel policy. The concern with incentivizing crop residue harvesting through a biofuel policy is that the policy may result in greater removal of residues, and thus greater loss of SOC, than would otherwise have occurred.

This assessment thus aims to answer two key questions:

- Does residue retention lead to greater SOC levels compared to complete residue removal (and conversely, does complete removal lead to SOC loss compared to retention)?
- How does the amount of retained crop residue affect SOC, and is there a threshold level above which additional residue retention does not offer greater benefits?

This study addresses these questions by assessing the difference in SOC between fields on which residue is retained and those on which it is removed. In addition, we examine impacts on SOC in relation to other factors commonly reported in the underlying studies, including tillage practices, soil type, fertilizer treatment, and length of experiment. Although there is high variability among geographic locations included in this meta-analysis that cannot be fully captured through our consideration of these additional parameters, we believe that a holistic view of the science reported to date is necessary to either confirm or challenge our understanding of sustainable residue management practices.

METHODOLOGY

We include all relevant studies we could find that were performed in the EU, identified using an online search engine. Our analysis includes 14 studies performed in Belgium, the UK, Denmark, Ireland, Sweden and France. These studies are listed in Appendix B. All of the studies we assessed used a paired-plot design, which directly compares SOC in identical plots that are given different treatments, such as complete residue removal versus varying levels of residue application. Many of these studies did not measure or report SOC levels at the beginning of the experiment, before the treatments were applied, and instead only report SOC levels after a certain number of years of applying the residue treatments. Here we assess the difference in SOC between plots that applied residues versus plots with complete residue removal, and do not assess changes in SOC over time with and without residue application or retention.

The studies included in this assessment employed various other agricultural management practices, in some cases to measure the effects of practices such as ploughing or fertilizer application. In most of the cases, soil was ploughed. In a few cases, the soil was ploughed using a tine plough, which lightly turns the soil but does not thoroughly mix it, which can be considered a type of "conservation tillage," or no tillage was performed. The experiments applied various fertilizer types (e.g., inorganic fertilizer versus manure) and fertilization rates. Residues were sourced from wheat, spring barley, maize, and unspecified mixed cereals. The reported residue yields varied from 3 to 10 t/ha. The reported residue retention rate varied from 4 to 20 t/ha. In some cases, additional residues from other fields were added to those produced on the experimental plots. Soil sampling depth varied from 10 to 30 cm. Study duration ranged from 7 to 54 years. A selection of these details is listed by study in Appendix B.

For the meta-analysis of SOC changes due to different residue treatment, we considered each paired-plot observation as an individual sample point. For example, suppose a study measured SOC on four plots with varying agricultural management techniques: (a) zero residue, no-till; (b) zero residue, plough; (c) 5 t/ha residue, no-till; and (d) 5 t/ha residue, plough. We would list two observations for this study in our analysis, one comparing plots a and c to infer the effect of residue application with no-till, and the other comparing plots b and d to infer the effect of residue application with ploughing. The combination of bulk density and SOC concentration measurements is necessary to calculate total SOC stocks for any plot of land, but not all studies reviewed here reported bulk density. For these studies, we estimated bulk density based on SOC concentration following a formula reported in Guo and Gifford (2002). To compare studies that measured SOC with different sampling depths, we estimated SOC at 30 cm for all studies following the depth profile given in Jobbágy and Jackson (2000). We acknowledge that using these data standardization techniques introduces error into our observations; however, restricting our analysis to studies that report bulk density and SOC at 30 cm sampling depth would result in too few studies to make meaningful comparisons. We argue that the error introduced by these data standardization techniques is a reasonable trade-off for the ability to learn from a larger number of studies.

We conduct simple and multiple linear regression analyses to infer relationships between variables in this meta-analysis. We use a threshold of $p < 0.05$ to indicate statistically significant relationships for all regressions. Probability values are a measure of the probability that a trend seen between two variables is actually due to the variation in the x-variable, rather than a spurious correlation resulting from the random scatter of data.

RESULTS

Residue application rate

Overall, our results strongly indicate that residue application results in greater SOC levels compared to complete residue removal. In most comparisons included in our analysis, plots on which residues were applied had higher soil carbon stocks than paired plots with no residue application. In reality, some natural variation occurs in soil carbon stocks from plot to plot, contributing to the error in our analysis. The lowest amount of residue left in fields in the studies included in our analysis is 4 t/ha. It thus appears that, in the contexts of these EU studies, leaving 4 t/ha or more residue in fields increases soil carbon levels compared to complete removal. The available data for the EU do not allow us to investigate the effects of applying smaller amounts of residue.

While it is clear from our data that applying residue results in greater SOC compared to complete residue removal, one key question is whether applying higher amounts of residue increases the rate of SOC accumulation. To compare rates of SOC accumulation across studies, we divide the difference in SOC between plots with residue application and paired plots with removal by the number of years of the experiment. This metric is similar to reporting the rate of soil carbon accumulation over time with residue application (t/ha/year), but again, we note that we are only able to assess differences between paired plots, not SOC changes over time. Overall, the difference in SOC stocks per year between plots with residue application compared to plots without residue application is positively correlated with the amount of residue applied ($p < 0.05$). This relationship is shown in Figure 3.

This result is heavily influenced by observations with residue application rates above 10 t/ha. Furthermore, this relationship has a low R^2-value (0.12), indicating that the regression has very low predictive power; in other words, this regression is unlikely to accurately predict actual net SOC accumulation that would be achieved with any given level of residue application. Figure 4 omits observations with residue application rates above 10 t/ha, and with this restriction, no relationship is observed between residue application rate and the difference in SOC stocks per year between plots with residue application versus removal. A strict interpretation of these data is that:

1. Residue application increases SOC compared to complete residue removal.
2. Within the range of 4–10 t/ha residue application, the application rate does not matter (e.g., applying 10 t/ha residue will have the same result on SOC change as applying 4 t/ha).
3. Applying more than 10 t/ha residue does result in greater SOC accumulation compared to applying less than 10 t/ha.

However, there is no logical reason why a threshold rate of residue application, over which additional input results in greater SOC gain, should exist. The lack of a relationship between residue application rate and SOC difference per year for application rates 10 t/ha and lower calls into question the validity of the correlation found in Figure 3.

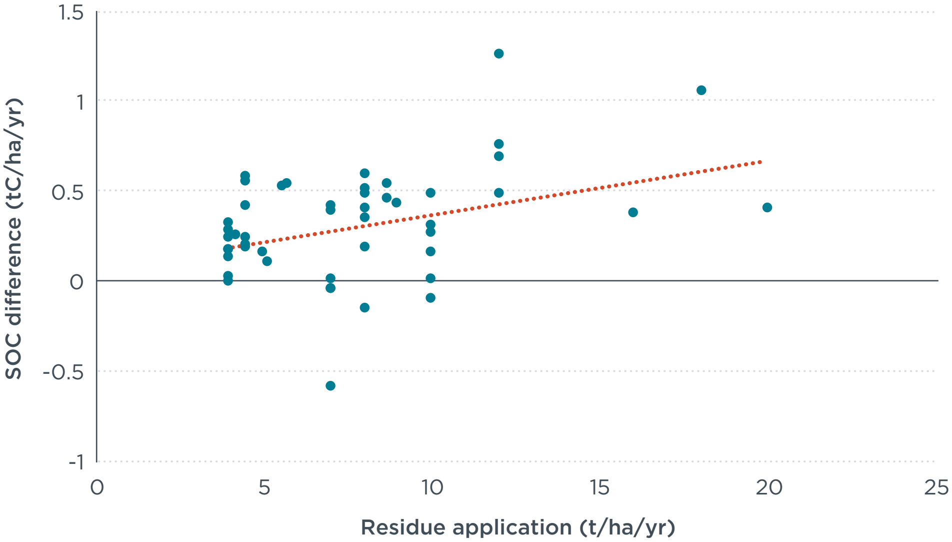

Figure 3. Annualized SOC difference between residue application and removal by residue application rate.

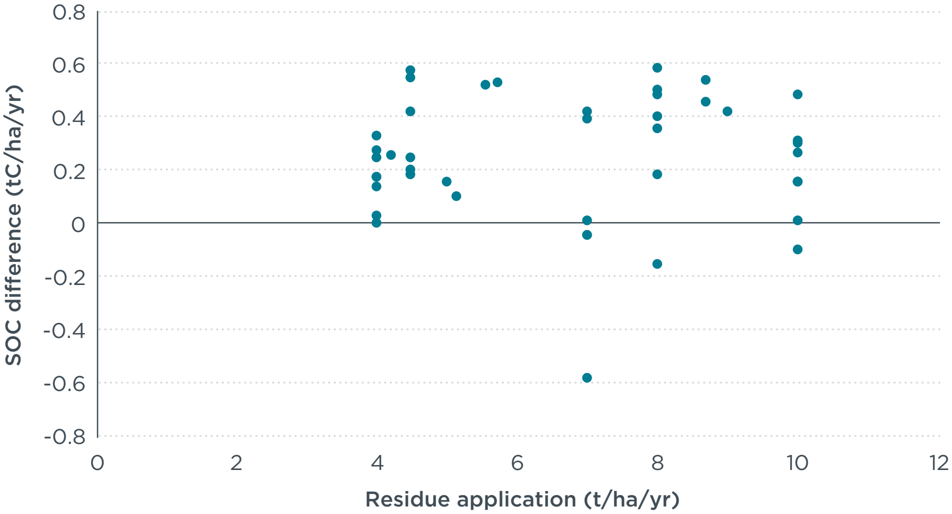

Figure 4. Annualized SOC difference between residue application and removal by residue application rate for rates ranging from 0–10 t/ha.

We thus consider our results to be inconclusive on the question of whether adding residue amounts greater than 4 t/ha results in higher SOC accumulation. This is unsurprising given the high variability amongst our data in experiment location, time period, crop, and other management practices.

Duration of residue treatments

Any effect of residue application on SOC should compound over time. One would thus naturally expect a greater difference in SOC between plots with residue application compared to those with removal the longer these experimental treatments occur. This idea is supported by our data. Figure 5 shows that overall, greater SOC gains were found with residue application compared to residue removal plots the longer an experiment had been ongoing. We perform a multiple regression analysis for total SOC difference between plots (residue application vs.

removal, in t/ha) versus the number of years of the experiment, with residue application rate as a covariate; this regression is significant with $p < 0.05$ for both variables and $R^2 = 0.37$, suggesting time has a significant effect on SOC accumulation.

There may also be reason to believe that such changes are rapid in the early years of an experiment and that the annual change decreases over time. Previous meta-analyses have found such a temporal pattern for SOC changes with land use change. For example, when a forest is converted to cropland, SOC is initially lost rapidly, and after a number of years the SOC stocks stabilize at a lower level than the initial stocks (Murty, Kirschbaum, Mcmurtie, & Mcgilvary, 2002). With residue application, one might expect to observe a slowing of SOC accumulation with time if soils begin to become saturated with carbon (Six et al., 1999; discussed further below). However, it is not clear from our data that SOC changes over time with residue treatments are necessarily nonlinear or stabilize at a certain point. Performing the multiple regression analysis on log-transformed data, a technique that should better fit a trend of slowing SOC accumulation with time, actually resulted in a poorer fit. In some cases in practice, farmers may begin retaining residues on fields on which they had previously harvested all collectable residues, and for these cases it is important to understand how long SOC recovery may take; however, we are unable to answer this question with the available data in the EU context.

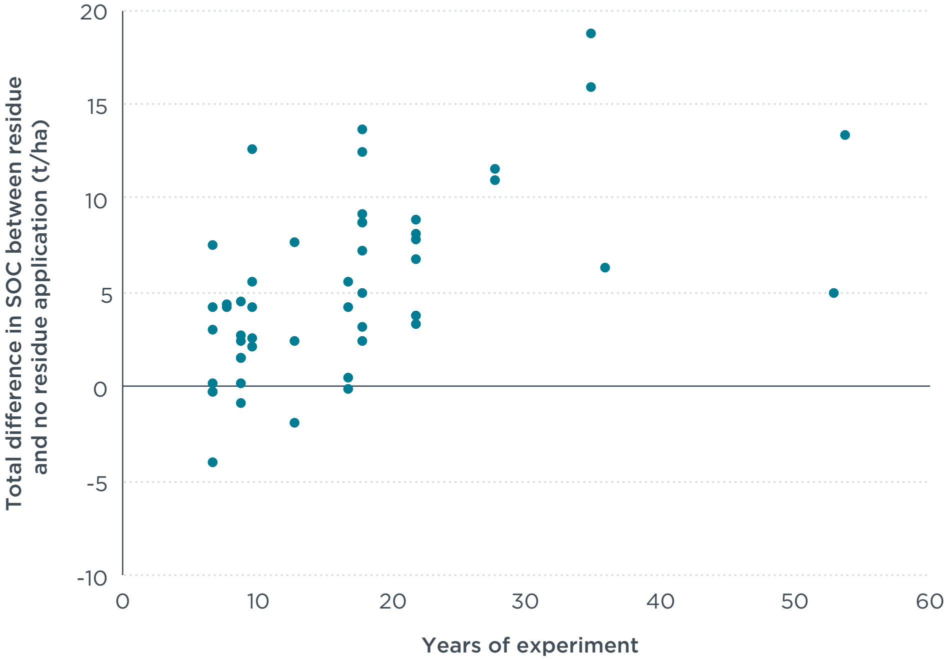

Figure 5. Difference in SOC between residue application and removal by number of years of experimental treatment.

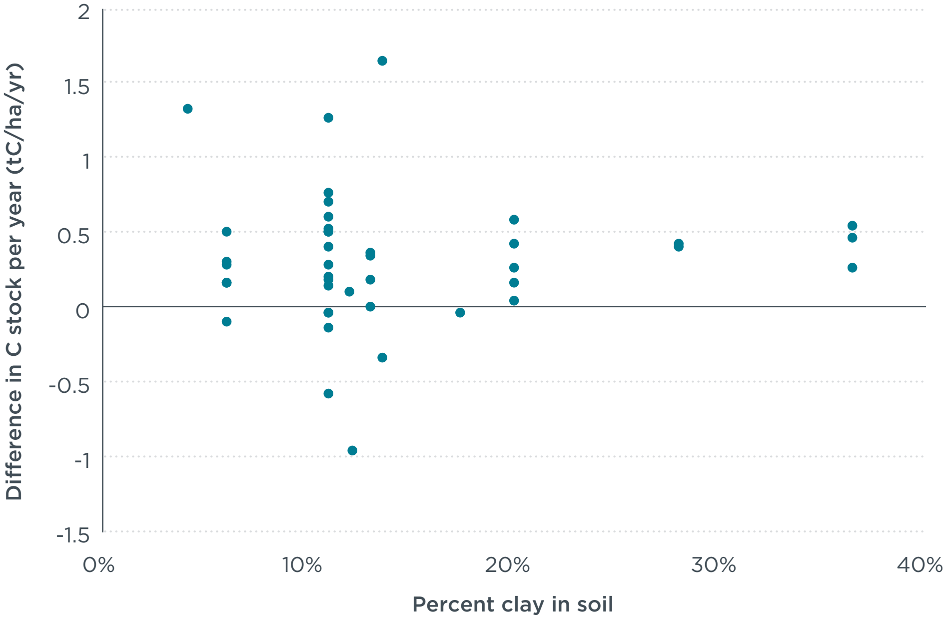

Figure 6. Difference in SOC between residue application and removal by clay content in soil.

Soil type and texture

There is also reason to expect that soil texture can affect how quickly SOC accumulates with residue application. SOC has been found to accumulate faster in clay versus silt fractions (Houot, Molina, Clapp, & Chassod, 1989), and clay may slow SOC loss from erosion and decomposition through increased soil aggregation (Bronick & Lal, 2005; von Lutzow et al., 2006). Conversely, sandy soils are prone to leaching, which may reduce carbon retention capacity (SoCo Project Team, 2009; Powlson et al., 2011). Within our dataset, however, there is no apparent relationship between clay content and the annualized difference in SOC between residue application and removal (Figure 6). Similarly, we found no difference in the annualized difference in SOC between residue application and removal in sandy soils (with >33% sand content or classified as "sandy") compared to not sandy soils. However, few studies included in our analysis were performed on soils with clay content greater than 20%, so we are unable to draw conclusions on the effect of clay content on SOC accumulation in high-clay soils. It is possible that a greater effect on SOC accumulation would be seen with additional data using soils with higher clay content.

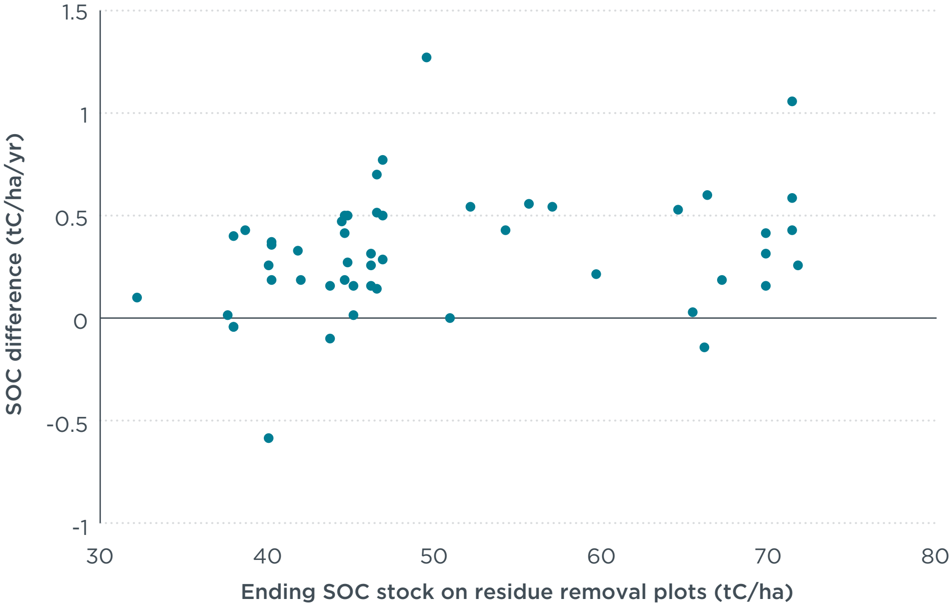

Figure 7. Annualized difference in SOC between residue application and removal by SOC stock at removal sites.

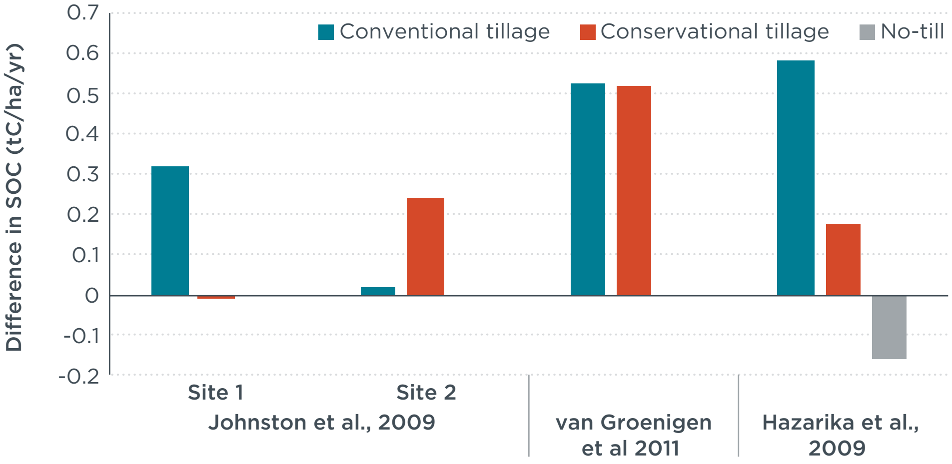

Figure 8. Difference in SOC between residue application and removal by tillage practices.

Some authors have indicated that SOC accumulation depends on the initial SOC; if it is very high, then residue retention might have a smaller effect due to SOC saturation (Six et al., 1999). We might thus expect to see lesser SOC accumulation on plots with high initial SOC, and greater SOC accumulation on plots with lower initial SOC. We do not have the data that would be necessary to answer this question, as the initial SOC stocks were not reported in many studies. Instead, we can use the ending SOC stock reported in the studies as an indicator of initial SOC stocks. It is likely that SOC stocks would have gradually decreased on at least some of these plots over the course of the experiments, but this measure still likely reflects large differences in initial SOC stocks across different geographic locations. We see no relationship between SOC difference (i.e., the difference between plots with residue retention and those with removal, annualized over the course of the experiment) and ending SOC stock on plots with residue removal (Figure 7; $p > 0.05$). The result is the same when we add the residue application rate as a covariate to the regression ($p > 0.05$). Our interpretation is that, within our dataset, residue application has the same effect on improving SOC levels in soils that already had relatively high initial SOC as is does in soils with low initial SOC. This result is consistent with our previously noted finding that SOC gains do not appear to have slowed over the duration of the experiments included in our analysis. Again, natural variability amongst experiments could mask such an effect. Furthermore, it is possible that a reduced SOC accumulation effect could be seen with residue application on soils with higher SOC levels than those included in our dataset. Six et al. (1999) suggest that SOC saturation occurs at concentrations greater than 5% in soil, and SOC concentration within our dataset among studies that reported this parameter did not exceed 3%. This suggests that SOC saturation is unlikely to occur in most arable soils in the EU, and thus that residue application should generally have a positive effect on SOC regardless of soil type.

Effect of tillage

In our review, only three studies specifically tested the combined effects of tillage and residue application at four sites; these findings are presented in Figure 8. In each of these studies, conventional tillage was compared with conservational or reduced tillage (e.g., turning soil with tines rather than, e.g., a mold-board plough), and the same amount of residue was applied across tillage treatments for each site. Only one study also included a no-till plot. In contrast to the U.S. data shown in Figure 2, with our EU dataset there is no clear interaction between tillage and residue application on SOC. As with other parameters, the lack of a clear result on tillage is likely due to the paucity of data, in particular a lack of results on no-till plots with residue application.

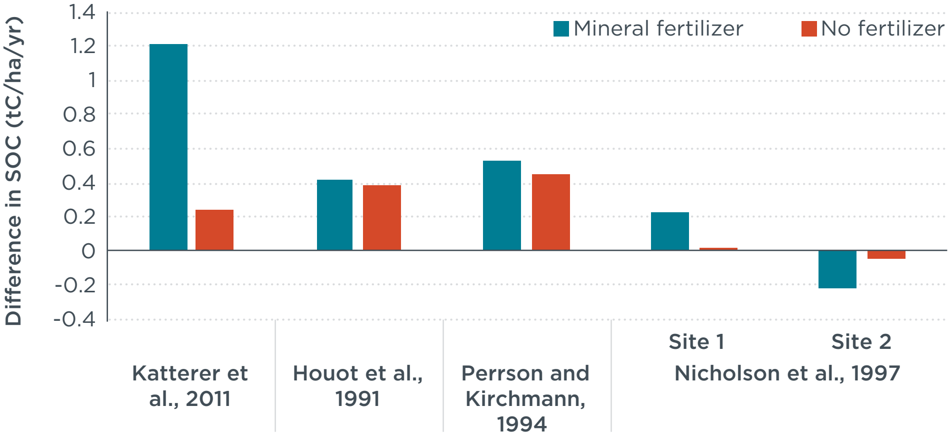

Figure 9. Difference in SOC between residue application and removal with fertilizer versus no fertilizer application.

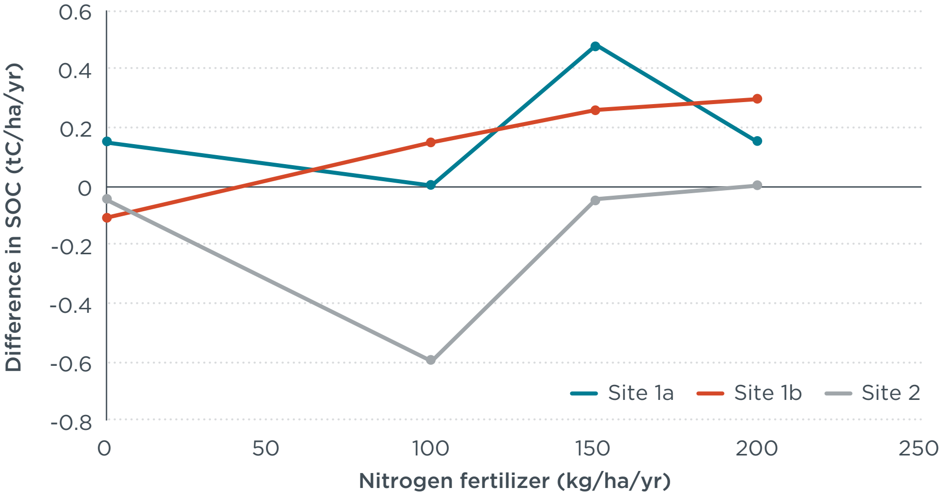

Figure 10. Difference in SOC between residue application and removal by level of nitrogen fertilizer application in Nicholson et al. (1997).

Fertilizer treatment

The decomposition of residues by microbes, and in particular the release of nitrogen contained in biomass residue, can be slowed if insufficient nitrogen is available in the soil. The addition of mineral nitrogen may thus be necessary to increase the speed of microbial activity in order to achieve the full fertilization benefits of the residue itself (Houot et al., 1989; Nicholson et al., 2014; Schjønning, Heckrath, & Christensen, 2009). However, it is not clear whether the effect of nitrogen availability on residue decomposition affects SOC levels in the long term. Our data show that the annualized difference in SOC with residue application versus removal is not consistently affected by the addition of mineral fertilizer in studies that compared fertilizer and no fertilizer treatments (Figure 9).

Nicholson, Chambers, Mills, and Strachan (1997) measured SOC on plots with varying levels of nitrogen fertilizer addition and with or without straw. In this case we see no consistent interaction between fertilizer and residue application on SOC levels (Figure 10). While there is reason to believe that mineral fertilizer addition may aid in soil nitrogen levels and could thus affect crop yields in future years, it does not appear that fertilizer addition affects SOC directly with residue application.

Slope

Lastly, we note that residue effects on SOC could be influenced by slope. Erosion generally increases with slope. The extent to which residue retention reduces erosion compared to complete residue removal may thus be greater on fields with significant slope, as erosion rates could be very high on slopes with complete residue removal. Slope was generally not reported among the studies included in our analysis, so we were not able to take this into account. We believe it probable that none of the studies included here reported results from land with high slope.

SUMMARY OF RESULTS

As with any meta-analysis, it is difficult to draw precise conclusions given the variation in the data and studies used. However, our data clearly support two ideas:

- In the EU, retaining residue amounts of at least 4 t/ha/yr generally results in greater SOC accumulation or reduced SOC loss compared to complete residue removal from crop fields.
- This SOC benefit increases over the years that residue is applied.

Whether other factors, including soil type, starting SOC levels, tillage, and fertilizer affect the SOC benefits of residue retention is not clear from our analysis. Our analysis suggests that, regardless of how these other management practices are performed, retaining some residue in fields will likely have a significant SOC benefit.

Policy recommendations for the use of crop residues in advanced biofuel production

Regulating the harvest of crop residues will likely be complex under any circumstance, as there exists high natural variability in agricultural systems. It is impossible to predict the net effect that residue management decisions will have on soil health and carbon storage on any farm. However, there is mounting evidence that certain agricultural practices can promote better soil health and sustainable crop yields. Our assessment of the available evidence demonstrates that residue retention leads to greater SOC levels on EU farms compared to complete residue removal. A key practice to ensure sustainable agriculture and sustainable cellulosic biofuel production should thus be the annual retention of a certain level of straw or other crop residues in fields.

The necessary amount of crop residue left in each field to ensure soil health benefits depends on that field's characteristics: slope, climate, erosion risk, and other agricultural management practices. Ideally, sustainable residue retention rates will be determined on a highly local basis. Our assessment does, however, support the idea that, in many cases, any level of residue retention 4 t/ha/yr or higher will likely result in SOC benefits compared to complete residue removal. However, this observation is a generalization of SOC impacts seen in EU studies, and does not mean that a minimum of 4 t/ha/yr of crop residue should be applied in all cases. These findings should also not be extended to the United States or other regions.

There is the potential for other sustainable management practices to support the role of crop residues in ensuring soil health and soil carbon sequestration. While our analysis did not show a clear effect of conservation tillage practices on soil carbon with residue retention, it is clear in the U.S. context that switching from conventional tillage to no-till, along with leaving residue in the fields, can promote SOC sequestration. Planting cover crops reduces erosion and may help protect soil health when some residue is harvested (United States Department of Agriculture, 2015). Avoiding residue harvest on high risk areas, such as slopes or riparian areas, also can help ensure soil health.

The maintenance of existing SOC levels in agriculture is often cited as a concern or goal (e.g., Kemp, 2015). However, we argue against the idea of using SOC levels as a metric to determine sustainable residue harvesting for biofuel production for two reasons. The first is that SOC is highly variable and long time periods are required to accurately measure SOC changes (Garcia-Oliva and Masera, 2004). The second reason is that SOC benefits can be realized without maintenance of existing SOC levels as long as residue harvest for biofuel does not result in greater SOC losses than would have occurred in the absence of biofuel demand. The role of biofuel policy in crop residue management should simply be to ensure that incentivizing biofuel does not lead to adverse environmental impacts. In this framework, regulation should focus on encouraging or requiring certain management practices known to protect SOC and soil health, rather than tying biofuel production to the achievement or maintenance of certain SOC levels.

To summarize, the findings in this study support the following recommendations for policies supporting sustainable cellulosic biofuels:

- Focus on encouraging or requiring sustainable management practices.
- Ensure leaving a minimum amount of crop residue in the field each year, according to sustainable harvesting practices.
- Determine sustainable harvesting amounts based on local conditions.
- Encourage complementary sustainable management practices such as no-till and cover crops.
- Avoid residue harvesting from high risk areas.

There is not necessarily a trade-off between cellulosic biofuel production and soil health; these goals can be complementary to one another. Following the guidelines outlined here can simultaneously support the development of a low carbon bioeconomy and sustainable agriculture.

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Appendix A

GAEC 4-6 implementation by the member states in 2016 (European Commission, personal communication)

Country	GAEC 4 minimum soil cover	GAEC 5 site specific conditions to limit soil erosion	GAEC 6 Maintenance of soil organic matter
Austria	All arable land must have green cover throughout the off season between harvest and replanting	No working land when it is frozen, waterlogged, flooded or covered in snow	Burning of stubble forbidden
Belgium	Region segregated in parcels depending on erosion rate. Different measures apply depending on erosion rate, e.g., conservational tillage	Winter crops, conservational tillage, or other measures required depending on erosion rate	Burning of stubble forbidden; reporting of soil acidity and carbon content required
Bulgaria	30% of specially classified areas should have unbroken/unseparated surfaces	Tillage must be perpendicular to slopes	Burning of stubble forbidden
Croatia	Crops or crop residue cover required during growing season	Tillage must be perpendicular to slopes	Burning of stubble forbidden
Cyprus	Green cover required on slopes in winter	Tillage must be perpendicular to slopes	Burning of stubble forbidden; residues should be used for grazing, soil cover, or incorporated into soil
Czech Republic	Crop residue, manure, or catch crops required on slopes	Conservational agricultural technologies required on land with high erosion risk	Burning of stubble forbidden; manure, residue, or nitrogen fixing crops required on at least 20% of land
Denmark	At least 50% of arable land must be covered by plants	Ploughing prohibited on slopes in winter	Burning of stubble forbidden
Estonia	Crop residues or green cover required for at least 30% of agricultural land in winter	Cover crops, cultivation of grasses, reduced tillage, and/or tillage perpendicular to slope required on slopes	Burning of stubble forbidden; successive cropping or crop rotation plans required
Finland	Vegetation or stubble required on managed uncultivated arable land and in groundwater areas	Crops or green cover required on arable land during growing season; tillage prohibited on 1m buffer strips along waterways	Burning of stubble forbidden
France	Crops, cover crops, or stubble required on fallow land	Ploughing prohibited on flooded land	Burning of stubble forbidden for most crops
Germany	Unmanaged green cover required on fallow land and agricultural land designated as Ecological Focus Areas	Ground cover required on areas with high erosion risk	Burning of stubble forbidden
Greece	Vegetation or stubble required on slopes during rainy season	Tillage must be perpendicular to slopes	Crop residues must be grazed or incorporated into the soil; permits required for stubble burning
Hungary	Stubble, cover crops or winter crops required during winter	Certain crops prohibited on slopes	Requirement for crop rotation for some crops
Ireland	Plants or crop residue required in autumn	Activities that increase erosion risk prohibited	Burning of stubble forbidden
Italy	Minimum soil cover or minimum tillage with residue retention required on unused arable land and high erosion areas	Furrows required on slopes to collect runoff	Burning of stubble forbidden; fertilizer application required when incorporating stubble into soil
Latvia	Vegetation or stubble required on slopes during winter	Maintenance of drainage systems required	Burning of stubble or dry grass prohibited
Lithuania	Arable land must be planted with agricultural plants	Agricultural crops prohibited in areas with high erosion risk	Burning of stubble or dry grass prohibited

Country	GAEC 4 minimum soil cover	GAEC 5 site specific conditions to limit soil erosion	GAEC 6 Maintenance of soil organic matter
Luxembourg	Ploughing prohibited on slopes	Requirement to prevent ravine erosion	Burning of stubble prohibited; requirements for crop diversity
Malta	Vegetation, stubble or mulch required on unterraced land	Tillage and planting must be perpendicular to slopes	Burning of stubble prohibited
Netherlands	Green manure crops required during winter	Tillage required to remove tire tracks	Burning of stubble prohibited
Poland	Vegetation, crop residues, or mulch required on high erosion areas; soil cover required and furrows banned on high slopes	Crops requiring furrows prohibited and soil cover required on slopes	Burning of stubble prohibited
Portugal	Vegetation required on high risk land	Restrictions on cropping in high risk areas	
Romania	Winter crops required or ploughing prohibited on at least 20% of arable land during winter	Tillage and planting must be perpendicular to slopes	Burning of stubble or pastures prohibited
Slovakia	Winter crops or stubble required on at least 40% of sloped arable land during winter	Requirement to prevent gully erosion	Burning of stubble prohibited; crop rotations must be maintained
Slovenia	Soil cover required	Ploughing perpendicular to slopes, stubble retention, or green cover required on steep slopes	Burning of stubble prohibited; crop rotations must be maintained
Spain	Inter-row soil cover required for permanent crops on slopes; tillage restrictions on non-irrigated land sown with winter crops	Tillage must be perpendicular to slopes	Burning of stubble prohibited
Sweden	Green cover required on at least 50% of arable land during autumn and/or winter in the southern part of Sweden	Vegetation required on sloped land near water courses during winter	Restrictions on burning of stubble
UK	Farmers must take reasonable steps to establish soil cover, including crops, cover crops, residues, etc.	Measures to limit soil and bankside erosion required	Burning of stubble prohibited

Appendix B

Studies included in the meta-analysis on residue management and soil carbon

Study	Place	Period (Years)	Crop type
Hazarika et al., 2009[a]	Devon, UK	23	Winter wheat
Houot et al., 1991[b]	Grignon, Yvelines, France	28	Fallow
Johnston et al., 2009[c]	Woburn, UK	17	Wheat and oilseed rape
Katterer et al., 2011[d]	Ultuna, Sweden	53	Cereal rotation (barley, oats, wheat and maize)
Nicholson et al., 1997[e]	Gleadthorpe, UK	9	Arable rotation
	Morley, UK	7	Arable rotation
Perrson and Kirchmann, 1994[f]	Uppsala, Sweden	35	Cereals
Powlson et al., 2011[g]	Rothamsted and Woburn, UK	22	Winter wheat and oilseed rape
Schjønning et al., 2004[h]	Ronhave, Denmark	36	Spring barley
Schjønning, 1986[i]	Ronhave, Askov, Jyndevad, Hojer, Denmark	10	Spring barley
Smith et al., 1997[j]	Rothamsted, UK	7	Continuous wheat, barley
Thomsen & Christensen, 2004[k]	Askov, Denmark	18	Continuous spring barley
Thomsen., 1993[i]	Denmark, Askov	10	Continuous spring barley
Trigalet et al., 2014[m]	Gembloux, Belgium	53	Cereal rotation (barley, oats, wheat and maize)
van Groenigen et al., 2011[n]	Carlow, Ireland	8	Winter wheat

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