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Analysing reduced tillage practices within a bio-economic modelling framework

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ABSTRACT

Sustainable intensification of agricultural production systems will require changes in farm practice. Within arable cropping systems, reducing the intensity of tillage practices (e.g. reduced tillage) potentially offers one such sustainable intensification approach. Previous researchers have tended to examine the impact of reduced tillage on specific factors such as yield or weed burden, whilst, by definition, sustainable intensification necessitates a system-based analysis approach. Drawing upon a bio-economic optimisation model, 'MEETA', we quantify trade-off implications between potential yield reductions, reduced cultivation costs and increased crop protection costs. We extend the MEETA model to quantify farm-level net margin, in addition to quantifying farm-level gross margin, net energy, and greenhouse gas emissions. For the lowest intensity tillage system, zero tillage, results demonstrate financial benefits over a conventional tillage system even when the zero tillage system includes yield penalties of 0–14.2% (across all crops). Average yield reductions from zero tillage literature range from 0 to 8.5%, demonstrating that reduced tillage offers a realistic and attainable sustainable intensification intervention, given the financial and environmental benefits, albeit that yield reductions will require more land to compensate for loss of calories produced, negating environmental benefits observed at farm-level. However, increasing uptake of reduced tillage from current levels will probably require policy intervention; an extension of the recent changes to the CAP ('Greening') provides an opportunity to do this.

1. Introduction

In the face of a growing world population, increased resource scarcity and the challenges of climate change mitigation, there is an increasing need for adaptation in agriculture and agricultural systems towards practices that lead to "Sustainable Intensification" (SI; Wilson, 2014). Within arable systems dominated by combinable crop production (e.g. wheat, oilseed rape), changes to cultivation practices, for example towards *reduced tillage*[1] (RT), *conservation tillage* or *zero tillage* (ZT), have the potential to provide multiple environmental benefits (Holland, 2004) that would contribute towards SI objectives. These cultivation practices do not involve soil inversion (which occurs with ploughing); however the extent of soil disturbance typically ranges from intensive deep RT (e.g. tine harrows) to very minor soil disturbance in ZT (e.g. direct drilling).

RT provides benefits in areas prone to soil erosion including reduced soil erosion, pesticide runoff and watercourse sedimentation, improved soil quality, reduced leaching of nutrients and lower greenhouse gas (GHG) emissions (Fawcett and Towery, 2002; Holland, 2004; Morris et al., 2010). In humid temperate regions, such as northwest Europe, soil erosion is less of a problem and the environmental benefits of RT systems are less certain (Davies and Finney, 2002). RT systems have, however, been found to have lower GHG emissions and more favourable energy balances because of a reduction in machinery use (e.g. Knight, 2004). Reduced machinery use also leads to cost savings (Vozka, 2007), which is the primary driver of RT use in these areas (Davies and Finney, 2002). Studies have specifically identified that RT has lower fuel costs (e.g. Sijtsma et al., 1998; Šarauskis et al., 2014). Fewer machinery operations are also required with RT leading to reduced labour costs and improved timeliness of crop operations (Morris et al., 2010). When comparing RT with conventional tillage (CT) Verch et al. (2009) identified increased net returns from a German RT system of approximately €100 ha^{-1}.

Whilst clear financial benefits of RT practices have been observed, crop yield effects are less clear. Van den Putte et al. (2010), in reviewing

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Abbreviations: CAP, Common agricultural policy; CT, conventional tillage; DRT, deep reduced tillage; GHG, greenhouse gas; GM, gross margin; NE, net energy; NM, net margin; WOSR, oilseed rape; RT, reduced tillage; RP, rotational ploughing; SI, sustainable intensification; SRT1, shallow reduced tillage 1; SRT2, shallow reduced tillage 2; SB, spring barley; WB, winter barley; WFB, winter field beans; WW, winter wheat; ZT, zero tillage.

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[1] Practitioners use a variety of names for the non-inversion tillage system. In this study, reduced tillage is used to refer to any tillage system that does not employ inversion. For a more detailed look at various terminologies used in the literature, see Table 1 in Townsend et al. (2016).

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Europe-wide field experiments, found an average yield reduction of 4.5% from RT (from 563 observations across different experimental years) though when ZT was considered individually there was an average yield penalty of 8.5% (171 observations). Arvidsson et al. (2014) found an average yield reduction of 1.8% from shallow RT experiments in Sweden (918 observations) and 9.8% lower for ZT (226 observations). Crop-specific effects of RT are confirmed by Van den Putte et al. (2010) with winter cereals and maize responding unfavourably to RT whilst the yields of other crops were unaffected. Climate-specific effects have been found, with a meta-analysis by Ogle et al. (2012) reporting reductions in yield for ZT systems for wheat and maize in the Northeast of the US, but increased yields in more southerly areas. Although RT tends to show an average yield reduction, when individual field experiments are considered, yields can be greater than with inversion-based tillage (e.g. Knight, 2004; Verch et al., 2009).

Although fuel, labour and machinery costs have been estimated to be lower for RT systems, there can be additional costs in RT systems resulting from greater weed, pest and disease burdens. Where present or where there is perceived to be a risk of their presence, farmers will apply additional crop protection inputs. Generally, extra herbicide is required for weed control under RT (Melander et al., 2013). Models of RT system costs have accounted for input use variability and have concluded that reduced fuel costs outweigh the costs of additional pesticide inputs (e.g. Lafond et al., 1993; Nail et al., 2007; Vozka, 2007). Greater amounts of fungicides may also be required, depending on the preceding crops in the rotation (Bürger et al., 2012). The fate of crop residues also influences tillage system costs as leaving crop residues in situ in RT systems can potentially increase molluscicide and fungicide requirements (Soane et al., 2012).

Consequently, whilst RT within a northwest European context provides possible cost and GHG savings, the potential trade-offs of RT approaches include yield reductions and increased crop protection costs. Currently, approximately 30–40% of arable land in England is under RT (Defra, 2010; Townsend et al., 2016). Given the identified benefits associated with the technique, it is pertinent to determine why there is not a greater area of land under RT.

Previous studies noted above have largely focused upon single issues of relevance to RT (e.g. profit; Verch et al., 2009); however, to achieve SI objectives it is necessary to examine the changes to cropping system approaches within a wider, system-based context. Sørensen et al. (2014) used a system-based approach to investigate tillage practices, demonstrating the value of this approach. This current study aims to address this issue, specifically utilising a bio-economic model, building upon Glithero et al. (2012), to investigate the influence of tillage type on a farm system and its outputs. Within our approach, we quantify the benefits, trade-offs and costs associated with different cultivation and crop establishment practices within a UK arable farm context.

2. Methodology

2.1. MEETA model

The MEETA (Managing Energy and Emissions Trade-Offs in Agriculture) model is a bio-economic optimisation model that determines optimal crop mix for three primary objectives: profit and net energy (NE) maximisation, and GHG emission minimisation. Profit is measured by total gross margin (GM), i.e. value of sales less variable costs of production for a given harvest year. Output from runs under each objective allows comparison of trade-offs between these competing objectives: for example, how much profit is foregone from reducing GHG emissions. The model was originally developed to establish trade-offs associated with increasing the supply of agricultural feedstocks for bioenergy production (Glithero et al., 2012). The model has also been used to consider the economic and environmental impacts of including dedicated energy crops (miscanthus and short rotation coppice grown for biofuel feedstock) within farm cropping systems and the extent to which marginal land is suited to bioenergy feedstock production (Glithero et al., 2015).

The model used here excludes dedicated energy crops and considers a 400 ha farm with a crop rotation that can include any of the following: winter wheat (WW), winter and spring barley (WB and SB, respectively), winter oilseed rape (WOSR) and winter field beans (WFB). The WW crop includes first, second and continuous wheats, i.e. first wheat is a wheat crop grown after a break crop (in the model this would be WOSR or WFB); second wheat is a wheat crop after first wheat and continuous wheat is where land is under wheat for three or more years. Straw can be baled from WB, SB and WW, or incorporated into the soil. Rotational constraints within the model limit the crops that can be grown, with break crops (WOSR and WFB) only being grown after a cereal crop. The crop mix generated is a single year representation of the average area of each crop grown.

A brief description of the three primary metrics of interest (GM, NE, GHG emissions) is given below; further details are provided in Glithero et al. (2012). The GMs include the variable costs of fertiliser, crop protection, seed, fuel for machinery operations and grain drying, and contractors' fees. Note that these GMs do not include the Basic Payment Scheme subsidy, part of the Common Agricultural Policy (CAP), as this is decoupled from production and therefore will not vary with crop mix. However, recent changes to the CAP ('Greening') do effect production and are included in the methods described below.

NE takes account of the energy required to produce the inputs, as well as the energy embedded in the machinery being used and the energy captured within the crop output. GHG emissions are calculated from the emissions required to produce fertilisers and sprays, the embedded emissions from machinery, soil N_2O (nitrous oxide) emissions (calculated as 1.6% of applied nitrogen (N) released as N_2O and a background soil emission of 1.4 kg N_2O–N ha^{-1} yr^{-1}). In reviewing the ZT literature, Soane et al. (2012) found that ZT tends to initially have higher N_2O emissions but that this is not a consistent finding. Therefore, the emission level was initially kept constant for all tillage systems modelled. A sensitivity analysis was used to assess how important these assumptions are to overall GHG emissions for the different ZT systems considered below.

It was assumed that tillage practices do not influence fertiliser or crop protection requirements. Reducing tillage intensity has been suggested to alter fertiliser requirements. Some sources have found that greater N application is required during the first years of ZT and lower amounts in later years — in part because of reduced leaching (Soane et al., 2012); however, there is insufficient data to robustly consider this and, moreover, effects are likely to be highly site- and farm system-specific; they are, therefore, not included in the model.

The original model contains an intensive conventional tillage (CT) process consisting of a single pass of a plough followed by two passes of a power harrow. Work-rates for different machinery operations (ABC, 2011) are based on a heavy soil type and thus represent a relatively energy-intensive tillage system. The CT system used in the original model was modified to reflect a range of different RT systems. A number of scenarios were considered to provide a systems approach to determining the value of RT systems. These are listed below but more details are given in the further sections of the methodology.

- Baseline scenario: In this scenario, the model parameters and assumptions reflected market conditions in 2011, which is identical to those in the original study (Glithero et al., 2012). These prices were specifically maintained to allow a direct comparison to the outputs presented in the previous work, with the current work, without the conflating effect of introducing more recent prices. All model scenarios, excluding the price sensitivity scenario, are based on the 2011 market conditions.
- Net margin scenario: To capture tillage system impacts on farm finances, total farm net margin (NM) was calculated as GM less