Towards Sustainable Intensification of Cropping Systems: Analysing Reduced Tillage Practices within a Bio-Economic Modelling Framework

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Abstract

Sustainable Intensification (SI) of agricultural production systems will require changes in farm practice. Within arable cropping systems, reducing the intensity of tillage practices (e.g. reduced tillage; RT) potentially offers one such SI approach. Previous researchers have tended to examine the impact of RT on specific factors (e.g. yield, weed burden) while, by definition, SI 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 net margins, in addition to quantifying farm-level gross margin, net energy, and greenhouse gas emissions. Results demonstrate that RT approaches are financially optimal given crop yield penalties of 0-14.2% (across all crops). In addition, increases in net energy and reductions in greenhouse gas emissions are associated with RT approaches. Yield reductions from the RT literature are small, suggesting that RT offers a realistic and attainable SI intervention. However, issues of increased crop protection costs and possible longer term weed burden (blackgrass) associated with RT techniques remain, arguably reducing the potential of RT as a longer term SI intervention strategy.

Keywords Reduced Tillage; Bio-economic Modelling; Sustainable Intensification.

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Introduction

In the face of a growing world population, increased resource scarcity and climate change mitigation, there is an increasing need for adaptation in agriculture and agricultural systems towards practices that are contemporaneously being defined as "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", "conservation tillage" or "no-till / direct-drilling", 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 tillage (tine harrows) to very minor soil disturbance (direct-drilling).

Reduced tillage[1] (RT[2]) 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 & 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 & Finney, 2002). RT systems have, however, been found to have lower GHG emissions and more favourable energy balances due to 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 & Finney, 2002). Studies have specifically identified that RT has lower fuel costs (e.g. Sijtsma et al., 1998; Šarauskis et al., 2014). Verch et al. (2009) comparing RT with conventional tillage (CT) identified increased net return from a German RT system of approximately €100 ha^{-1}.

While clear financial benefits of RT practices have been observed, crop yield effects are less clear. Van den Putte et al. (2010), in reviewing Europe-wide field experiments found an average yield reduction of 2.7% from RT, whilst Arvidsson et al. (2014), found an average yield reduction of 1.8% from RT experiments in Sweden. In a meta-analysis of 74 studies, Ogle et al. (2012) report reductions in yield for ‘no-till’ systems for wheat and corn (maize) in excess of 0.5 tonnes carbon ha^{-1} in the Northeast of the US, but increased yields in more southerly areas. Other crop specific effects of RT are confirmed by Van den Putte et al. (2010). When individual field experiments are considered, yields can also be greater under RT (e.g. Knight, 2004; Verch et al., 2009).

Although fuel and machinery costs have been estimated to be lower for RT systems, there are potentially additional costs incurred in RT system resulting from a greater risk of weed, pest and disease burdens, requiring additional crop protection inputs. Extra herbicide is generally required for weed control under RT (Melander et al., 2013). Models of RT system

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[1] Practitioners use a variety of names for the non-inversion tillage system. In this paper, reduced tillage is used to refer to any tillage system that does not employ inversion.

[2] Abbreviations: Reduced tillage (RT); conventional tillage (CT); rotational ploughing (RP); shallow reduced tillage 1 (SRT1); shallow reduced tillage 2 (SRT2); deep reduced tillage (DRT); direct drilling (DD); gross margin (GM); net margin (NM); net energy (NE); greenhouse gas (GHG); winter wheat (WW); winter barley (WB); spring barley (SB); oilseed rape (OSR); winter field beans (WFB).

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 might 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).

Hence, while 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. Previous studies noted above have largely focused upon single issues of relevance to RT; however, to achieve SI objectives it is necessary to examine the changes to cropping system approaches within a wider, systems-based context. This current study aims to address these issues, 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 trade-offs, benefits and costs associated with different cultivation and crop establishment practices within a UK arable farm context.

Methodology

MEETA model

The MEETA (Managing Energy and Emissions Trade-Offs in Agriculture) model is an optimisation model that determines optimal crop mix for three primary objectives: profit and net energy (NE) maximisation and GHG emissions minimisation. Profit is measured by total Gross Margin i.e. value of sales less variable costs of production for a given harvest year; however, as we show here, MEETA can also be used to calculate Net Margins. Net energy captures the energy surplus (or ‘balance’) after deducting energy used in the farm’s production processes from the energy contained in the crop-based outputs. GHG emissions are linked to the different production processes within the model and include embodied emissions from inputs such as machinery and fertilisers. Model outputs from runs under each objective allow comparisons of trade-offs between these competing objectives to be made: how much profit or net energy is foregone from reducing GHG emissions for example.

The model considers a 400 ha farm with a rotation that can include any of the following crops: winter wheat (WW), winter and spring barley (WB and SB, respectively), winter oilseed rape (OSR) and winter field beans (WFB). The WW includes a first, second and continuous wheat and straw can be baled from the WB, SB and WW. As well as considering a standard farm system (Glithero et al., 2012), the model has also been used to examine marginal land impacts and the use of dedicated energy crops (Glithero et al., 2015). 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) were based on a heavy soil type and thus represent a relatively energy-intensive tillage system. Crop mix for maximum profit and associated net energy and GHG emissions, with full tillage (plough + power harrow) is presented below (**Table 1**). Assumptions reflect market conditions in 2011; further details in Glithero et al. (2012).

Table 1: *Results from the MEETA model (Glithero et al., 2012).*

		Gross margin maximised	**Net energy maximised**	**GHG emissions minimised**
Crop mix (ha)	Winter wheat (SR, 75% N)	133.33	200.00	0
	Winter barley (ASR, SR)	133.33	0	0
	Winter oilseed rape	133.33	0	0
	Winter wheat (50% N)	0	0	200.00
	Winter field beans	0	200.00	200.00
Finance	Overall farm costs	263,284	197,567	179,446
	Overall farm revenue	549,066	466,238	421,519
	Gross margins (£ farm^{-1})	285,782	268,172	242,188
Energy	In	9,367	5,752	5,090
	Out	35,115	31,952	26,033
	Net (GJ farm^{-1})	25,727	26,159	20,937
GHG emissions	Kg CO_2-eq farm^{-1}	1,767,137	935,308	764,305

Key: SR – straw removed; ASR – grown after the previous crop had straw removed; % N – percentage of nitrogenous fertiliser applied relative to recommended levels.

GHG emissions vary substantially across the three objectives, largely in response to the amount of purchased nitrogen used; differences in profitability and net energy are relatively small in comparison. The CT system of tillage used to generate the results in **Table 1** was modified to reflect five different RT systems, as follows.

Minimum tillage processes

RT systems in England employ a wide range of equipment and tillage practices; in particular, there is variation in tillage depth and number of passes (SMI, 2005). These vary with soil and weather conditions, crops and crop positions in rotations. To consider this level of variability, a number of different RT systems are compared within our approach (**Table 2**).

Table 2: *Tillage systems investigated in the MEETA model.*

Tillage system	Abbreviation	Description
Rotational ploughing	RP	Reduced tillage (two passes of a medium disc harrow) for break crops but CT before wheat and barley.
Deep reduced tillage	DRT	A one-pass cultivator, consisting of tines and discs. As the soil is heavy, we assume two passes.
Shallow reduced tillage 1	SRT1	Two passes of a medium disc harrow.
Shallow reduced tillage 2	SRT2	Two passes of a spring-tine harrow.
Direct drilling	DD	Seed planted into the stubble from the previous crop.

Work rates for DRT and SRT2 were taken directly from ABC (2011) whilst the work rate for SRT1 was calculated from average contractors’ work rates. The number of cultivation / establishment passes is two for all crops and tillage options apart from DRT where WFB only has a single pass (**Table 3**). The one-pass cultivator requires a large tractor whilst the disc and tine harrows require a medium tractor. There is no secondary tillage and it is assumed that two passes provide a tilth suitable for establishment of the next crop. All tillage options include the same drill as the original model, apart from OSR, which is assumed to be broadcast simultaneously with the tillage operations in all RT options except for the no-till option where the seed drill is required. [The original model assumes a precision drill is used; this has a slower work rate than the cultivation drill often used for drilling crops in cereal rotations. However, substituting in a cultivation drill has very little impact on overall output values and, therefore, was retained for this analysis.]

The indirect energy and GHG emissions are calculated based on the weight of the equipment assuming that is constructed of steel (**Table 4**). Equipment weights were average values from representative industry sources.

Table 3: *Work rates and number of passes per crop for the tillage options.*

Tillage system	**Field operation**	**Work rate (min ha^{-1})**	**Number of passes per crop**				
			WW	**OSR**	**WB**	**SB**	**WFB**
CT	Plough (6 furrow; heavy land)	70	1	1	1	1	1
	Power harrow 4 m; heavy land)	67	2	2	2	1	0
	Precision drill	43	1	1	1	1	1
RP	Plough (6 furrow; heavy land)	70	1	0	1	1	0
	Power harrow 4 m; heavy land)	67	2	0	2	1	0
	Medium disc (2-3 m)	42	0	2	0	0	2
	Precision drill	43	1	0	1	1	1
DRT	One-pass cultivator (4.5 m; heavy land)	24	2	2	2	2	1
	Precision drill	43	1	0	1	1	1
SRT1	Medium disc (2-3 m)	42	2	2	2	2	2
	Precision drill	43	1	0	1	1	1
SRT2	Spring-tine harrow (6 m; heavy land)	23	2	2	2	2	2
	Precision drill	43	1	0	1	1	1
DD	Precision drill	43	1	1	1	1	1

Table 4: *Embodied energy and GHG emissions for the farm machinery.*

Machine	**Weight (kg)**	**Indirect energy (MJ hr^{-1})**	**Indirect emissions (kg CO_2-eq hr^{-1})**
One-pass cultivator (4.5 m)	7,350	56.35	3.83
Medium disc harrow (2-3 m)	1,720	13.19	0.90
Spring-tine harrow (6 m)	3,500	26.83	1.81

Net margins

The total gross margin calculated by the MEETA model excludes machinery costs apart from fuel and any work undertaken by contractors. To more appropriately capture tillage system impacts on farm finances, a net margin (NM) was calculated based on gross margin less machinery and labour costs. The NM is similar to the adjusted gross margin used in Glithero et al. (2015) to investigate ownership of machinery; however, the authors made no allowance for the effect of machinery usage on depreciation. The current NM included depreciation and labour costs, which were adjusted to reflect the level of machinery usage.

To calculate NM, time and labour constraints were relaxed within the MEETA model to capture a scenario in which all farm operations (excluding baling and swathing, which require a contractor) are carried out with the farm's own equipment. The NM was then calculated based on the machinery requirements for the crop mix given when the system is optimised for GMs. Overall machinery use will depend on the crop mix and the tillage operations used; for each crop, it was assumed that non- tillage and drilling machinery costs remained the same.

Machinery purchase prices and labour costs were taken from (ABC, 2011) whilst depreciation rates, spares & repairs costs, and insurance rates were taken from ABC (2001). The depreciation rate was taken as a straight-line depreciation with the rate calculated based on the hours of machinery use; for example, the annual depreciation rate for a medium tractor ranges from 15% for a use of 500 hours yr^{-1} to 27% for a use of 1,500 hours yr^{-1}. Interest on capital was assumed to be 3%.

Trade-offs from reduced tillage use

To investigate whether potential yield penalties from RT outweigh any potential cost saving benefits, sensitivity analysis was undertaken to determine acceptable threshold yield penalties. While actual yield penalties for RT in England can be found in the literature, these frequently relate to data obtained prior to the to the ban of stubble burning in England and Wales (*The Crop Residues (Burning) Regulations 1993*); in these studies the straw was burnt prior to the next crop, which is likely to have aided weed and disease control. Yields from shallow RT were lower after straw incorporation rather than straw burning (Graham et al., 1986; Christian et al., 1999), suggesting RT systems became less favourable following the straw burning ban. Other evidence suggests that WW yields tended to be lower under RT (Turley et al., 2003), while Knight (2004) found higher yields under RT. Hence, given this variability in data, the impact of yield reductions was examined by reducing yields for all crops from the 100% baseline to establish the threshold at which the benefits, derived from reduced costs, over the CT system, are negated.

The model also examines the impact of additional herbicide under RT to control for weeds. The most problematic weed in the UK is blackgrass and there are a number of different herbicides commercially used to treat for blackgrass; to capture this it was assumed that RT leads to a requirement of an additional generic herbicide application (both an additional chemical as well as an additional spray operation).

2014 prices

After running MEETA using the default (2011 price) values, the model was run with prices updated to a 2014 market environment. Diesel costs were assumed to be unchanged. Fertiliser prices were taken from (ABC, 2014): the 2014 nitrogen price of £750 t^{-1} N is 20% lower and the 2014 phosphorous price of £620 t^{-1} P_2O_5 55% greater than the default values. Potash price for 2014 was similar (2% lower) to that used in the original model. Chemical costs are the authors' own calculations based on the overall crop protection costs for crop types from ABC (2011) compared to ABC (2014; **Table 5**). Crop prices were generally lower in 2014 than in 2011 (**Table 6**).

Table 5: *Pesticide costs and number of applications per crop. Calculated using the original calculations using prices from ABC (2014).*

Crop	**Pesticide category**	**No. of sprays**	**Original price (£ ha^{-1})**	**New price (£ ha^{-1})**	**Difference (%)**
Wheat	Fungicides	3	68.95	77.93	+ 13.0
	Herbicides	3	36.01	44.04	+ 22.3
	Growth regulators	2	22.54	23.50	+ 4.3
	Insecticides	1	5.80	4.96	- 14.5
	Seed treatments and molluscicides[a]	1	14.19	14.81	+ 4.4
	Seed treatments and molluscicides[b]	1	16.09	16.79	+ 4.3
W. barley	Fungicides	2	45.97	51.95	+ 13.0
	Herbicides	2	24.01	29.36	+ 22.3
	Growth regulators	1	11.27	11.75	+ 4.3
	Insecticides	1	5.80	4.96	- 14.5
	Seed treatments and molluscicides	1	13.72	14.32	+ 4.4
S. barley	Fungicides	2	45.97	51.95	+ 13.0
	Herbicides	2	24.01	29.36	+ 22.3
	Seed treatments and molluscicides	1	15.61	16.29	+ 4.4
OSR	Fungicides	2	29.14	22.13	- 24.1
	Herbicides	3	89.43	80.36	- 10.1
	Insecticides	2	12.87	11.50	- 10.6
	Seed treatments and molluscicides	2	20.66	24.50	+ 18.6
WFB	Fungicides	2	37.01	30.33	- 18.0
	Herbicides	2	64.93	73.33	+ 12.9
	Insecticides	2	12.87	13.25	+ 3.0

a) For a first winter wheat; b) For a second or continuous winter wheat.

Table 6: *Crop prices from the original model and new prices reflecting average crop prices from November 2013 to October 2014.*

Crop	**Original price (£ tonne^{-1})**	**New price (£ tonne^{-1})**	**Change (%)**
Wheat (grain)[a]	172.36	144.56	- 16.1
Wheat (straw)[b]	43.00	43.50	+ 1.2
Barley (grain)[a]	164.42	122.64	- 25.4
Barley (straw)[b]	59.00	51.92	- 12.0
OSR[c]	374.08	290.49	- 22.3
Field beans[c]	206.67	221.30	+ 7.1

a) Defra (UK weekly commodity prices, source HGCA); b) Defra commodity prices: Hay & Straw, England and Wales average prices. c) Selected feedingstuffs prices, Great Britain.

Net margins were also calculated for 2014 using updated machinery costs and labour wages (£10.19 hr^{-1}) from ABC (2014). Contractor fees were based on machinery costs assuming a high usage rate, a 25% overhead and a 35% surcharge on the labour rate (£13.76 hr^{-1}, **Table 7**).

Table 7: *Contractors' costs in the 2011 and 2014 MEETA models.*

Machinery	**2011 contract cost (£ hr^{-1})**	**2014 contract cost (£ hr^{-1})**	**Difference (%)**
Small tractor	25.01	23.90	-4.4
Medium tractor	35.81	35.28	-1.5
Large tractor	50.21	44.61	-11.2
Combine harvester	121.00	123.48	+2.0
Swather	57.00	57.87	+1.5
Baler (round bales)	45.63	53.51	+17.3

Results

Crop mix

Substituting a plough-based CT system for RT changes the optimal crop mixes. For optimised GMs, RP favours increasing OSR area to half the rotation whilst increasing WW slightly, at the expense of WB. For all other RT options, OSR and WW are increased at the expense of WB area but there is an equal amount of WW and OSR (**Table 8**).

For optimised NE, the RP and full RT systems (SRT1, SRT2, DRT and DD) still favour half wheat with straw harvested but OSR is now favoured over WFB as the break crop; this is due to the OSR crop now being broadcast from the tillage machinery, which avoids having a separate drilling operation, whilst WFB is drilled. As with CT, the optimal crop mix for minimised GHG emissions for the RP and full RT systems has WW, with the minimum nitrogen fertiliser level, and WFB in equal proportions.

Table 8: Crops mixes for RT systems for optimised gross margins, net energy and GHG emissions for the complete reduced tillage systems.

Objective	**Gross margin maximised**	**Net energy maximised**	**GHG emissions minimised**
Crop		**Ha**	
Winter wheat (SR, 75% N)	186.5	200.0	0
Winter barley (ASR, SR)	27.0	0	0
Winter oilseed rape	186.5	200.0	0
Winter wheat (50% N)	0	0	200.0
Winter field beans	0	0	200.0

Key: SR – straw removed; ASR – grown after the previous crop had straw removed; % N – percentage of nitrogenous fertiliser applied relative to recommended levels.

Outputs based on gross margins

Gross margins were greater for the RT systems (**Table 9**). The high cost for the CT system results from having two passes of a power harrow, which has a low work rate and requires a large tractor. This results in time and labour requirements exceeding the available farm resources and, therefore, contractors are required to complete the process. This adds approximately £85 ha^{-1} onto the costs compared to the RT systems. These are additional to the contractor fees incurred by all tillage systems for the use of the baler and swather.

Although the RP system only has 50% RT, the GMs were much greater than for the CT system; lower time and labour requirements for land preparation free up sufficient resources on farm to conduct these operations and, therefore, contractor requirements are much lower, significantly reducing costs. The full RT systems have similar GMs; interestingly, DRT has an almost identical GM to SRT1. Although SRT1 requires a smaller tractor, the work rate is lower negating the benefit of using a lower powered machinery input.

Table 9: *Key output data for the different tillage options (based on the crop mixes for optimised gross margins).*

	CT	**RP**	**SRT1**	**SRT2**	**DRT**	**DD**
GM (£ farm^{-1})	285,782	326,522	351,508	355,175	351,366	357,717
GM (£ ha^{-1})	714.46	816.30	878.77	887.94	878.42	894.29
NE (GJ farm^{-1})	25,727	26,211	27,684	27,910	27,668	28,067
GHG (kg CO$_2$-eq)	1,772,947	1,679,049	1,599,274	1,579,982	1,600,597	1,566,22
Fuel use (L farm^{-1})	91,951	71,193	42,605	48,294	48,515	38,661.36
Contractors' fees (£ farm^{-1})	43,748	11,364	9,689	9,689	9,689	9,689

CT – conventional tillage; RP – rotational ploughing; SRT1 – shallow reduced tillage, discs; SRT2 – shallow reduced tillage, spring-tines; DRT – deep reduced tillage; DD – no-till/direct drill.

Outputs based on net energy and GHG emissions

Net energy increased for the RT systems; for the DD system the optimised NE crop mix gives a NE value 7.7% greater than for the CT system. When the crop mix was optimised for minimum GHG emissions the emissions are lower from the RT systems with the DD system having 16.4% lower GHG emissions than the CT system. These result from lower fuel use and lower allocation of embedded energy and GHG emissions in the machinery.

Outputs based on net margins

Removing machinery and labour constraints led to a change in the optimal crop mix for all tillage systems as WB is replaced by a 50:50 WW:OSR rotation, reflecting the increase in available resources and different timing of operations for WB relative to WW and OSR (WB 'spreads the harvest' and thus reduces total workload).

The RP system results in similar machinery costs to the CT system (**Table 10**). The full RT systems have greater NMs resulting from a combination of lower machinery, fuel and labour costs. The NM for the DD system is £210.20 ha^{-1} greater than the CT system. These results indicate greater financial benefits are derived from using RT than the GMs suggest; this is because NMs take into account the benefits of reduced labour and machinery costs alongside the reduced fuel use.

Table 10: *Net margins and machinery, labour and fuel costs for the tillage systems (based on the crop mixes for optimised gross margins).*

	CT	**RP**	**SRT1**	**SRT2**	**DRT**	**DD**
GM (£ farm^{-1})	323,759	337,296	352,914	356,581	352,772	358,982
GM (£ ha^{-1})	809.40	843.24	882.28	891.45	881.93	897.45
NE (GJ farm^{-1})	25,987	26,819	27,788	28,013	27,771	28,161
GHG (kg CO_2-eq)	1,744,560	1,673,224	1,590,358	1,571,066	1,591,680	1,558,385
Machinery costs (£ ha^{-1})	297.99	287.41	226.65	211.85	276.74	206.46
Fuel costs (£ ha^{-1})	145.24	111.40	72.35	63.19	72.71	57.19
Labour costs (£ ha^{-1})	68.64	59.63	47.40	41.73	42.01	38.02
Net margins (£ ha^{-1})	446.31	499.74	611.77	641.41	566.72	656.51

CT – conventional tillage; RP – rotational ploughing; SRT1 – shallow reduced tillage, disc harrows; SRT2 – shallow reduced tillage, spring-tines; DRT – deep reduced tillage; NT – no-till/direct drill.

Trade-offs

An overall yield reduction of 14.2% is required for the GM of the DD system to equate to the CT system GM (with normal yields; **Fig. 1**). Reducing crop yields changes the optimal crop mix, resulting in an increased WB area until an equal amount of land is used for WW, WB and OSR. An 8.12% yield reduction is required for the GMs of the RP to equal those of the CT system (with normal yields). With respect to the net energy metric, the DD system can incur a 7.0% yield reduction (**Fig. 2**) before NE equates to the CT system (with normal yields); the RP system can incur a 2.23% yield reduction. GHG emissions were divided by the output of the system in kg of crop output; yields have to be 10.7% lower from the DD system for the GHG emissions kg^{-1} food to be equal to those from the CT system (with normal yields; **Fig. 3**).

Adding an additional herbicide application (one spray and spray application) to the DD system leads to a 2.5% decrease in GMs (when optimising for GM), 0.2% decrease in NE (when optimising for NE) and a 0.7% increase in GHG emissions (when optimising for GHG emissions). When the DD's NM is considered there is an additional £4.81 ha^{-1} cost from machinery, fuel and labour resulting from the use of an additional herbicide.

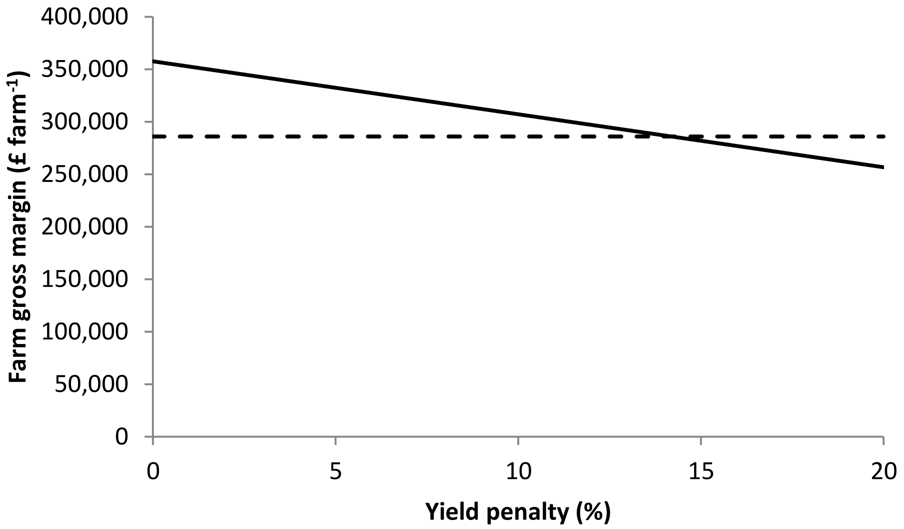

Figure 1: *Gross margins per farm for the DD system with crop yield penalties (solid line). The dashed line represents the gross margin per hectare for a CT system without yield penalties.*

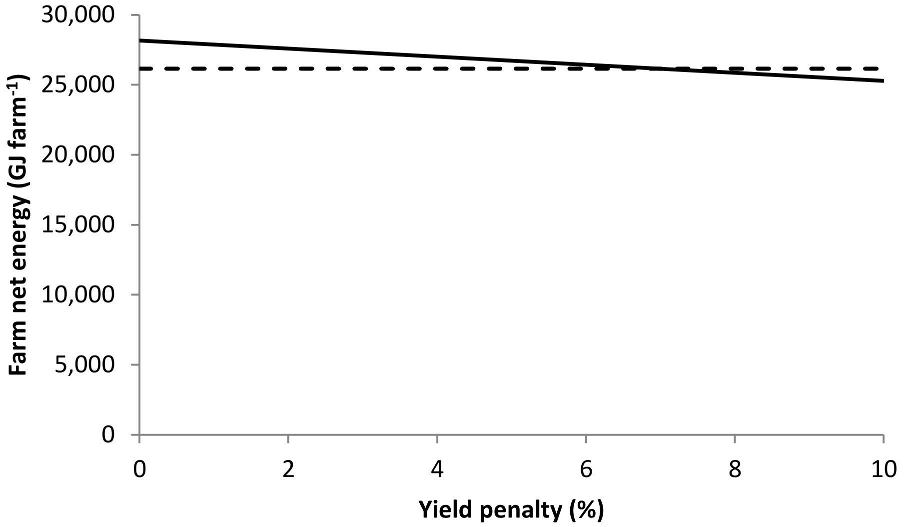

Figure 2: *Net energy per farm for the DD system with crop yield penalties (solid line). The dashed line represents the net energy for a CT system without yield penalties.*

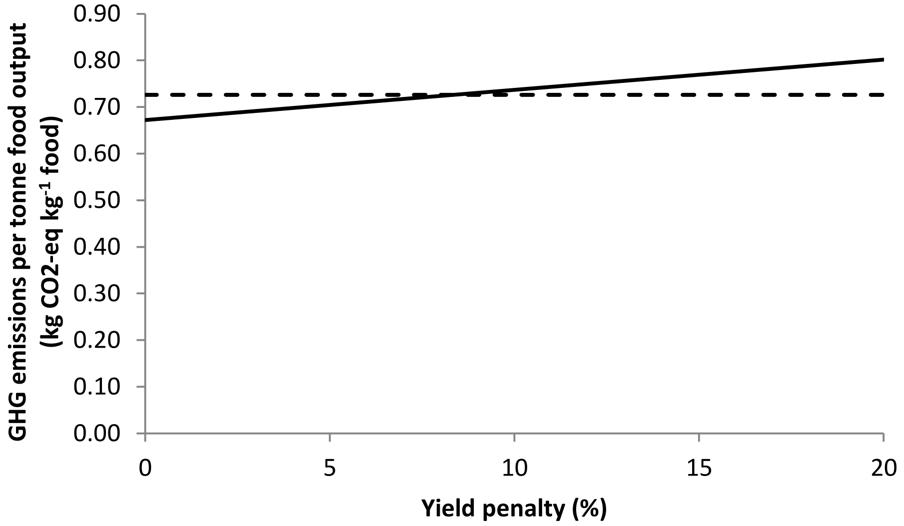

Figure 3: *GHG emissions per tonne output per farm for the DD system with crop yield penalties (solid line). The dashed line represents the GHG emissions per tonne output for a CT system without yield penalties.*

2014 prices

Gross margins are approximately 17% lower in 2014 than in 2011 due to the general decrease in crop prices and an increase in chemical input prices (**Table 11**). For the CT system under 2014 market conditions, WFB is favoured over OSR as the break crop due to the price of OSR decreasing whilst the price of WFB has increased. Under these prices, the crop mix for the full RT systems changes to 50% WW (straw baled) and 50% WFB. This is the same crop mix optimised for NE and it is also very similar to the system optimised for minimised GHG emissions - the only difference for the latter being that straw is not collected and the minimum nitrogen fertiliser rate is applied to WW.

Table 11: *Optimised GMs, NE and GHG emissions for the CT system with 2014 prices.*

		Gross margin maximised	**Net energy maximised**	**GHG emissions minimised**
Crop mix (ha)	Winter wheat (SR, 75% N)	200.00	200.00	0
	Winter wheat (50% N)	0	0	200.00
	Winter field beans	200.00	200.00	200.00
Finance	Gross margins (£ farm^{-1})	233,356	233,359	207,971
Net energy	GJ farm^{-1}	26,159	26,159	20,937
GHG emissions	Kg CO_2-eq farm^{-1}	935,308	935,308	764,306

Key: SR – straw removed; % N – percentage of nitrogenous fertiliser applied relative to recommended levels.

Given the above results (**Table 11**), sensitivity analysis was used to investigate the output prices at which each crop of WOSR and WFB becomes favourable in the rotation. For the rotation to start including OSR alongside WFB, the price of OSR must increase by 9% (to £316.63) and at the same time the price of WFB must decrease by 9% (to £201.38). For the OSR to be the sole break crop, the price of OSR must increase by 12% (to £325.35) and at the same time the price of WFB must decrease by 12% (to £194.74).

Both DD and DRT favour WFB over OSR as the break crop for the optimised GMs. The other full RT and the RP systems favour a combination of OSR and WFB for the optimised GM crop mix; these systems have greater GHG emissions and, for RP, lower NE than the CT system because OSR requires nitrogen fertilisers whereas the WFB do not (**Table 12**).

Table 12: *Output from the different tillage systems (based on the crop mixes for optimised gross margins).*

	CT	**RP**	**SRT1**	**SRT2**	**DRT**	**DD**
GM (£ farm^{-1})	233,356	246,496	268,858	272,524	269,850	276,898
GM (£ ha^{-1})	583.39	616.24	672.15	681.31	674.63	692.25
NE (GJ farm^{-1})	26,159	25,850	27,390	27,615	27,177	27,624
GHG (kg CO_2-eq)	935,308	1,064,566	1,155,161	1,135,869	847,968	809,992
Contractors' fees (£ farm^{-1})	38,406	14,263	12,708	12,708	18,567	18,567

CT – conventional tillage; RP – rotational ploughing; SRT1 – shallow reduced tillage, discs; SRT2 – shallow reduced tillage, spring-tines; DRT – deep reduced tillage; DD – no-till/direct drill.

Net margins were calculated with WW (straw baled), and 50% WFB. The NMs are approximately 25% lower than the NMs for the 2011 prices (**Table 13**). Machinery, fuel and labour costs are very similar, however GMs are much lower due to the general decrease in crop prices; the overall NMs are also much lower. The differences in NMs between the tillage systems tend to be similar between the original and 2014 prices; however, the RP system in 2014 has similar NMs to the CT system, whereas in the original the NMs were much higher for the RP system. Under the CT system, the power harrow is not used before WFB but it is used for OSR. Therefore, when the GMs favour selection of WFB over OSR for both the CT and the RP systems, there is only a minor difference in the cultivation work rates of the CT and the RP system.

***Table 13:** Net margins and machinery costs for the tillage scenarios with 2014 prices when labour and machinery/time constraints are removed (based on the crop mixes for optimised gross margins).*

	CT	**RP**	**SRT1**	**SRT2**	**DRT**	**DD**
GM (£ farm^{-1})	268,199	270,220	283,753	287,418	285,682	291,899
GM (£ ha^{-1})	670.50	675.55	709.38	718.55	714.21	729.75
NE (GJ farm^{-1})	26,159	26,282	27,114	27,339	27,229	27,624
GHG (kg CO_2-eq)	935,308	924,761	853,426	834,134	843,542	809,922
Machinery costs (£ ha^{-1})	284.92	286.38	224.85	209.65	263.63	199.89
Fuel costs (£ ha^{-1})	110.02	104.96	71.12	61.95	50.75	50.75
Labour costs (£ ha^{-1})	62.44	63.57	53.38	46.96	39.13	39.13
Net margins (£ ha^{-1})	323.11	325.57	431.13	461.91	426.97	490.72

CT – conventional tillage; RP – rotational ploughing; SRT1 – shallow reduced tillage, disc harrows; SRT2 – shallow reduced tillage, spring-tines; DRT – deep reduced tillage; DD – no-till/direct drill.

Discussion

By reducing tillage intensity farmers can increase their gross margins and net energy per hectare while lowering GHG emissions. The benefits of RT systems are still observed when taking into account potential yield reductions and increased herbicide requirements. Given the relatively large threshold yield reductions that are required before RT systems are less financially attractive than CT, this suggests that RT can provide both a means of sustainable intensification (SI) and, based upon the results presented above, a framework for quantifying the impact of financial, energy and environmental metrics associated with this potential SI practice.

Previous authors have identified crop yield reductions from RT systems in comparison to CT systems; however, these yield reductions have typically been modest (less than 5% in magnitude as reported by Van den Putte et al., 2010). By contrast, the yield threshold testing approach presented here has identified that more substantial yield penalties from RT can be incurred, yet still achieve a greater financial return than CT systems. Moreover, there is the potential for RT systems to result in greater yields (Knight, 2004; Verch et al., 2009). One potential yield-improving factor associated with RT is better crop establishment from improved timeliness of field operations as a result of the lower labour and machinery requirements of the system.

Where RT systems lead to additional crop protection inputs, in particular for control of weeds such as blackgrass, model results indicate that increased crop protection costs are not a large barrier to the financial viability of RT systems. Cost savings represent a key driver of RT uptake in Northern Europe (Morris et al., 2010) and our results demonstrate substantial cost savings from the adoption of RT systems, further incentivising the commercial uptake of the system.

Cost savings result from lower fuel inputs as well as lower contractor requirements, as well as the flexibility to grow a greater area of more valuable crops in the rotation. Time and labour constraints during the cultivation period force the crop mix to include winter barley, a less valuable crop, to spread the workload and limit contractors' costs; as the utilisation of RT reduces cultivation time, a greater area of the more valuable crops, wheat and OSR, can be grown. This also demonstrates that the benefits of RT depend on the baseline conditions from which measurement of these benefits takes place; where time and labour is less constrained during the cultivation period less benefit is likely to be seen from utilising RT.

Net Energy is generally greater under RT: this holds for where the farm has its own labour and machinery (**Table 10**) and where greater use is made of contractors (**Table 9**); in both cases NE increases as machinery costs fall. The exception is rotational ploughing (RP) for when GMs are optimised, where there is either a small increase or a reduction (**Table 12**); this is a result of crop mix and from retaining some inversion tillage within the system.

Despite the potential financial, energy and environmental benefits of RT, uptake of these practices will be affected by the prior beliefs of farmers (Andrews et al., 2013), in particular regarding yield penalties that may be incurred, as well as farm-specific factors such as farm size, crop rotation, machinery available, climate, soil type and weed burden. As shown by Ogle et al. (2012), RT can have beneficial yield effects in drier, warmer climate conditions and is thus more suited to areas with these conditions. Soil type strongly determines the feasibility of RT (Davies & Finney, 2002; Morris et al., 2010). Rotation choice is more important under RT (Jordan and Leake, 2004) whilst the need to undertake ploughing in rotations that include root cropping could limit RT on farms where the rotation is not suitable.

Control of blackgrass represents a major current and potential threat to arable cropping systems in the UK; however, while anecdotal evidence indicates control of blackgrass through RT approaches is more problematic than via CT approaches, as we have shown here, it is possible to incorporate RT with inversion, plough based cultivations, and still get environmental and financial benefits. In a survey of tillage methods on English arable farms, Townsend et al. (n.d.) found that 46% of farms were using RT; however, this was typically as a small part of the overall system with ploughing used for the majority of the land, reflecting a rotational ploughing system. The requirement to hold machinery suitable to both CT and RT simultaneously will typically lead to greater machinery depreciation costs than would result from a single tillage system approach. It is possible that where ploughing is not being used, instead of utilising RT equipment farmers are directly broadcasting seed (in particular OSR) into the stubble of the previous crop, thus avoiding the expense of two sets of tillage equipment.

Glithero et al. (2015) identified that decision making with respect to levels of machinery ownership was a key financial driver in determining optimal crop mix. In the MEETA results, the RT systems did not require the large tractor, which is partly responsible for the RT systems having much higher NMs. This does highlight a key point that gaining the full benefits of switching from a CT system to a RT system would require a change in the machinery present on the farm: this is not a cost free process and includes both capital and learning costs; as noted above, the benefits are uncertain and thus a farmer’s attitude to this risk is also relevant. In contrast to the results here, some RT machinery requires powerful tractors; in particular, large RT trains. Farm size is a determinant of whether RT practices are likely to be used (Townsend et al., n.d.) and this could be due to larger farms being able to finance much larger tractors and afford multiple sets of tillage equipment when rotational ploughing is used.

In addition to the above farm-specific issues, our results demonstrate that input and output price variability can lead to contrasting financially optimal crop mixes. A standard risk management strategy that farmers adopt to address price and yield variability is to have a wider mix of crops in their rotation (Hardaker et al., 2004); if CT systems reduce the flexibility of crop choices they will be less attractive to risk averse farmers. The farmer's subjective probability of the effect of moving from CT to RT will also affect uptake. In combination with financial rewards that, although positive (**Tables 9** and **10**) are relatively small, these factors go some way to explain the modest uptake of RT practices in countries such as the UK.

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