Private Incentives for Sustainable Agriculture: Soil Carbon Sequestration

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1. Introduction

This paper is part 3 of a series concerned with harnessing private incentives to enhance the sustainability of agricultural production. Paper 1 outlines key principles and insights from existing research on the general requirements to achieve changes in agriculture to enhance sustainability, while Paper 2 applies those insights to water pollution caused by agriculture. This paper builds on those insights by examining the opportunities to increase sequestration of carbon in agricultural soils.

Conversion of land to agriculture has decreased soil carbon by about 40 to 60 percent compared with pre-agriculture levels (Sanderman et al. 2010). Globally, this loss of soil carbon (C) has resulted in at least 150 trillion tonnes of carbon dioxide being emitted to the atmosphere in total (compared with about 10 trillion tonnes per year from fossil fuels).

Given the large areas of land used for agriculture, even modest increases in soil C levels would make worthwhile contributions to offsetting emissions. However, currently, there is much uncertainty and debate as to the total potential of agricultural soils to store additional C, the rate at which it can be done, the ‘permanence’ of the stored C, the economics of measures to increase soil C, the best policy approaches to the issue, and how best to measure changes in soil C.

As a mitigation activity, sequestration of carbon in soils has two important characteristics. First, when a sequestering practice is adopted, carbon storage typically increases, but at a diminishing rate through time until it plateaus at a new steady-state equilibrium (Figure 1) (Gramig 2012; Hoyle et al. 2013; West et al. 2004). Consequently, only a limited amount of sequestration is possible on any piece of land. Furthermore, this limited opportunity can only be exploited once; if the same management practice is delayed and implemented at a later date, it will ultimately sequester the same amount of carbon (Figure 1). Second, sequestration is reversible. To retain stored carbon the sequestering (or an equivalent) practice must be continued; reverting to the previous practice re-emits the carbon (Figure 1). For these and other reasons, sequestration creates some particular challenges for initiatives and programs, which we will explore later.

[Figure 1: *Stylized dynamics of carbon sequestration*]

The next three sections address the on-farm practices that can be used to sequester carbon in soils. The main practices are described and then evidence is presented about the effectiveness of each of those practices at sequestering carbon. The economic benefits and costs to the farmers of those on-farm practices are discussed. Strategies used by governments to promote soil carbon sequestration in existing programs are presented, and potential opportunities for PepsiCo to contribute in this area are assessed.

The geographic focus is mainly on broadacre agriculture in developed countries, such as the United States, Canada, and Australia, but many of the issues raised are more broadly relevant to agricultural systems around the world.

The aim was for the report to be relevant to corn, oats, and potatoes. Research literature on soil carbon sequestration in corn crops is extensive. There is less evidence available about soil carbon in oat crops, but it is judged that the evidence for wheat and other cereals is broadly relevant to oats. Unfortunately, there seems to have been almost no research into soil carbon sequestration for potato crops.

2. Farming practices for sequestering carbon

In essence, soil C levels can be increased by either of two means: by increasing the return or input of carbon-containing biomass back into the soil, or by reducing the decomposition of soil organic matter and the rate of loss or 'turnover' of soil C back to the atmosphere. The main available practices are outlined in the following sub-sections.

Increasing the growth of agricultural plants

An increase in plant growth will result in an increase in the amount of carbon captured by photosynthesis on a given site. This could come about through the planting of a more productive plant species (e.g., Subak 2000), or by boosting the growth of existing species by fertilization or irrigation. In the case of the latter, this may increase both the amount of product removed (harvested) and the amount of unremoved residue kept on site and returned to the soil.

Offsetting the increased return/input of carbon to the soil can be an increase in decomposition rates under fertilized and/or irrigated conditions (Khan et al. 2007; Sanderman et al. 2010). Also, emissions associated with the pumping of water and/or the manufacture and transport of fertilizer negate some (and in some circumstances all) of the gains made by sequestering extra carbon (Schlesinger 1999, Mosier et al. 2005, Powlson et al. 2011). Another consideration is Nitrous Oxide (N_2O), a greenhouse gas (GHG) that is 296 times more potent than carbon dioxide (CO_2) (based on 2001 IPCC TAR 100 year global warming potentials). Agriculture is responsible for roughly half of global N_2O emissions. Although the processes responsible for agricultural N_2O emissions are variable and erratic (e.g., Leip et al. 2011, Reay et al. 2012), the single greatest predictor of N_2O emissions is nitrogen fertilizer application rates, with roughly one percent of applied N fertilizer emitted as N_2O, on average. Particularly relevant to fertilizer-induced sequestration is that N_2O emissions tend to increase exponentially with N application rates (Shcherbak et al. 2014).

More carbon can be returned to the soil without increasing primary productivity by reducing the 'harvest index' or amount of product that is removed/harvested relative to the total plant biomass that is grown (Sanderman et al. 2010). This may come at the cost of reduced harvest of the economic product.

Retaining unharvested biomass within the field

Retention of crop residues within the field, rather than removing, grazing or burning them, can contribute to raising soil carbon levels (e.g., Liu et al. 2014). Residue retention can have agronomic benefits through reduced evaporation and erosion (Incerti et al. 1993). In some cases, removal or burning of crop residues can improve weed control and delay herbicide resistance (Walsh et al. 2013; Lyon et al. 2016). On the other hand, there can be disadvantages of retaining crop residues in the field. For one thing, crop residues can have other uses (e.g., as animal fodder and bedding or as a fuel source—Robertson 2006; Wilhelm et al. 2007; Herr et al.

2011; Kirkegaard et al. 2014). In some cases, residues left in the field can complicate cultivation and pre-emergent weed control.

Replacing crops with pasture

Including pasture phases in cropping rotations, or increasing the duration of pasture phases, can sequester carbon (e.g., Chan et al. 2011). This is because pastures generally return more carbon to the soil (depending on the tillage practices used in the cropping phase, it can also result in reduced cultivation). There is, however, a drawback: pasture is usually grazed by methane-emitting livestock. As methane is a 23 times more potent greenhouse gas than CO_2 (based on 2001 IPCC TAR 100 year global warming potentials) emissions from the grazing livestock offset the carbon benefits and may completely negate them. In some cases, there may even be a net increase in emissions (e.g., White and Davidson 2015; Thamo and Pannell 2016).

Replacing annual pastures with perennial pastures

Sequestration in pastures is greatest if the pasture species is perennial (a plant that lives for several years, rather than re-growing annually). As well as having a longer growing season and thus greater assimilation of carbon through photosynthesis, perennial species tend to allocate a greater proportion of photosynthate below ground. The viability of substituting annuals with perennials depends on agro-climatic circumstances and may be more likely to be practical in pastoral rather than cropping systems.

Cover crops

“Cover crops are grasses, legumes or forbs planted to provide seasonal soil cover on cropland when the soil would otherwise be bare—i.e., before the crop emerges in spring or after fall harvest” (Minnesota Department of Agriculture 2017). During a bare fallow between crops, the return/loss of carbon from the soil back to the atmosphere continues without any input of new organic material of offset it. Replacing the bare fallow with a cover crop changes this. Bare soil also tends to be more erosion prone. When soil erodes, the soil carbon associated with it can be lost too. The potential for cover cropping is likely to depend on local agro-climatic conditions: not all farming systems have a bare fallow phase, and in some farming systems that do, the climatic conditions during the ‘fallow’ period may simply be too harsh for plant growth. In other farming systems the bare fallow may be employed to allow soil moisture to build up for a cash crop. Employing cover crops in these systems would thus reduce the yield of the cash crop by using up soil moisture (e.g., Blanco-Canqui et al. 2015; Meier et al. 2017). In a long-term trial of an intensively-tilled two-year rotation with either corn or potato grown in Maine, Griffin and Porter (2004) found the use of cover crops and green manuring had negligible impact on soil carbon, whereas a single application of paper mill sludge, manure and/or compost raised carbon levels by 25 to 53 percent (but see the next sub-section).

Importing organic matter to the field

Applications of organic amendments or materials such as compost or manure to soil represent a direct input of carbon (Lal 2004). They can also increase soil carbon indirectly if they lift the productivity of the agricultural plants. Adding organic material sourced from offsite does not necessarily result in *net* additional sequestration though, because in many cases this material would otherwise be returned back to the soil anyway, just at another location (e.g., Powlson et al. 2011). Indeed, because of this effect, manure application is not deemed a GHG mitigating practice in some countries including Canada and France (Minasny et al. 2017).

Applying biochar

Biochar is created by the pyrolysis of feedstock biomass (typically straw, woody materials or manure) to produce carbon-rich biochar, which is similar to charcoal. There has been interest in applying biochar to agricultural soils. Compared with the unprocessed feedstock biomass, biochar is relatively stable and inert (Krull et al. 2009), meaning that a greater proportion of the carbon in the original material can be sequestered relative to the case where the feedstock remained at its original location and decomposed naturally. Because biochar is relatively stable, it does not require farmers to continue to practice a modified farming system – an advantage compared with most other approaches. A further advantage is that quantification of biochar applications is relatively easy and once-off; thus avoiding on-going, expensive transaction costs for inspection and measurement associated with conventional soil carbon (Butt and McCarl

2004). Biochar applications have also been found to increase crop growth in some circumstances (e.g., Chan et al. 2007; Major et al. 2010).

Academic interest in biochar has grown substantially since 2000 (Sanroman et al. 2017). Despite this, widespread commercial adoption of biochar application by farmers is yet to occur. Possible reasons for this are that the fertility benefits of biochar applications have been found to be highly variable, with the measured effects on crop yields ranging from highly positive to somewhat negative (Bach et al. 2016). Possible causes of this variability include differences in feedstock material and pyrolysis processes, crop type, application rates, co-products applied with the biochar such as fertilizers, and variation in the agro-climatic-soil conditions in which applications occur (Blackwell et al. 2010; Jeffery et al. 2011; Liu et al. 2013). The varied results may come to be better understood in future, but the current uncertainty about yield responses to biochar applications presents an obstacle to widespread commercial adoption (Bach et al. 2016).

Zero-till, reduced tillage

Cultivation releases carbon stored in the soil, primarily through changes in soil structure that enhance the degradation of soil organic matter, and also potentially, by increasing erosion rates (Sanderman et al. 2010). Hence the adoption of zero-till or reduced tillage can reduce the return of soil carbon back to the atmosphere, and thus increase soil carbon levels. The capacity of zero-till to positively influence soil carbon levels tends to be better than that of reduced tillage (e.g., Sanderman et al. 2010, Kämpf et al. 2016). Overall, the adoption of conservation tillage is perhaps the most commonly discussed way of sequestering carbon in agriculture (e.g., Lal and Kimble 1997; Follett 2001; West and Marland 2002; Antle et al. 2007; Grace et al. 2010; Syswerda et al. 2011; Lal 2015). However, the efficacy of zero-till as a means of sequestering carbon has been called into question, as outlined in the next section.

Land Retirement or afforestation

Retiring land from agricultural uses to a more natural vegetated state can increase carbon sequestration in various ways. When land is retired from agricultural production less carbon is removed in harvested material, meaning more carbon is available to enter the soil. Depending on the agricultural land use that is retired, there can also be an end to actions that destabilize soil organic matter, like tillage. Afforestation/land retirement may often result in perennial species replacing annuals. Retired land is less likely to be bared and thus exposed to erosion. Land retirement can also reduce emissions of the other greenhouse gases (N_2O and CH_4) associated with agricultural production. Negatives from land retirement include loss of income and indirect leakage of CO_2 in other locations (discussed later).

Heterogeneity

The performance of all of the above practices, in terms of production, profit and carbon sequestration, is highly variable from situation to situation. Results depend on soil type, climate, and the farming system (e.g., the crop rotation) (Meier et al. 2017). Because climate is one of the factors influencing rates of carbon sequestration in soils, climate change itself may affect sequestration, raising questions about the temporal stability of sequestration and sequestering practices (Baldock et al. 2012).

3. Evidence on the effectiveness of practices

There has been a great deal of research on the potential for different farming practices to contribute to increasing soil carbon (Sanderman et al. 2010; Lewandrowski et al. 2004). Table 1 presents a summary of estimates of the potential for increased sequestration from the practices outlined in the previous section.

[Table 1. *Practices for sequestering carbon in agricultural soils*]

From the perspective of carbon sequestration at a site (ignoring economics, leakage, and other factors), the best options appear to be importing organic matter to the field, and land retirement or afforestation. On the other hand, the least beneficial of these practices (from a carbon sequestration perspective) are increasing the growth of agricultural plants, retaining unharvested biomass within the field, cover cropping, and zero-till or reduced tillage.

The negative assessment of the carbon sequestration potential of zero-till (e.g., Baker et al. 2007; Powlson et al. 2014; Sommer and Bossio 2014; VandenBygaart 2016) is particularly noteworthy given that it is the most widely promoted action for carbon sequestration in agriculture. Reasons for its poor performance include: (a) that many farmers do not practice zero-till every year, with the risk that any carbon sequestered in the zero-till years will be lost during the years that include tillage (VandenBygaart 2016), (b) the possibility that increased emissions of N_2O under zero-till may fully offset the benefits of increased sequestration of CO_2 (VandenBygaart 2016), (c) the risk that "the apparent increase in soil organic carbon (SOC) under no-till results from redistribution of C nearer to the soil surface and is therefore not a net increase in SOC stock" (Powlson et al. 2014, p. 679; and see also Manley et al. 2005; Baker et al. 2007; Piccoli et al. 2016; Du et al. 2017)., and (d) weaknesses in the way that soil carbon is sometimes measured (Powlson et al. 2014), meaning that measured increases may not be real.

To further explain point (c), conventional tillage inverts the soil, burying residue and organic materials from the soil surface deeper within the soil profile. With the adoption of no-tillage this inversion ceases, concentrating the carbon-rich material in the topsoil where, because in routine testing by commercial farmers (and in many agronomic studies in which soil carbon has been measured) sampling is often limited to the top 10 or 15 cm, it is then detected as an 'increase' in soil C. For instance, a meta-analysis of 69 paired experiments from across the globe comparing conventional and no-tillage practices found no-tillage *increased* soil carbon by 3.15±2.4 t/ha (mean±95 percent confidence interval) in the top 10cm of soil, but *decreased* it by 3.3±1.6 t/ha in the 20–40cm soil layer (Luo et al. 2010). The net result, with the entire top 40 cm considered, was no significant change in carbon levels between tillage practices.

4. Farm-level economics of sequestering farm practices

"The economic potential to sequester carbon is much lower than the technical potential reported in soil science studies" (Lewandrowski et al. 2004, p.i).

Farm-level economic performance of practices that sequester soil carbon is a key driver of their adoption and influences the potential for an initiative or program to be successful. The farm-level economics of the practices are heterogeneous from region to region, season to season, farm to farm, and sometimes even from field to field within a farm. This is often not well captured in published studies that analyze the farm-level economics of the practices. The studies tend to analyze the economics for a typical case or for a small number of cases, rather than attempting to reflect the full heterogeneity.

For some of the practices, obtaining a rigorous estimate of the farm-level economics is very difficult because they have complex flow-on effects on the farming system. An example is switching from crop to pasture, which in many cases would cause a reorganization of the farming system. These complexities are often not fully captured in published studies of the farm-level economics.

We can sometimes get a sense of the heterogeneity if we can observe the extent to which a practice is used in the long term. For example, reduced tillage is used on about 40 percent of cropland in the United States (Wade et al. 2015). Taking this adoption statistic to be loosely indicative of the farm-level economics, a simplistic but indicative and useful conclusion could be that reduced tillage has substantial economic benefits on around 30 percent of land, is marginally beneficial or marginally negative on around 20 percent of land, and has negative net benefits on around 50 percent of land.

Even where a practice is highly beneficial to some farmers, it does not follow that it is beneficial to all farmers. Reflecting this diversity, there is very high adoption of zero-till in Australia (80-90 percent), moderate adoption in the United States (40 percent), and low adoption in Europe, Asia and Africa (Derpsch et al. 2010).

The practices of interest here have all been available to farmers for some time, so farmers have had time to assess their farm-level economic performance. If they are still not being grown, it is reasonable to conclude that they are not judged by farmers to be strong economically.

Increasing the growth of agricultural plants

The economics of irrigation are highly site-specific, depending on the cost of water, how much is available, and how much production can be boosted in by irrigation (e.g., depending on local climate). In many cases, irrigation water is a highly productive input. On the other hand, the fixed costs of irrigation can be high, so positive economic returns are not assured in all cases. In some cases, moisture availability to crops is such that the need for irrigation is low. For example, for potato production systems in Maine, irrigation is only needed to supplement rain for very short periods during the growing season (Halloran et al. 2013).

In most agricultural soils, application of nitrogen fertilizer is highly profitable, with the yield gain, relative to no nitrogen fertilizer, depending on crop type, soil type, production system and weather (Pannell 2017).

Yield increases from either of these important inputs (irrigation water or nitrogen fertilizer) can result in increases in soil carbon as underground or above-ground crop residues break down. However, it is doubtful that this consideration would increase optimal input rates by more than a trivial amount. Such increases may not be socially desirable in any case; nitrogen fertilizer is associated with additional CO_2 emissions during manufacture and transport and is also a significant cause of water pollution (see paper 2).

Retaining unharvested biomass within the field

There has been little research on the economics of retaining unharvested crop biomass within the field. In some farming systems, these residues were traditionally removed (e.g., collected, grazed or burned) to provide feed for livestock, to facilitate the planting of the following crop or for reasons of weed control (e.g., Llewellyn et al. 2012). Over recent decades, retention of crop residues has increased in popularity.

Retention of crop residues is often associated with the use of zero-till. As a result, it is widely adopted by a sub-set of the farmers who have adopted zero-till or reduced tillage – as mentioned above, there has been adoption of zero or reduced tillage on 40 percent of the crop area in the United States (Wade et al. 2015) and 90 percent in the main cropping regions of Australia (Llewellyn et al. 2012). This widespread adoption reflects that the benefits of residue retention outweigh the costs in these cases.

On the other hand, in farming systems where crop residues are an important source of feed for livestock (e.g., many farms in Africa or Asia), there is a significant opportunity cost from retaining the residues within the field (Pannell et al. 2014). As a result, most of these farmers have not been willing to adopt residue retention.

Replacing crops with pasture/Replacing annual pastures with perennial pastures

As part of a broader study, Lewandrowski et al. (2004) analyzed the economics of converting cropland to grassland across the United States under a hypothetical scheme where farmers would be paid for their carbon sequestration. However, this practice change was seldom predicted by their model. This is partly because, in their analysis, land converted to grass was not allowed to be grazed or hayed. While allowing these practices would make the land use more attractive, it would also increase emissions and reduce sequestration. As a result of this restriction, it tended to be more profitable to undertake afforestation (which was also assumed to receive payments) rather than convert to pasture, due to higher sequestration rates for afforestation.

In some parts of the world, most farms consist of a mix of crop and pasture land. This is the case, for example, in much of the wheatbelt of Australia. In these farming systems, farmers are likely to substitute between crop and pasture more readily. Indeed, they already adjust the allocation of their land between crop and pasture on an annual basis depending on economic and weather conditions. A challenge here is that conversion from crop to pasture is likely to be temporary, with a switch back to cropping likely when agronomic, economic or weather conditions dictate (Monjardino et al. 2004).

Cover crops

The literature on the economics of cover cropping in relation to soil benefits has been described as “essentially non-existent” (Blanco-Canqui et al. 2015, p. 2,469). However, judgments can be made from their level of adoption by farmers, which is very low, despite the availability of incentive payments in many cases. This indicates that the benefits arising from nitrogen fixation and soil stabilization are often outweighed by high costs, a lack of financial benefits and a resulting increase in the complexity of the farming system. The potential for negative impacts on the subsequent cash crop has also been identified as a reason for the poor uptake (Schomberg et al. 2014 and references therein). Roesch-McNally et al. (2017) describes how some farmers have overcome barriers to adoption of cover crops, but finds that the barriers are still significant.

Various studies confirm the low level of adoption of cover crops. Wade et al. (2015) found that cover crops were used on less than 2 percent of cropland in the United States. In 2012 less than 5 percent of the total row cropland in the United States was planted to cover crops (Dunn et al. 2016), and in the U.S. Midwest, cover crop plantings were equivalent to only 2.3 percent of the total agricultural lands (Roesch-McNally et al. 2017). An earlier analysis of the U.S. Midwest (Illinois, Indiana, Iowa, and Minnesota) suggested that between 2001 and 2005, only 11 percent of farmers had planted cover crops, and the mean minimum payment required to incentivize those not growing them to adopt was estimated at approximately $57/ha (Singer et al. 2007). Christianson et al. (2013) suggested the incentive required for cover cropping to breakeven in the Midwest was in the order of $164 to $221/ha annually, with a qualification that there was considerable uncertainty about these estimates.

Using a model of U.S. agricultural production to analyse the potential for the widespread uptake of cover crops, Marshall (2012) suggested that while farmers in the southern plains would require relatively small incentives to adopt cover crops, in other regions, particularly the Cornbelt, the threshold incentive level to invoke significant adoption was about $75/ha. Cover crops that fixed nitrogen required less incentivization.

As noted, incentive payments are available to encourage cover cropping in some areas of the United States; farmers in Maryland can receive up to $75/ac ($186/ha) for planting cover crops in the fall (Maryland Department of Agriculture 2018). Accordingly, the adoption of cover cropping in Maryland has been quite strong, though the extent of dis-adoption that would occur should the payments cease is not known (Claassen and Ribaudo 2016).

Importing organic matter to the field

The economics of applying organic materials such as compost or manure are highly site-specific, depending on the cost and local availability of amendments, transport and application costs (they are often low in density, making haulage expensive per unit of weight), extent and duration of productivity benefits, extent to which they can replace other fertilizer inputs, and risk of contaminents in the material (weeds, disease, refuse, heavy metals), meaning any generalizations about the costs of these practices are difficult.

In an analysis of potato production in Maine, the costs of spreading composted dairy manure on fields at 19 t/ha was estimated to increase production costs by about 2.6 percent while purchasing the compost based on local prices ($30 – $40/t) would increase production costs by roughly 30-40elt percent (Halloran et al. 2013). For a traditional barley-potato rain-fed production system, the breakeven cost of compost was $23/t. However, if a value was placed on the plant nutrients contained in the compost then breakeven costs reduced considerably, with compost applications become viable in their own right in some circumstances.

Importantly, as local supplies of suitable organic materials are often limited, and transport of these materials rapidly becomes prohibitively costly as distance increases, if the application of organic materials were to become widespread, costs would rise substantially. [1]

Applying biochar

The farm-level economics of biochar depend on a set of factors: application rates; frequency of applications; feedstock material from which the biochar is made; and transport distance (both the feedstock and biochar tend to be bulky/low density, making them relatively expensive to transport on a per weight basis—Blackwell et al. 2009). From a farmer's perspective, the degree of incentivization required to render biochar applications attractive depends on the agronomic/production benefits obtainable, if any, as a result of biochar application. From a broader climate-policy perspective, the same feedstock used for biochar could often be used to produce bioenergy rather than biochar, so there is an opportunity cost associated with using the feedstock to make biochar (McCarl et al. 2009).

The fertility benefits from applying biochar are highly variable. Thus the few studies that have investigated the economics of biochar typically use an average assumed yield response (e.g., McCarl et al. 2009; Galinato et al. 2011; Dickinson et al. 2015). McCarl et al. (2009) investigated

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[1] For example, Keplinger and Hauck (2006, p. 437) reported that "Model output generally illustrated the diseconomies of manure production, i.e., marginal manure values decreased and maximum manure hauling distances increased as manure production increased. Derived synthetic demands for manure indicated that the value of swine slurry and dairy dry scrape (low-value manures) becomes negative at fairly low levels of manure production. Broiler litter and layer manure (high-value manures) were found to be much more valuable than dairy dry scrape and swine slurry, but also required greater hauling distances because of their greater nutrient content."

the economics of biochar production from corn residue. Their standard assumptions included a perpetual 5 percent increase in corn yield from a once-off 5-tonne per hectare application of biochar, and they concluded that biochar production was unprofitable under these conditions. For it to break even would have required a carbon price of \$58 or \$71/tCO_2-e, depending on the pyrolysis process used to make the biochar. Alternatively, without a carbon price, biochar application could break even if it increased yield by 43 to 193 percent, depending on the pyrolysis process. In a meta-analysis of 16 studies, Jeffery et al. (2011) reported that the greatest yield increase from biochar application in practice was 39 percent, which is below the break-even economic level according to McCarl et al. (2009).

Zero-till, reduced tillage

Zero-till and various forms of conservation tillage are widely practiced in countries with broad-scale commercial agriculture, including the United States, Australia, Argentina, Brazil and Canada. Adoption rates in these countries range from around 40 percent of crop area in the United States (Wade et al. 2015) to 90 percent in the main cropping regions of Australia (Llewellyn et al. 2012). Adoption of no-till in most other counties has been less extensive, and it is likely that it is less suitable for those countries for a mix of technical and economic reasons.

The economics of no-till are complex and difficult to quantify because the practice can have multiple impacts on the farming system (Pannell et al. 2014). There are many studies of the economics (e.g., Aase and Schaefer 1996; Stonehouse 1997; Janosky et al. 2002), but many are too simplistic to provide reliable results. Nevertheless, the persistence of high adoption rates in certain countries can be taken as evidence that the farm-level economics are favorable in many cases in those countries. Given the U.S. adoption rate of 40 percent, there are likely to be significant areas (e.g., an additional 10 percent) where adoption could be increased at low cost. This differs from cases where adoption is already very high, in which case there is little room for up-side. Conversely, in cases where adoption has been sustained at very low levels for some time, the economics are probably too adverse for substantial increases to be realistic.

Land retirement or afforestation

Lewandrowski et al. (2004) used a spatial and market equilibrium model of the U.S. agricultural sector to estimate the cost of afforesting crop and pasture land. They also examined the cost of increasing the adoption of zero-till/reduced tillage. Their model represented the production of 10 crops (corn, sorghum, oats, barley, wheat, rice, cotton, soybeans, hay, and silage) plus livestock production (dairy, beef, pork, poultry) across the 48 contiguous U.S. states. The sequestering practices they examined were afforestation of cropland, afforestation of grassland, and net conversion from conventional to conservation tillage (which they modeled as an unspecified combination of no-till and reduced tillage with more than 30 percent of crop residue retained at seeding). From their results, it is possible to estimate the likely areas of practice change that would be adopted by farmers under different amounts of annual payments (Figure 2).

[Figure 2: *Uptake of sequestering practices in the U.S.*]

According to these results, payments of $350 per hectare per year offered to all farmers would be sufficient to incentivize afforestation of fewer than 10 million hectares of cropland. Afforestation of pastureland and conversion of cropping practices to conservation tillage would be more responsive to incentive payments. Nevertheless, these results imply that very large budgets would be required to achieve these levels of conversion.

These results take into account the income received for the new practices, which in the case of afforestation was the value of standing timber after 15 years with establishment costs annualized over this timeframe. Also captured in these estimates are any commodity price increases (or decreases) induced by these practice changes. However, the benefits in terms of CO_2 sequestration would be tempered by changes in non-CO_2 emissions, and there may be indirect leakage in other countries (i.e., increases in agricultural production in response to higher prices caused by these decreases in agricultural production) which are not captured in these results.

Aside from removing greenhouse gases from the atmosphere, increasing soil C content can also contribute to other improvements, including: reduced soil erosion, improved nutrient retention, improved pH buffering, improved soil structure, increased water infiltration and increased water-holding capacity (Incerti et al. 1993; Sanderman et al. 2010; Meyer et al. 2015; Murphy 2015; Petersen and Hoyle 2016). If these changes provided large enough benefits for farmers, they could help to encourage adoption of carbon sequestering practices. However, placing an economic value on these agronomic benefits is challenging and has seldom been attempted in the literature. An exception is Petersen and Hoyle (2016) who estimated agronomic benefits of around AUD$1 –2/ha/year per tonne of soil C in the wheatbelt of Western Australia. They found these benefits to be sensitive to local conditions (e.g., they were lower under lower rainfall), so it is difficult to make generalizations about the economic value of increased soil carbon from an agronomic perspective.

5. Challenges in ensuring that apparent benefits from sequestration are real

There are several well-recognized problems that are likely to affect sequestration initiatives and may require management, depending on the type of initiative, specifically, permanence, leakage and additionality.

Permanence

As CO_2 emissions reside in the atmosphere for 300+ years (Archer 2005), if a unit of carbon sequestration is to fully offset a unit of emissions, the sequestration needs to be permanent. In programs where farmers receive payment for sequestering carbon, this need has been recognized in two ways: (a) by imposing a condition that sequestration activities must be maintained for a specified time frame, and (b) discounting the payments offered to farmers for shorter time frames (Thamo and Pannell 2016).

Understandably, farmers are reluctant to commit land to be permanently devoted to a particular activity, in case the economics of agriculture change in such a way that other production activities become far more attractive. Historically, agricultural production methods and crop types have changed substantially in all developed countries. For example, the locations in the United States where corn was grown changed dramatically over the course of the 20th century (Beddow and Pardey 2015). The economic cost of being constrained to production patterns and technologies used in the early 1900s would have been enormous. Recognizing this, some schemes allow farmers to commit to sequestration for only a short period. In such schemes, the annual payment for sequestration is effectively an annual interest rate times the cost per unit of CO_2 emission.

Under a purely voluntary scheme with no payments, the risk of non-permanence is, of course, even greater. Continued adoption depends on farmers believing that the sequestering practices remain sufficiently attractive.

An alternative to permanent sequestration that has attracted attention in the literature is temporary sequestration or 'carbon rental' (e.g., Feng et al. 2002; Lewandrowski et al. 2004; Keeler 2005; Murray et al. 2007; Kim et al. 2008; Cacho et al. 2013). Historically, international acceptance of temporary sequestration has been poor, with the question of how to appropriately value/scale temporary offsets relative to permanent abatement being one source of contention (e.g., World Bank 2011).

Leakage

'Leakage' refers to greenhouse gas (GHG) emissions that occur as a result of activities undertaken to mitigate or offset GHG emissions. The degree of leakage needs to be quantified and set against the sequestration benefits of an activity. The leakage from sequestering CO_2 may occur in another location, at another time, or in another type of greenhouse gas.

Leakage can be categorized into two different forms:

i. 'Indirect'—emissions resulting from substitutions or market adjustments occurring in response to the sequestration.
ii. 'Direct'—emissions directly resulting from the sequestration activities.

Indirect leakage can be significant, and has received considerable attention in the literature (e.g., Gan and McCarl 2007; Sun and Sohngen 2009). For example, the sequestration benefit from substituting cropping with pasture can be partly or fully lost if the resultant reduction in cropping production is made up for by increased cropping elsewhere—especially if this involves land-use change like rainforest clearing. This indirect leakage could be on the same farm, on a different farm, or even in a different country, incentivized by changes in commodity prices. Similarly, leakage can be an issue with land retirement. The reduction in agricultural production may ultimately lead to the conversion of land to agriculture in another location. Leakage may be less if degraded, less-productive land is retired. Despite the scholarly attention that has been paid to indirect leakage, anticipating and accounting for it in practice can be very difficult.

Direct leakage occurs where the sequestering activity itself also produces emissions. A key example is the conversion of cropland to pastures because pasture is commonly used for grazing of livestock which emit methane, an even more potent greenhouse gas than CO_2. Because sequestration occurs only up to a maximum total level (Figure 1), while livestock continue to emit methane for as long as they are run on the pasture, this example of direct leakage can result in the leakage eventually outweighing the sequestration. In some situations, this can result in perverse outcomes even when farmers are paid for sequestration. Clearly, the risk of leakage needs to be carefully considered when a practice is being considered as an option for sequestration.

Leakage is also relevant to voluntary sequestration activities. A voluntary reduction in the production of an agricultural output could prompt an increase in production elsewhere in the market.

Additionality

Lack of additionality is a potential concern when farmers receive payments or offset credits to incentivize carbon sequestration. As far as possible, credits or incentive payments should only be provided for sequestration that is ‘additional’. That is, the aim of the policy is to increase sequestering projects that result in abatement that would not have occurred in the absence of the policy. There would be no increase in sequestration if the project activity would have occurred in the normal course of business. Inadequate assessment of additionality is a common flaw in carbon sequestration schemes (Trexler 2011).

An example of non-additionality relates to the widespread adoption of zero-till by crop farmers in many countries even without government funding support. For example, in Australia, zero-till is routinely used by most farmers (Llewellyn et al. 2012). Any program offering payments to farmers who adopted zero-till would generate very little additional adoption. In the United States where just under 40 percent of the 2010-11 area of four major crops was sown using zero-till or strip-till (Wade et al. 2015), the prospects of a program generating additional adoption are greater, but care is required. (Of course, it is also important to consider the level of sequestration that is achievable, and the evidence is that this is zero-to-low for zero-tillage (Table 1).)

Some schemes take a lenient view of additionality in order to encourage greater participation. However, as Erickson et al. (2011) show, the resulting gains in the supply of offsets would come at the cost of a significant reduction in the effectiveness of the scheme, in terms of reducing emissions.

When assessing additionality the following questions need to be addressed.

i. Is the sequestering practice additional?
ii. If so, what is the 'benchmark' farming practice that it would displace?
iii. How much of the abatement resulting from the new practice is additional?

Much of the discussion about additionality is focused on identifying a) and b) (e.g., Woodhams et al. 2012). Both require information that is not observable, and so is difficult to obtain. However, point c) is equally challenging. It requires determination of the net level of sequestration (i.e., also accounting for leakage) for both the sequestering practice and the alternative practice it displaces. The requirement to answer question c) means that the measurement and monitoring (and associated transaction costs) that are often considered onerous for the sequestering activity are also required for the benchmark activity. Further, c) can vary in space and time even if a) and b) are unchanged.

Additionality is not a relevant consideration for purely voluntary adoption with no incentive payments.

Transaction costs

A common theme in the literature is that satisfying requirements for additionality, non-leakage and permanence increases transaction costs, particularly the costs of monitoring and measuring. For example, ensuring permanency requires on-going monitoring of land management to ensure that the sequestering activity is being continued. This monitoring is relatively difficult for soil carbon given that some of the methods for increasing soil carbon are not easily detected by comparatively cheap monitoring methods, like remote sensing.

The transaction costs may be reduced by simplifying the policy but at the cost of increased levels of uncertainty and reduced efficiency of the program (Cacho et al. 2013; Capon et al. 2013; Cowie et al. 2012; Subak 2000). For example, in programs in Australia and Canada, additionality is or was assessed in a highly simplified way, known as the “common practice” method. This uses empirical survey data to determine whether a practice is common in a district. If, in the absence of a sequestration policy, a practice is undertaken by no more than a certain low percentage (e.g., 10 percent) of potential adopters, it is treated as being additional (Woodhams et al. 2012).

There are numerous problems with the common-practice approach to assessing additionality. The threshold for assessing additionality is arbitrary. It is based on the number of farmers who adopt and ignores the area of land on which the practice is used. Because of the way it works, it rules out the most cost-effective sequestration options and favors the least cost-effective ones. Furthermore, its apparent benefit of reducing transaction costs is largely illusory in any case. Once a sequestration program is in place, a new challenge emerges: estimating what the extent of adoption would have been in the absence of the program. This requires the same high level of monitoring and measurement as program managers were trying to avoid by using the simplified approach. Thus, reductions in transaction costs with the simplified common-practice approach will be short-lived.

This leaves us with a dilemma. The transaction costs of monitoring and measuring to accurately assessing additionality, leakage and permanence are likely to be so high as to counteract much of the benefit of the program and to discourage participation. On the other hand, simplifications that sufficiently avoid most of the transaction costs are likely to leave the sequestration program ineffective because of lack of additionality, excessive leakage or impermanence.

Another strategy to limit transaction costs used by several schemes for soil carbon sequestration is to pay participants ‘per area’ enrolled in the scheme rather than ‘per tonne’ of actual sequestration achieved. In ‘per tonne’ approaches, the actual amount of sequestration is measured/estimated for each individual situation. As a result, transaction costs are higher, but accuracy is greater. In ‘per area’ approaches, fixed standard sequestration rates are assumed, so payments per ha are the same, regardless of how much carbon is actually sequestered. Transactions costs are lower, but accuracy is poorer. Although the ‘per acre’ approach is used in practice, Antle et al. (2003) argue that ‘per tonne’ approaches are more efficient, because they capture the heterogeneity in biophysical and economic conditions. For a case study of the dryland grain growing systems in the U.S. Northern Plains, they found that sequestration delivered by the per-hectare approach is as much as five times more costly (i.e., more inefficient) than by the per-tonne approach.

Richards and Huebner (2012) reviewed ten standards/protocols for carbon offset schemes[2] to assess how they addressed additionality and permanence. Across all schemes and standards, they found problems with additionality and permanence that bring into question the credibility of the resulting offset credits. The pervasive nature of these problems led them to doubt the likelihood of being able to design a carbon-offset protocol/standard with low transaction costs yet reasonable credibility. They argued that the widespread weaknesses identified existed because the transaction costs of truly rigorous systems would be too high to be politically unacceptable.

6. Strategies Used by Governments to Promote Sequestration

Initiatives to promote sequestration of carbon in soils face some of the same challenges as initiatives to reduce water pollution from agricultural sources. In particular, like water pollution,

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[2] The reviewed standards mainly focused on forest-based sequestration, but some of them also apply to agriculture.

soil carbon sequestration is a diffuse activity; target areas for sequestration are widely dispersed and numerous, and observations of the existing level of soil carbon are hard to make by a centralized program. These characteristics contribute to the high transaction costs required for effective programs (discussed above).

In most existing policies and schemes to promote sequestration, landholder participation is voluntary, with participation incentivized financially, either through direct payments or through the provision of carbon credits or offsets that can be on-sold to emitters (Thamo and Pannell 2016). In some cases, governments directly purchase the credits (e.g., Australia's Emission Reduction Fund). In other cases, polluters can buy the sequestration credits in lieu of paying a carbon tax (as was possible under Australia's now-defunct Carbon Farming Initiative and carbon tax) or to allow them to operate within an emissions cap (e.g., the Specified Greenhouse Gas Emitters Regulation in Alberta, Canada). Due to concerns about the quality and legitimacy of sequestration (e.g., Edis 2014), there can be restrictions on how many credits can be used to meet these emissions targets or caps (Erickson et al. 2011). For instance, Australia has placed restrictions on the amount of internationally-sourced credits that can be used to meet domestic targets (Climate Change Authority 2014b), and credits from sequestration[3] generated under the Clean Development Mechanism have been barred from the EU emissions trading scheme (Gillenwater and Seres 2011).

Even in the absence of mandated requirements to offset emissions, polluters can buy sequestration credits to voluntarily offset their emissions (e.g., for marketing purposes). For instance, many airlines offer passengers the option of offsetting their travel emissions by paying an extra fee with their ticket. The Chicago Climate Exchange was an example of a market that allowed polluters to voluntarily purchase emissions offsets, until it closed in 2010 due to lack of trade. However, voluntary offsetting continues through various other systems. As of 2017, voluntary carbon projects aimed at offsetting emissions were underway in 83 countries (Hamrick and Gallant 2018). Agriculture, forestry and land-management projects constitute

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[3] In this case, the sequestration is from afforestation and reforestation rather than agricultural soils.

around 13 percent of these projects by number and 23 percent by volume of offsets in CO_2 equivalents (Hamrick and Gallant 2018).

There are a number of standards designed to ensure the quality of voluntary offsets (Richards and Huebner 2012). Even with these standards, the offsets polluters use to voluntarily reduce emissions tend to be regarded as lower quality than offsets supplied to mandatory schemes, and they usually trade at much lower prices.

A number of policies and schemes exist to promote the uptake of sequestration. While these more commonly target sequestration through afforestation and reforestation, there are several examples that promote sequestration of soil carbon, as outlined in the following subsections.

Chicago Climate Exchange Soil Carbon Management Offsets

The Chicago Climate Exchange, which was based on voluntary but legally-binding commitments to reduce emissions, began operating in 2003. Participation by farmers was also voluntary. It included tradable credits for carbon offsets from sequestration as a result of continuous no-till or strip-till cropping in the United States and Canada (CCX 2008). To be eligible, farmers had to leave at least two-thirds of the soil surface undisturbed when tilling, retain at least two-thirds of the crop residues, with offsets issued at 0.2 to 0.6 tCO_2 per acre per year (CCX 2008). Prices peaked at over U.S.$7 per tonne in 2008, before crashing to less than U.S.$0.10 per tonne and then closing in 2010 (Gans and Hintermann 2013).

The additionality of offsets issued by the Chicago Climate Exchange was the subject of criticism, particularly for offsets for soil carbon sequestration through tillage changes, as the rules allowed farmers who had been practicing reduced-tillage for many years to join the scheme and claim and receive credits (Kollmuss et al. 2010).

The permanence requirement (the minimum period for which the reduced tillage had to be practiced) was five years. To offset the risk of re-release of carbon after this time, 20 percent of the total sequestration claimed was set aside and not credited (CCX 2008), although this was criticized as being an inadequate discount (e.g., Kollmuss et al. 2010).

Beyond these concerns, we note that a relatively recent review of the potential for soil carbon sequestration found that likely overall levels of sequestration due to zero-till are zero to low (Sanderman et al. 2010), casting further doubt on the effectiveness of the CCX scheme.

Alberta's Specified Greenhouse Gas Emitters Regulation

Commencing in 2007, Alberta's Specified Greenhouse Gas Emitters Regulation requires polluters who emit more than 100,000 tCO_2-e/year to reduce their emissions intensity by 12 percent per year (Kollmuss et al. 2010). Firms unable to meet this obligation are required to either: (i) purchase credits from firms who have exceeded their obligations; (ii) pay a penalty to the regulator (capped at Can\$15/tCO_2-e prior 2015, increasing to Can\$20 and then Can\$30/tCO_2-e in 2016 and 2017 respectively) (Alberta Agriculture and Forestry 2017a); or, (iii) purchase offsets from sectors not covered by the scheme (Swallow and Goddard 2013; Climate Change Authority 2014a). Carbon sequestration in agricultural soil was originally the biggest source of offsets (although it has recently been surpassed by wind energy), making it the offset credit scheme in which soil carbon has played the greatest role (Climate Change Authority 2014a). The practice used to sequester this soil carbon is the adoption of zero-till or reduced tillage, with only agricultural land in Alberta eligible (Alberta Agriculture and Forestry 2017c; Alberta Agriculture and Forestry 2017a). There is no direct measurement of credited sequestration; rather sequestration is assumed to occur at a fixed rate with no temporal or spatial variation.

Sequestration rates are assumed to be 0.06 tonnes/acre/year in the Dry Prairie and 0.11 tonnes/acre/year in the Parkland area (Alberta Agriculture and Forestry 2017b). As of November 2017, returns to farmers from offsets are about Can\$0.70 and Can\$1.40/acre respectively for each of the two assumed sequestration rates (Alberta Agriculture and Forestry 2017b). These very low payment rates are unlikely to have incentivized many farmers to change their farming practices.

Under the scheme, offsets are supposed to be "above and beyond 'business as usual'" (Alberta Agriculture and Forestry 2017a). Zero-till and reduced tillage practices were already widely practiced in Alberta, prior to the introduction of the offset scheme. The scheme, therefore, adopts a ‘scaling or discounting approach’ to additionality, whereby the assumed rates of sequestration for no-tillage practices are scaled down by the proportion of area that was already cropped with no-tillage practices in 2006. All farmers practicing no-tillage, including those who adopted it prior to the commencement of the scheme in 2007 are then allowed to participate in the program and claim offsets (Government of Alberta 2012b). As a result, the additionality of the program is likely to be poor.

Additionality was further degraded because the scheme rules allowed farmers already practicing conservation cropping in 2007 to join the scheme and be credited for what it is estimated they would have sequestered during the previous five years (Climate Change Authority 2014a). After receiving this once-off payment, many smaller farmers did not find it cost-effective to continue to remain in the scheme (Herr et al. 2011; Climate Change Authority 2014a).

No permanency obligations are placed on participants. Rather the volume of credits granted for undertaking the sequestering practice is scaled down based on the expected likelihood of the sequestration being released. Based on expert opinion the likelihood of reversal is assumed (at the sector level) to be 7.5–12.5 percent over the next 20 years (Government of Alberta 2012a). However, this raises further doubts about additionality. If around 90 percent of farmers would continue with zero-till even in the absence of payments, then the practice is clearly not additional except for a small minority of farmers.

Emissions Reduction Fund

Australia’s Emissions Reduction Fund (ERF) is a government scheme in which public money is used to purchase abatement. It operates by a reverse auction process; parties bid the price they are prepared to accept in order to undertake a voluntary action that mitigates or offsets emissions, and the government chooses to accept the most cost-effective bids. While the ERF is open to many sectors of the economy, it was envisaged that agriculture, through soil sequestration, would be the leading participant. Indeed, when the scheme was first proposed, it was suggested that by 2020 at least 150 million tonnes of CO_2 could be sequestered in soils annually, for a price of AUD$10/t$CO_2$.

The ERF commenced in late 2014 and, as of June 2016, the Australian Government had entered into AUD$1.73 billion worth of contracts to purchase abatement equivalent to 143 million tonnes of CO_2-e at an average price of AUD$12.10/t$CO_2$-e (CER 2016). Despite the initial high hopes that farmers would dominate the winning bids, agricultural soil carbon accounted for only 5.5 percent of this abatement (7.8 million tonnes of CO_2 over 10 years, equating to 0.78 million tonnes annually).

Permanency rules in the ERF require farmers to continue the sequestering practice for either (i) 100 years, or (ii) a shorter, 'temporary' 25 year period, after which the sequestered carbon can be freely re-released (Macintosh 2013). However, to compensate for the shorter period of sequestration in the second option, the amount of sequestration farmers are paid for is scaled down by 20 percent (House of Representatives 2014). It is questionable whether this 20 percent discount is adequate to compensate for the lower value of the shorter storage period. A further weakness is that some of the sequestered carbon is permitted to be released after less than 100 or 25 years. Although a farmer's sequestration occurs over a period of years, it can all be released 100 or 25 years after the farmer's first year in the program. Sequestration purchased in a farmer's 25th year in the program would be permitted to be released within 12 months. Despite this, the ERF's 20 percent discount applies to all sequestration, regardless of timing, which is very generous to farmers. As of 2016, more than 90 percent of the bid-winning sequestration in the ERF was of the 25-year, temporary type.

In the ERF additionality was handled by a requirement that abatement projects must be new and unlikely to be occurring as a result of another/different government program. However, a new activity could still occur as part of the normal course of business, and so not be additional. There is a high risk that these non-additional projects will win in the reverse auction because farmers can afford to make very low bids (Burke 2016).

Despite the scheme's rules being highly favourable to farmers, the role of soil carbon sequestration in the ERF has been minor, suggesting that other factors such as transaction costs, uncertainty about climate policy and the future of the scheme (Dumbrell et al. 2016), and a fear of losing future flexibility have remained obstacles to farmer participation.

7. Potential Opportunities for PepsiCo to Contribute to Sequestration of Carbon in Agricultural Soils

Assessing whether actions are worth promoting

To be worthwhile promoting a practice for sequestration of carbon in soils, the practice needs to satisfy several criteria.

i. It should be technically effective at sequestering carbon.
ii. It should not be associated with high levels of leakage.
iii. It should not be so unprofitable that widespread adoption would be very costly.
iv. It should not be already adopted by most farmers.
v. If the promotion strategy relies on incentive payments or offsets, the practice should not be so profitable for farmers that it will be adopted in future even without a payment or offset system.

Table 2 shows a subjective assessment of each of the practice option against these criteria, based on the evidence and literature outlined earlier in this report. Based on these criteria, none of the options provides a compelling opportunity. For each of the practices assessed, the overall situation is summarised in Table 3. These overall assessments make it clear that the opportunities to mitigate climate change through the promotion of carbon sequestration in agricultural soils are limited. Several options have zero or low technical effectiveness (Increasing the growth of agricultural plants; retaining unharvested biomass within the field; cover crops; zero-till, reduced tillage). Several are associated with high levels of leakage (replacing crops with pasture; land retirement or afforestation) or would be at risk of causing reductions in sequestration at other sites (importing organic matter to the field). Two are technically effective but financially costly in many or most situations (applying biochar; land retirement or afforestation). Several are already widely adopted and so at high risk of being non-additional (increasing the growth of agricultural plants; retaining unharvested biomass within the field; zero-till, reduced tillage).

[Table 2. *Assessment of practices for sequestering carbon in agricultural soils against criteria for assessing whether to promote the practice*]

[Table 3. *Overall assessment of potential to mitigate climate change through promotion of carbon sequestration in agricultural soils, based on assessment of specific criteria in Table 2*]

None of the options is without disadvantages. An option that appears to be worth considering further is to focus on regions where zero-tillage has so-far been adopted at a modest-to-moderate level (e.g., 20 to 50 percent of cropland) and contribute to efforts to increase its adoption in those regions. It would be best to avoid targeting regions with very high adoption, as there is then little scope for a further increase. Conversely, it would be best to avoid targeting regions with zero or very low adoption, as this probably reflects that zero-tillage is unsuited to this region or this farming system. An exception to the latter could be regions where zero-till has had no research or extension previously, although there are not many regions where this remains the case. The logic of targeting areas with moderate existing adoption is that there will likely be farmers at the margin of adopting it who need a little persuasion or support to do so. Even though the effectiveness of zero-till as a means of sequestering carbon has been assessed as zero to low, it may still be worth promoting if a large response can be generated at low cost.

Having established that the opportunities appear very limited, we now discuss the strategies available to agribusiness firms, using the same categories as in paper 2 (water pollution): targeting, informing and persuading, empowering, coordinating and incentivizing.

Targeting

Targeting could include identifying those countries, regions, farms/farmers, fields, crops or production systems for which the opportunities to sequester carbon in soils are relatively high because the overall costs of doing so are relatively low. Tables 2 and 3 could be used to inform a strategy for an analysis to inform this targeting.

Informing and Persuading

The aim of informing and persuading farmers is to get as far as possible with existing available sustainable practices without having to provide additional financial support or other forms of incentive. An agribusiness firm could lead an initiative to collate and analyze information and provide it to farmers, potentially directly, or potentially via other existing extension channels.

We know that many farmers are willing to adopt sustainable practices if they are win-win (in terms of their public and private net benefits) and that some can be persuaded to adopt them if they are win-neutral or even win-lose to some extent. The “lose” option has clear limits: evidence shows some adoption (in the right socio-economic circumstances) of sustainable practices that impose low net costs on farmers, but that adoption tends to fall away rapidly as the net costs on farmers increase. Farmers’ willingness to adopt is also influenced by their beliefs about how beneficial the practices will be in terms of public environmental benefits. Environmentally concerned farmers are prepared to make more of a private sacrifice if they are convinced that the public benefits are larger. The targeting exercise (see above) could contribute in this respect by providing convincing information that particular practices in particular locations are most likely to generate public benefits.

The biggest challenge with this option is the lack of compelling practices that are worth informing and persuading farmers about. It appears that none of the available practices generally satisfies all of the criteria needed to make them worth promoting (Table 2 and Table 3). If sequestration of carbon in soils is adopted as a target, it may be best to start with efforts to enhance the suite of available technical options (see the *Empowering* section below).

Empowering

This approach is about improving the technical options available to farmers. It could involve an agribusiness firm investing in highly targeted R&D to improve existing technical options or develop new options, with the objective being to reduce the private costs and/or increase the benefits (public and/or private) of the technical options. For example, an analysis could be undertaken to identify specific contexts where investment in technology development is most likely to lead to adoption of new practices, and where adoption is most likely to deliver increased sequestration.

The advantage of this strategy is that, if successful, it would increase the willingness of farmers to voluntarily adopt sustainable practices. For example, providing a new or improved practice with positive private net benefits for farmers would improve sequestration outcomes by improving the propensity for farmers to voluntarily adopt sustainable practices.

Coordinating

This is about PepsiCo using its networks, reputation, and profile to influence and organize other firms and agencies so that efforts to pursue sustainable agricultural outcomes are well aligned and mutually reinforcing. It involves PepsiCo adding value to the other analyses of this project by sharing and advocating them with other relevant firms and agencies.

For example, results of the Empowering analysis could be shared with research agencies to encourage them to target their research efforts appropriately. This could be supported by advocating for an approach to policy that better accounts for additionality, leakage, and permanence, rather than the existing relatively weak approaches to these issues.

The strategy might also involve PepsiCo coordinating with other firms or NGOs to jointly fund initiatives, such as the analyses needed to support targeting of effort, or the R&D to develop new technologies.

Incentivising

We understand that Pepsi is unlikely to choose to provide direct financial support to farmers to incentivize their decisions about adoption of sustainable practices. However, Pepsi may be able to contribute to incentivization in other ways, such as: by informing and collaborating with public regulatory and funding bodies (part of the *Coordinating* strategy), or by designing their contracts with farmers in innovative ways that provide the required incentives.

8. Conclusion

There has been strong interest and substantial public investment in programs to encourage or incentivize sequestration of carbon in agricultural soils. It has been seen as a strong potential contributor to the mitigation of climate change – a strategy that would help to buy time while the transition to renewable energy sources is underway.

Unfortunately, our review of the issue does not instill optimism about the potential for carbon sequestration in agricultural soils to make a difference to climate change. Our bottom line is that there appears to be no existing agricultural practice available that has the characteristics needed for it to be worth promoting as a general or widespread practice for farmers to adopt.

"We observe that the tendency to over-state the quantity of possible C sequestration, and overlooking of the constraints, often occurs in verbal presentations and non-refereed conference proceedings; in refereed scientific publications assumptions leading to over-estimation may be implicit rather than explicitly expressed … even thoroughly well-researched reviews of mitigation possibilities … can inadvertently give readers an exaggerated impression of the potential for soil C sequestration. This can arise because readers overlook the limitations mentioned above, and even the caveats stated within the papers." (Powlson et al. 2011, p.52).

Challenges identified in this review include the following:

i. Limited effectiveness of some of the agricultural practices for sequestering carbon in soils, including the most widely advocated practice of zero-tillage.
ii. Lack of private economic benefits from some of the practices that are relatively effective at sequestering carbon. In the absence of additional financial incentives, such as government payments or the ability to sell offsets to polluters, the carbon-effective practices often result in negative economic outcomes for farmers.
iii. High levels of leakage occurring as a result of some of the sequestration practices. This means that there are additional emissions, either on or off the farm where the sequestration practice is adopted, offsetting and potentially outweighing the benefits from the sequestration itself.
iv. High transaction costs required to ensure the integrity of a scheme designed to promote sequestration of carbon in soils.
v. From the perspective of an agribusiness firm interested in supporting strategies to increase soil carbon sequestration, there are a couple of options that may be worth

> further consideration. One is to look for low-cost opportunities to encourage zero-till. This means targeting efforts to areas with moderate existing adoption and aiming to influence farmers who are on the borderline of adoption. A third option is to invest in research and development to attempt to develop new practices that generate positive net benefits for farmers, as well as public benefits from carbon sequestration.

On the other hand, it may be preferable to investigate other strategies by which PepsiCo could contribute to the mitigation of climate change. Options could include strategies to reduce emissions of greenhouse gases from agriculture, or the possibility of making greater use of renewable energy sources to power PepsiCo processing and storage facilities or move material along its supply chains.

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Table 1. Practices for sequestering carbon in agricultural soils

Practice	**Sequestration potential**[a]	**Estimated sequestration rates from reviews and meta-analyses (tCO_2/ha/yr)** [b]	**Confidence that practice is likely to deliver on its sequestration potential**[c]
Increasing the growth of agricultural plants	0/★	*With fertiliser* Mediterranean climes: No stat. sig. increase (Aguilera et al. 2013) Multi country and regions, applied to grassland only: 1.1 (Conant et al. 2001) *With irrigation* U.S.: −0.6 – 2.8 (Eagle et al. 2012)	Low (Sanderman et al. 2010)
Retaining unharvested biomass within the field	★	Multi country and regions: ~1.3 (Minasny et al. 2017)	Moderate (Sanderman et al. 2010)
Replacing crops with pasture	★/★★	Multi country and regions: ~1.8 (Minasny et al. 2017) U.S.: 2.4 (mean) 0.4 – 4.2 (range) (Eagle et al. 2012)	Moderate (Sanderman et al. 2010)
Replacing annual pastures with perennial pastures	★★	U.S.: Include perennials in crop rotations 0.5 (mean) 0 – 1.2 (range) (Eagle et al. 2012) Replace annuals with perennial crops 0.7 (mean) -0.9 – 2.0 (range) (Eagle et al. 2012)	Moderate (Conant et al. 2001; Sanderman et al. 2010)
Cover crops	★	Multi country and regions: 1.2 (Poeplau and Don 2015) Mediterranean climes: 1.0 (Aguilera et al. 2013) U.S.: Eliminate summer fallow 0.6 (mean) -0.2 – 1.2 (range) (Eagle et al. 2012) Winter cover crops 1.3 (mean) -0.1 – 3.2 (range) (Eagle et al. 2012)	Moderate (Sanderman et al. 2010)

Importing organic matter to the field	★★/★★★	Multi country and regions: ~1.8 (Minasny et al. 2017)[d] Mediterranean climes: 4.8 (Aguilera et al. 2013) U.S.: 0.2 – 5.1 (Eagle et al. 2012)	High (Sanderman et al. 2010)
Applying biochar	★★★	Compared to normal soil organic matter, biochar's stability is less dependent on climatic and edaphic factors, meaning sequestration rates largely just depend on application rates[d]. However, in some trials, detrimental effects on plant growth have been observed at high application rates; e.g., 10t/ha, (Blackwell et al. 2010), 120t/ha (Mia et al. 2014).	High
Zero-till, reduced tillage	0/★	Multi country and regions: ~1.1 (Minasny et al. 2017); 1.6 – 2.9 (West and Post 2002); 0.8 (Virto et al. 2012); No stat. sig. increase (Luo et al. 2010) U.S.: 1.2 (mean) −0.24 – 3.22 (range) (Eagle et al. 2012)	Moderate (Sanderman et al. 2010)
Land Retirement or afforestation	★★★	Multi country and regions: ~2.2 (Minasny et al. 2017); −0.1 – 4 .9 (Smith et al. 2008); 3.7 (Conant et al. 2001); 1.1 – 4.5 (Qin et al. 2016) Temperate conditions: 2.6 (Kämpf et al. 2016) Mainly sub-tropical and tropical conditions: 1.2 (Post and Kwon 2000)	High (Sanderman et al. 2010)

Source: Developed by authors.

[a] Qualitative assessment of the practice's potential to sequester carbon (0 = nil, ★ = low, ★★ = moderate, ★★★ = high), following Sanderman et al. (2010)

[b] From reviews and meta-analyses only (usually involving multi-country datasets) and not individual studies

[c] Qualitative assessment of the reliability of the practice to deliver its sequestration potential, following Sanderman et al. (2010)

[d] Depends on nature of the material and the application rates and frequency

Table 2. Assessment of practices for sequestering carbon in agricultural soils against criteria for assessing whether to promote the practice

Practice	**Technically effective at sequestering carbon (from Table 1)**	**Not associated with high levels of leakage**	**Not more than slightly unprofitable for a target group of farmers**	**Not already adopted by most farmers in the target group**	**Not highly profitable to target farmers AND initiative uses incentive payments or offset**
Increasing the growth of agricultural plants	0/★	✓	✓	✓ in developing countries	
Retaining unharvested biomass within the field	★	✓	✓	Not in large-scale commercial farming, but ✓ in some smaller scale systems	✓ if payments or offsets used
Replacing crops with pasture	★/★★		✓ in certain mixed farming systems	✓ in many crop-intensive regions	✓ in certain mixed farming system if payments or offsets used
Replacing annual pastures with perennial pastures	★★		✓ in certain mixed farming systems	✓ in many crop-intensive regions	✓ in certain mixed farming system if payments or offsets used
Cover crops	★	✓ if not grazed		✓	✓ if payments or offsets used
Importing organic matter to the field	★★/★★★	May result in reduced carbon storage at the source site		✓	✓ if payments or offsets used

Applying biochar	★★★	✓		✓	✓ if payments or offsets used
Zero-till, reduced tillage	0/★	✓	✓	✓ for some farmers in countries or regions where adoption is less than 50 percent (e.g. U.S.)	✓ for some farmers in countries or regions where adoption is less than 50 percent (e.g. U.S.) if payments or offsets used
Land Retirement or afforestation	★★★		✓ for low-fertility land	✓	✓ if payments or offsets used

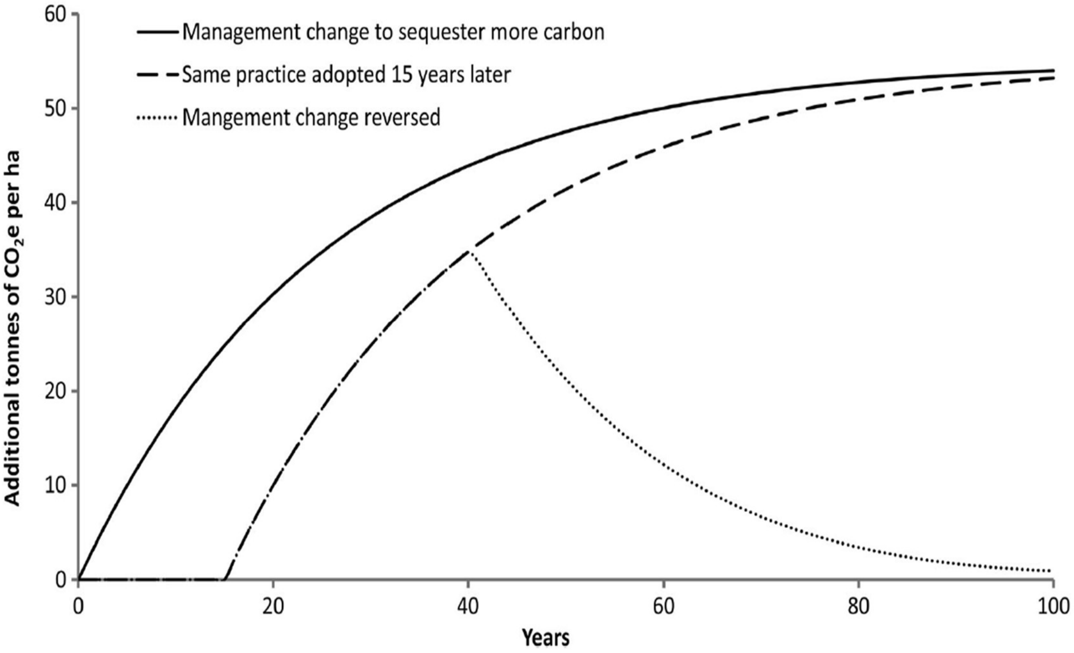
Source: Developed by authors.

Table 3. Overall assessment of potential to mitigate climate change through promotion of carbon sequestration in agricultural soils

Practice	**Overall assessment**
Increasing the growth of agricultural plants	Zero to low technical effectiveness. Largely already adopted in developed countries.
Retaining unharvested biomass within the field	Low technical effectiveness. Already adopted by many or most farmers in large-scale commercial farming systems.
Replacing crops with pasture	Associated with high levels of direct leakage due to grazing of livestock.
Replacing annual pastures with perennial pastures	Associated with high levels of direct leakage due to grazing of livestock.
Cover crops	Low technical effectiveness. Unprofitable in many situations.
Importing organic matter to the field	Effective locally, but maybe at the cost of reduced carbon storage at the site from which the organic matter is sourced.
Applying biochar	Effective but poor economic returns.
Zero-till, reduced tillage	Zero to low technical effectiveness. Largely already adopted in some developed countries.
Land Retirement or afforestation	Effective but associated with high levels of indirect leakage. Costly to farmer except on low-fertility land.

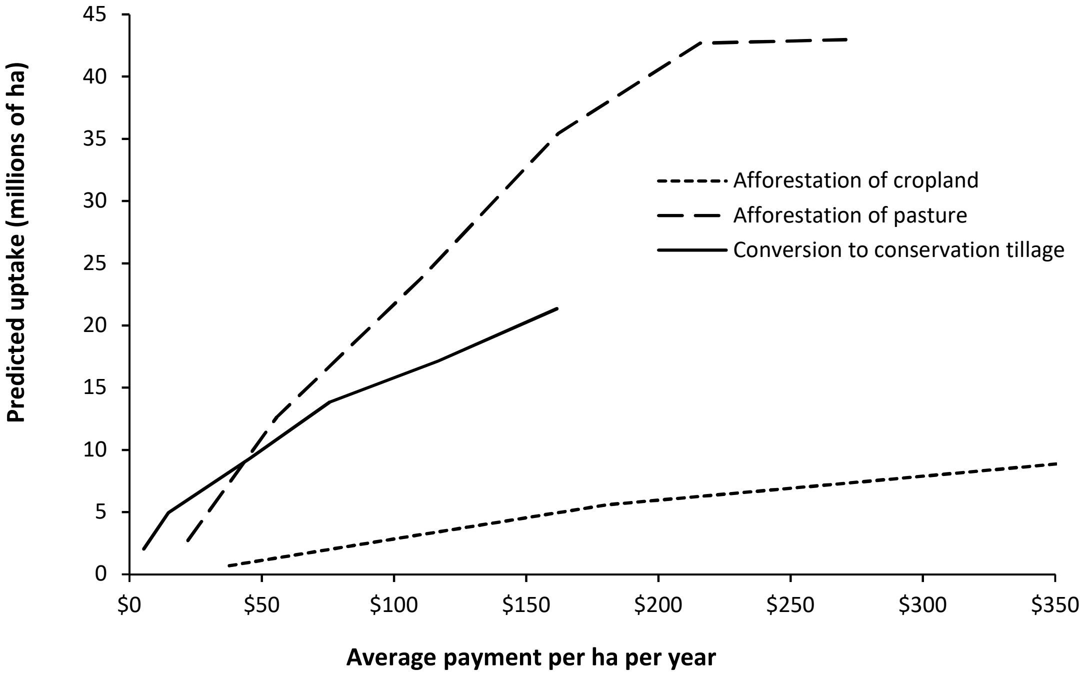
Source: Developed by authors based on assessment of specific criteria in Table 2.

Figure 1. Stylized dynamics of carbon sequestration



Source: Developed by authors.

Figure 2. Uptake of sequestering practices in the U.S. agricultural sector predicted to occur in response to an annual incentive payment



Source: Derived using data from Lewandrowski et al. (2004)