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Optimal Combinable and Dedicated Energy Crop Scenarios for Marginal Land

Abstract:

Modern biomass energy sources account for less than 2% of primary world energy supplies while major economies have enabled legislation that aims to increase bioenergy production. In response to controversies over first generation biofuel, it has been argued that 'marginal land' should be used to produce dedicated energy crops (DECs). However, defining marginality of agricultural land is complex, and moreover, DECs would have to out-compete current agricultural production in these areas. Utilising a bio-economic farm-level modelling approach we investigate the impact that crop yield penalties resulting from production in marginal land contexts have on financially optimal farm-level crop plans. Where farm businesses choose to de-invest in own farm machinery, yield reductions of less than 10% for winter wheat result in a financially optimal switch to 100% miscanthus production. By contrast, in the presence of own farm machinery, winter wheat yield penalties of 30% are required before 100% miscanthus production is financially optimal. However, under circumstances where DECs also suffer yield penalties on marginal land, the financially optimal crop mix includes combinable crops. The results demonstrate that the optimal crop mix is dependent upon the relative combinable and DEC yields, together with farm-level decisions towards machinery ownership. The focus of much policy attention relating to production of DECs on 'marginal land' is therefore argued to be incomplete. Policies which encourage farmers to de-invest in own farm machinery, or incentivise the purchase of specific DEC machinery, may play an important role in assisting the development of DEC production.

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1. Introduction

The need to achieve new and renewable sources of energy to secure sustainable energy futures has been well documented [1,2]. Legislation and policy incentives have been put in place in a number of developed countries and regions, including the USA [3] and Europe [4] which aim to increase energy supplies and achieve reductions in greenhouse gas emissions to mitigate climate change effects. While global energy supplies continue to be dominated by fossil fuels (accounting for 80% of primary energy supply; [2]), energy from renewable sources is increasing, driven by governmental incentives and technological advancement across a number of areas including solar, wind and bio-based energy supplies [1]. However, renewable energy still represents a modest contribution to overall energy supplies (3.8%; [1]) with modern biomass (wood and forest residues, agricultural crops and wastes and urban residues) specifically accounting for less than 2% of primary energy [2]. These data are set against projections that bioenergy could potentially account for 15% of global primary energy supply by 2050 [5]. Bioenergy was initially hailed as a 'green' solution to energy needs, particularly in the context of the early 2000s, when global food prices were at relatively low levels [6]; however, controversy over the use of land for bioenergy quickly surfaced (the 'food vs. fuel' land-use debate, see [7]). More recently discussion on bioenergy production has placed increased emphasis on co- or waste bio-products and use of lower-grade or marginal land with the intention of limiting the food production effects of bioenergy production [13].

Within the land-use debate the word marginal, in relation to land, occurs frequently and often encompasses a wide range of definitions. In the UK "marginal land" has been defined as land unsuitable for food crops [8; 9; 10], land where food crop production will be lower than average [9], land that is economically marginal [11; 9] and land that has low agricultural or biodiversity value [8]. Gopalakrishnan et al. (2011)[12] noted that in most cases "*marginality is defined or implied as relative to the agroeconomic profit that could be derived by growing a major crop*". Given the range of definitions within the literature it can be difficult to determine the amount of marginal land, and the potential this land can be put to, within the UK. Currently there are no UK or EU policies that include a definition of marginal land with respect to agricultural land use for food and bioenergy production possibilities.

The use of marginal land for growing dedicated energy crops (DECs) has been suggested numerous times [8;13;14] and has been incorporated, using different definitions, into various estimates for the amount of these crops that can be grown in the UK. Lovett et al. (2009)[15] estimated that there was 362,859ha of 'lower grade' land available in England to grow miscanthus taking into account a range of agricultural and yield considerations. More recently, Lovett et al. (2014) [16] have suggested that there is 1.4 M ha of grade 4 and grade 5 land available in the UK for perennial energy crops. Bauen et al. (2010) [17], using maps of agricultural land quality, DEC yield maps and current land use data, estimated that 248.4kha of miscanthus and 389.1kha of SRC could be grown in England and Wales. These estimates are much lower than Haughton et al.'s (2009) [18] estimate that 3.1Mha of DECs could be grown in

England. Other research has estimated that 3.4Mha of arable and grassland will be available for biomass crop production in the UK in 2030 [19]. However, drawing upon a survey of arable farmers in England, Glithero et al. (2013)[20] noted that farmers would be potentially willing to respectively grow 50,700ha and 89,900ha of SRC and miscanthus under the assumption that those farmers willing to consider growing DECs would convert 9.29%[1] of their utilised agricultural land to DECs. The most recent official data for England shows that only 2600 ha of SRC and 7000 ha of miscanthus are grown [22].

In addition to area considerations, production estimates for DECs must take into consideration variability of DEC yields [23;24;25]. Richter et al. (2008)[26] noted that there was a strong correlation between miscanthus yields and water availability, with the crop losing up to 40% of its yield in drought conditions. SRC has also been found to be susceptible to drought conditions [27]. However, the relative potential between the productivity of DECs and other land uses are generally not considered. It is often assumed that while yields of arable crops will be reduced on marginal land, DECs grown in the same conditions will not suffer yield penalties, or not suffer penalties to the same extent as arable crops [17]; these differential yield impacts have further strengthened calls for DEC production on marginal land (e.g. [15;28]). The validity of the assumption that DECs do not suffer yield penalties on marginal land is central to analysis of DEC production prospects, given the potential for this land to be used for food crops; furthermore, lower yielding food crops may be financially preferable to DECs that do not suffer yield penalties. Moreover, land that is unsuitable for arable related machinery is also likely to be unsuitable for machinery required for growing and harvesting DECs [17].

It is clear that DECs on any agricultural land will have to compete with other established agricultural uses and that typically this will be combinable arable cropping or livestock farming (root crops, such as potatoes and sugar beet, have relatively high margins). In a French modelling study of farmers' adoption of switchgrass and miscanthus Bocqueho and Jacquet (2010)[29] found that these DECs were generally less profitable than conventional arable rotations, albeit that DECs could be competitive diversification crops if appropriate contracts were offered. Alexander and Moran (2013)[30] accounted for farmer risk aversion with respect to perennial crop selection and identified that small variations in arable crop yields could have significant impacts on optimal crop mix at the farm level. The variable nature of the potential returns from DECs and the different characteristics of energy crops, can also affect crop mix decision making; for example, Glithero et al. (2013)[20] found that miscanthus was more attractive to English arable farmers than SRC.

Bio-economic farm models (BEFMs) are often used to analyse potential farmer behavioural responses to new technologies and crops. Jannsen and van Ittersum (2007)[31] noted that there are two types of BEFM, empirical (constructed from data to extrapolate future behavioural outcomes) and mechanistic (drawing on existing knowledge and theory of agricultural practices, and simulating future behaviour from this). Jannsen and van Ittersum argue that empirical models, by their nature, should not be used to model structural change in farm businesses as such models are bound by their assumptions and datasets and therefore cannot easily deal with alternative farm systems or technologies. Mechanistic models can be used to model structural changes in a farm business, such as the adoption of bioenergy cropping and the potential removal of on farm assets, if allowance for these is made in the model assumptions and development. The Silsoe Whole Farm Model [32] includes options to examine different machinery and labour criteria within a farm business to assess potentially optimal cropping and business scenarios under alternative resource use implications; as such, structural changes in the farm business can be investigated using this mechanistic model. However, with the above notable exception, previous research drawing upon farm-level optimisation modelling approaches tends to assume that the farm has a set of fixed resources available, including labour and machinery, and that farmers will choose an optimal crop plan given this resource availability at the outset. Some models allow for a combination of own on-farm labour and machinery availability, supplemented by contract service possibilities once the on-farm resources are fully utilised within a particular crop activity period (e.g. [33;34]). Other models have examined optimising farm-level mechanisation *per se*. [35], noting the importance of labour as a key constraint. Less explicit approaches to capturing the impact of fixed resource constraints have assumed labour and machinery are totally divisible [36], effectively representing a 'contracting only' scenario. Alexander and Moran's (2013)[30] farm model builds upon Sherrington and Moran's (2010)[37] model, and as noted, investigated bioenergy cropping potential within the context of risk averse farmers in the UK. The model included contract and on-farm machinery options, with all crop operations charged at contract rates, albeit that farmers would in general use own machinery before considering contracting - an explicit assumption in Sherrington and Moran's (2010)[37] earlier model. Hence, while previous work has assumed a range of different approaches to capturing fixed resource, there is a paucity of approaches that examine the impact of *different* fixed farm–level resource endowments on optimal production plans. We hypothesise that including or excluding the presence of own farm machinery will arguably lead to potentially very contrasting optimal business and cropping strategies, particularly when examining potential crop switching from annual combinable arable crops to perennial DECs.

The aim of this paper is to explore the farm scale effects of relative arable and DEC crop yield reductions scenarios representing production on marginal land, and to investigate the influence of the presence or absence of on-farm machinery in these scenarios. The simulation model used is briefly outlined in section 2.1 followed by the alterations to this model to incorporate DECs in section 2.2. The assumptions and methodology for the yield penalty scenarios are shown in section 2.3. The results from these scenarios are shown in section 3, followed by a discussion in section 4. Overall conclusions from the modelling work are presented in section 5.

2. Method

To investigate the impact that crop yield penalties have on optimal crop mix given conventional cropping and DEC possibilities, a modelling approach was adopted. An existing model of combinable crop possibilities, the Managing Energy and Environmental Trade-offs in Agriculture (MEETA) model [34], was adapted to include DECs (miscanthus and SRC) and marginal land by constructing a series of reductions to the standard crop yield figures in the original model and the yields for the newly introduced DECs. The original MEETA model is briefly outlined in section 2.1, the characteristics of DEC and the method for incorporating DECs into the MEETA model is outlined in section 2.2, and the method for simulations of crop yield reduction is outlined in section 2.3.

2.1 Overview of the MEETA Model

The MEETA model combines bio-economic modelling and LCA approaches. The model was designed to investigate the trade-offs between energy, emissions and finances at the farm level in England, with a specific emphasis on cereal straw production as a feedstock for bioenergy [34]. The MEETA model is a linear programming optimization model that uses a single year time-frame to represent multi-year cropping and rotational aspects typically observed in arable production. The original MEETA model is parameterised for common combinable crops typically found on cereal farms in the UK; winter wheat (first [WW], second [SWW] and continuous [CWW]), winter oilseed rape [OSR], winter field beans [WFB], winter [WB] and spring barley [SB]. The model takes the input and output parameters for these crops; seed, fertilisers, crop protection, crop machinery and labour operations, grain drying requirements, diesel used by machinery during crop operations, individual output yields of grain and straw, contract costs for machinery, plus energy used and generated, and greenhouse gas [GHG] emissions associated with inputs and outputs. The outputs that can be generated from the model include the optimal crop areas, the farm gross margin [GM], the GHG emissions, and net energy generated from the farm. The MEETA model can be optimised for maximum farm GM, maximum net energy, or minimum GHG emissions. Full details of the original MEETA model and the data that parameterises the model are presented in [34] and hence are not reproduced here; however it is important to note that the MEETA model represents contemporary agricultural practice and the structure of the model facilities both modular development and sensitivity testing in order to establish the level of confidence associated with the results generated. The following sections describe the additional developments and features embedded within the MEETA model within this paper.

2.2 DECs of SRC and Miscanthus production characteristics and their inclusion in the MEETA model

SRC willow and miscanthus were not included in the original MEETA model [34]. This section outlines the production and policy factors associated with DECs and their inclusion into the modelling framework to generate an extended MEETA model.

SRC willow is a perennial crop that requires a two year establishment period; during this time frame, a range of activities are required, including drawing upon labour and machinery resources and the variable costs of production incorporating crop establishment and management; appendix A details the data that is additionally incorporated into the MEETA model reflecting commercial practice. The crop is established by the planting of SRC willow cuttings at a density of 15,000 cuttings per hectare [31;32]. Following the establishment phase the crop is harvested triennially. During each three year cycle, fertiliser and herbicide are required in one of these three years. A typical output from SRC under UK conditions is 35 odt (oven dried tonnes) per hectare (ha) every three years [39]. In addition, a herbicide application is required to remove the crop at the end of its 30 year lifespan: during this 30th year the land cannot be used. Overall, the establishment and removal of SRC therefore takes a total of three years of the 30 year lifespan.

In contrast to SRC willow, miscanthus does not require a final removal phase, but does require a two year establishment period out of a total 20 year lifespan. Establishment typically requires the application of four herbicides, but no fertiliser. Establishment also requires a number of crop operations (also detailed in appendix A) to enable the planting of miscanthus rhizomes at a density of 14,000 per hectare [39;40]. Following the two year establishment phase the crop can be harvested annually, requiring an annual application of fertiliser. Typical output from miscanthus under UK conditions is 13 odt/ha annually [39]. Details of the machinery used, frequency and timing of each crop operation, energy use, GHG emissions, costings and literature sources are detailed for SRC and miscanthus in Appendix A.

In England, farmers have until recently been able to apply for a grant to cover 50% of the establishment costs associated with SRC and miscanthus, provided they grow more than three hectares of either crop, and the crop output is used for second generation biofuels, heat, combined heat and power; or power generation [41]. The allowed establishment costs can include the actual costs (suppliers, materials and contracting costs) and any on-farm costs (use of own machinery where applicable) [41]. In the model, the establishment grant is included as 50% of the respective contracted machinery costs of SRC and miscanthus planters (this specialist machinery is typically contracted in with associated labour), the diesel costs for these machines (fuel is separately accounted for the MEETA model), and the respective costs of the miscanthus rhizomes and SRC cuttings.

The MEETA model was designed for an annual combinable cropping scenario; the inclusion of DECs into the MEETA model requires that the long term nature of these crops is captured as a single year representation of the activities and outputs over the full time that the crop is in the ground. This is achieved by accounting for the establishment, crop production and harvesting, and crop removal phases over the given perennial crop's lifespan as an average one-year representation.

2.3 Estimating Financially Optimal Crop Mixes given DEC and Combinable Crop Possibilities including Sensitivity Testing

In order to test the impact of combinable crop yield penalties resulting from production of these crops on 'marginal land', two assumptions were investigated as detailed below.   In addition, the extended MEETA model was run with and without own on-farm machinery, to test the sensitivity of optimal results under different farm resource scenarios that may be encountered by farmers considering DEC production (the MEETA model can buy in contract machinery where needed). In order to ensure tractability of the model runs, the original inclusion of WFB in the

MEETA model was removed on the basis that OSR represents the main break crop grown in combinable cropping scenarios in England, and WFB accounted for only 1.9% of arable land in England in 2011 [42]. In addition to testing for sensitivity in relation to on-farm machinery ownership, the sensitivity of the MEETA model was tested via incremental changes in the relative yields of the crops within the model, in order to establish the threshold relative yields where optimal crop mix changes.

2.3.1 Assumption 1: Marginal Land leads to Reductions in the Yield of Combinable Crops only.

It has been suggested that DECs can be grown on marginal land where combinable crops would suffer yield losses or be unsuitable. To test this assumption, yields of the combinable crops were reduced individually, and in combination, from 100% of their base-line model yields, to 0%, in increments of 10%. Further detail in model output was captured by decreasing the increment step size (to 1%) over appropriate yield reduction ranges, to show where optimal crop mix changes occurred. For each incremental yield reduction step, the model was run to obtain financially (GM) optimal crop areas, GM, net energy, and GHG emissions (carbon dioxide, nitrous oxide, methane and carbon dioxide and total greenhouse gas emissions) metrics.

2.3.2 Assumption 2: Marginal Land leads to Reductions in the Yield of both Combinable Crops and DECs.

The second assumption tested is that SRC and miscanthus are also subject to yield penalties on marginal land, in addition to yield penalties for combinable crops. This is investigated by holding the reductions of the combinable crops at the common yield reductions for all combinable crops (i.e. for a 10% yield reduction in WW, all other combinable crops are assumed to incur a 10% yield reduction); the yields of the DECs are then reduced in increments of 10% to calculate the optimal cropping patterns under different yield penalty scenarios.

2.3.3 With and without own on-farm machinery

If farmers were to consider growing large areas of DECs then it is possible that they would seek to undertake large scale structural changes of their business. One typical scenario would include the sale of their own on-farm machinery, choosing in contrast to buy in contract labour and machinery to perform crop activities. The MEETA model was therefore run: i) with, and ii) without, own on-farm machinery to investigate the impacts of the presence or absence of own on-farm machinery on the optimal crop mix, GM, GHG emissions and net energy metrics. Running the MEETA model with and without own on-farm machinery provides information on whether the presence or absence of own on-farm machinery results in optimal crop mix changes at different yield reduction penalty points.

3. Results

3.1 Assumption 1: Yield Reductions in Combinable Crops, without own on-farm machinery

The initial model runs showed that given wheat (WW, SWW, CWW) yields at 100% of base-line, reducing WB and SB yields does not influence optimal crop mix. Under the above assumptions, optimal crop mix is 50%:50% WW:OSR, given OSR yields at 100% of their base-line yields. When OSR yields are set to 90% of their base-line yields, a homogeneous crop pattern of CWW is optimal. Given WW yield at 90% of base-line, reducing SB yields once again makes no difference to optimal crop mix under 100% base-line yields for OSR and WB. Given WW at 90% base-line yield, and WB and OSR at 100% base-line yields, the optimal crop mix is a third each of WW:WB:OSR. However, with wheat yields at 90% of base-line and given a reduction in the yields of WB or OSR below 100% of base-line yields (as captured by setting WB and OSR yields at 90%), the optimal crop mix is 100% miscanthus.

Given that the switch from combinable cropping into a homogenous cropping pattern of miscanthus occurs between 100% and 90% of the base-line yields of WW, WB and OSR, the yield of combinable crops over the 100% to 90% region were investigated in further detail using 1% incremental yield penalty steps. This resulted in a slightly wider variety of optimal crop mixes occurring, and highlighted specific yield penalty points where the switch between crops occurred. Four crop mixes were seen in the larger, 10% yield penalty scenarios. In the smaller, 1% yield penalty scenarios, a further optimal crop mix of WW, SWW and OSR occurs given WW yields between 97% and 99% of base-line yields; SB yield penalties again make no difference to the optimal crop mix. Note that miscanthus enters the optimal crop mix when WW yields are at 97% of base-line. The range of crop mixes and frequency of occurrence is presented in Figure **1**. An optimal cropping of 100% miscanthus occurs in 91% of the simulation runs where combinable crop yields are reduced in increments of 10% (from 100% to 0%) and in 49% of the runs where combinable crop yields are reduced in increments of 1% (from 100% to 90%).

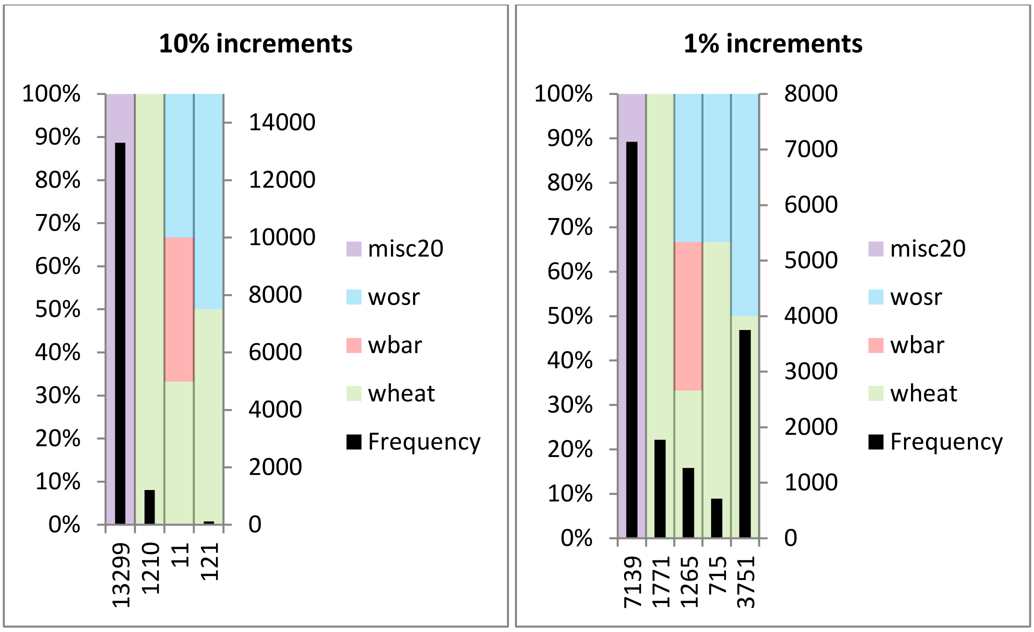


Figure 1: Optimal crop mixes and frequency of occurrence under assumption 1 without own on-farm machinery (frequency on the x axis). The left plot represents the results from the reduction in yield from 100% to 0% in increments of 10%. The right plot represents the results from the reduction in yield from 100% to 90% in increments of 1%. In each plot the percentage area given to each of the 4 crops is shown on the left-hand axis with the number of times that the crop mix occurs in the 14,561 simulation runs shown on the right-hand axis and on the x axis labels. Misc20 is 20 year miscanthus, wosr is winter oilseed rape, wbar is winter barley and wheat is winter wheat

The GM, net energy, and GHG emissions from the farm alter as the optimal cropping pattern changes. The base-line yield GM is £174,500. However, when combinable crop yield penalties lead to 100% miscanthus being optimal, the farm GM falls to £149,500, a decrease of 14% from base-line. Concurrently there is an increase of 227% in the net energy from 25,990GJ, with 100% combinable crop yields, to 84,860GJ with 100% miscanthus. Additionally, a 68% decrease in total GHG emissions occurs from 1,744,560 tCO_2eq, under the 100% combinable crop yields base-line, to 565,050 tCO_2eq with 100% miscanthus. The above results for the GM and net energy represent the maximum and minimum values across all yield penalty scenarios examined. However, the GHG emissions extend from 1,764,550 tCO_2eq under a crop mix of a third each of WW:WB:OSR, to 565,050 tCO_2eq under 100% miscanthus.

3.2 Assumption 1: Yield Reductions in Combinable Crops, with own on-farm machinery

Given the presence of own on-farm machinery, a wide variety of optimal crop mixes are observed under different yield penalty scenarios. While WW yields remain at 100% of base-line, no miscanthus or SRC enters the optimal crop mix. However, given WW yields at 90% of base-line, miscanthus enters the optimal crop mix, albeit that a reduction in WW yields to 70% of base-line yield values is required before 100% miscanthus is optimal. The key difference between the without own on-farm machinery, and with own on-farm machinery simulations, is that given the presence of own on-farm machinery, optimal crop mixes which contain DECs alongside combinable crops occur more frequently than in the absence of own on-farm machinery, where typically complete switching between combinable cropping and miscanthus occurs, Figure **2**. An optimal cropping of 100% miscanthus occurs in 58% of the simulation runs, and by contrast, a 100% continuous WW optimal crop plan occurs in 7% of simulations; overall miscanthus appears at some level in 85% of the simulation runs.

The GM, net energy and GHG emissions from the farm alter as the optimal cropping pattern changes. The GM decreases from £285,780 at 100% base-line yields, to £177,770 when yield penalties lead to 100% miscanthus production being optimal; a decrease of 38% in GM. Concurrently there is an increase of 230% in the net energy produced from 25,730GJ at 100% base-line yields, to 84,860GJ with 100% miscanthus crop production. Moreover, a 68% decrease in total GHG emissions occurs from 1,767,140 tCO_2eq under the 100% base-line yield scenario, to 565,050 tCO_2eq, given 100% miscanthus. Therefore, the GM ranges between £177,769 and £285,780, net energy ranges between 19,640GJ to 84,860GJ, and GHG emissions range between 565,050 tCO_2eq and 1,767,140 tCO_2eq.

In order to compare the GM from the ‘with’ and ‘without’ own on-farm machinery scenarios, it is necessary to account for deprecation and other costs of utilising own on-farm machinery, in contrast to complete contract service utilisation. For the 400ha farm modelled with own on-farm machinery, machinery depreciation and associated costs of £137,000 must be deducted from the GM, resulting in an ‘adjusted GM’ that ranges between £148,780 and £40,770, for 100% base-line yields leading to combinable cropping, and 100% miscanthus production, respectively. This is a reduction in 73% in ‘adjusted GM’ as the optimal crop mix changes to 100% miscanthus production. Comparing this with the scenario where all machinery is contracted, these’ adjusted GM’ figures are lower than the GM achieved with only using contractors.

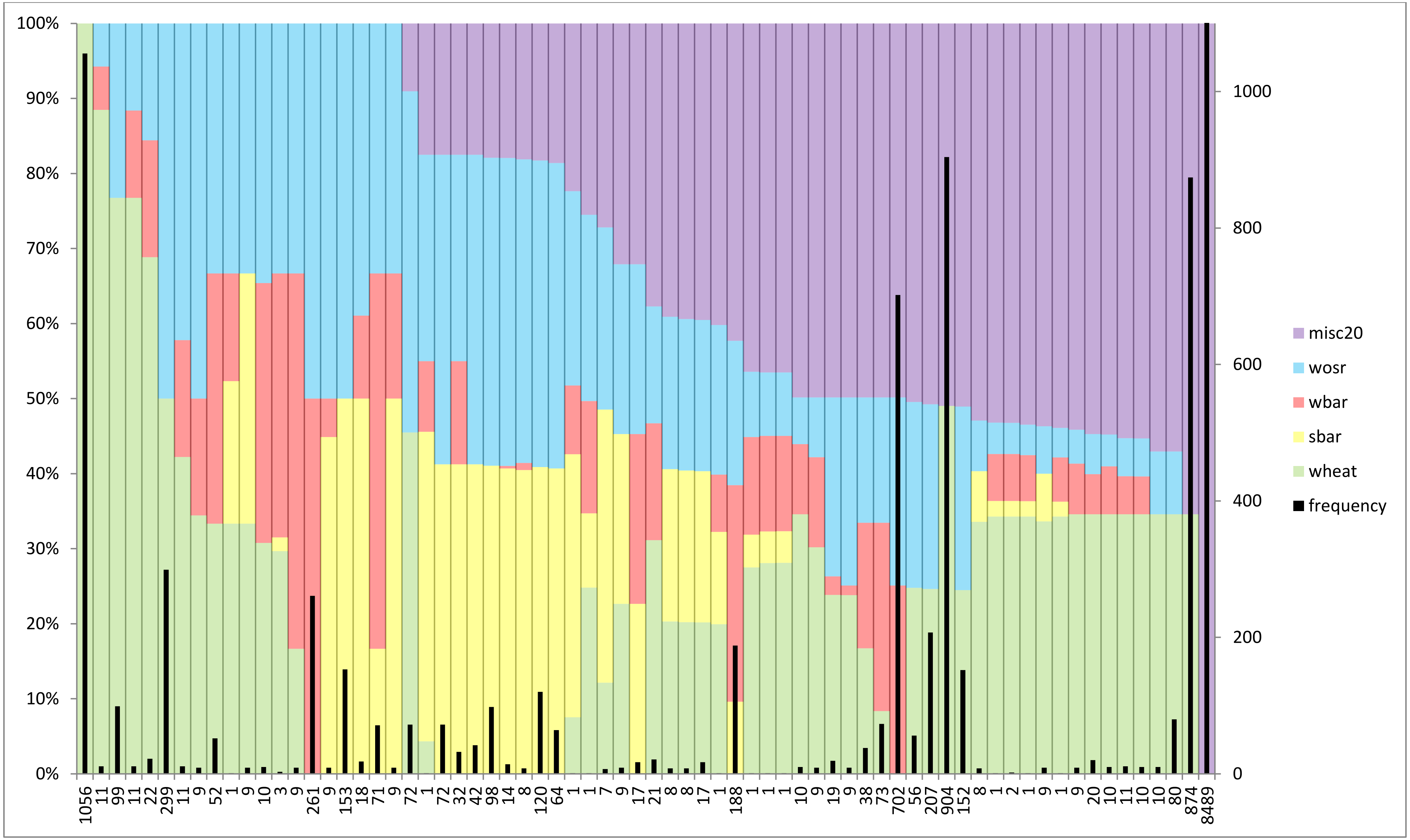
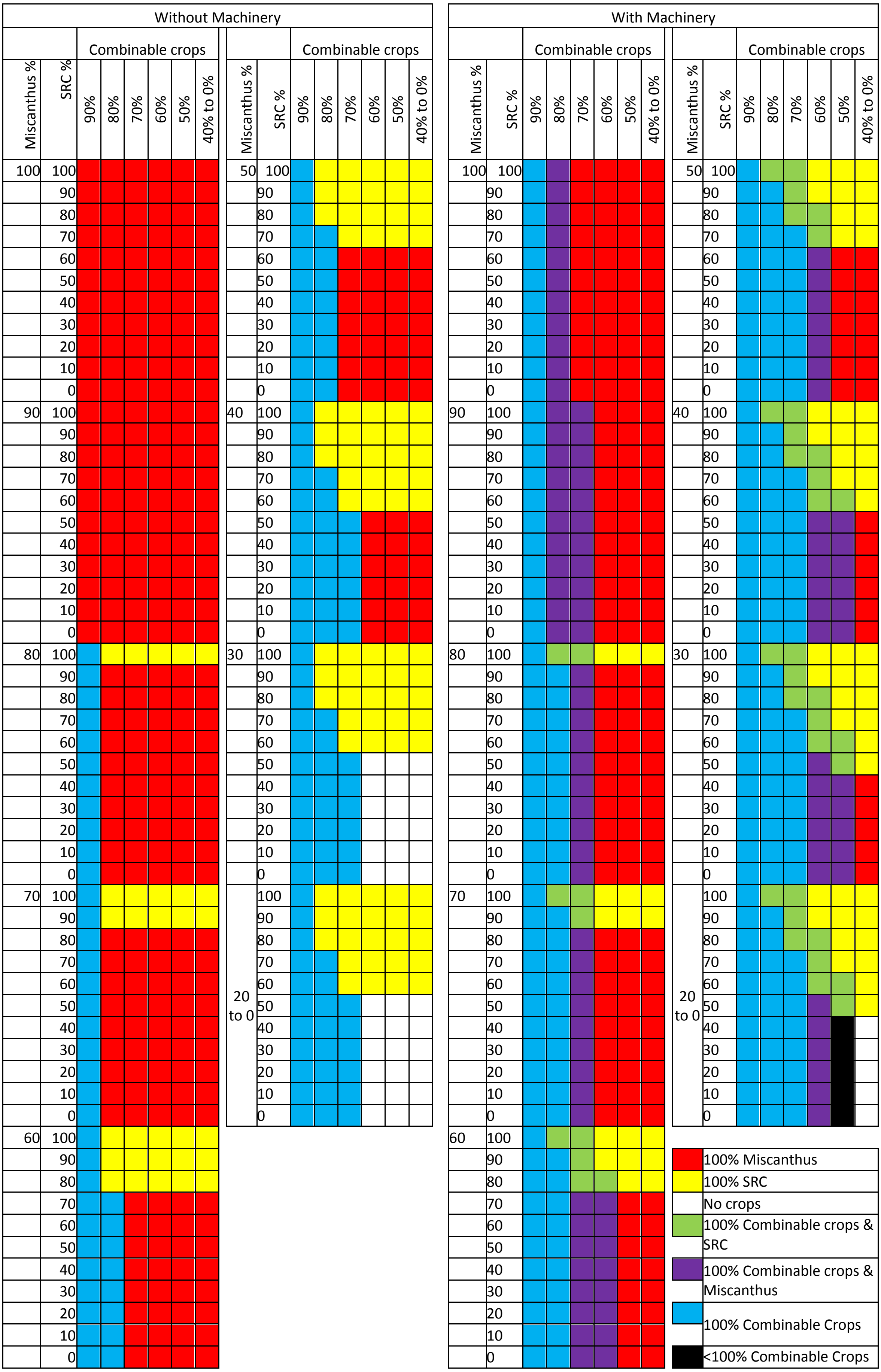


Figure 2: Optimal crop mixes and frequency of occurrence under assumption 1 with own on-farm machinery (frequency on the x axis). The percentage area given to each of the 4 crops is shown on the left-hand axis with the number of times that the crop mix occurs in the 14,561 simulation runs shown on the right-hand axis and on the x axis labels. Misc20 is 20 year miscanthus, wosr is winter oilseed rape, wbar is winter barley, sbar is spring barley and wheat is winter wheat. Note that the 100% misc20 cropping scenario occurs in 8489 of the simulation runs which exceeds the y axis limits.

3.3 Assumption 2: Reductions in yields of combinable crops and DECs, without own on-farm machinery

Given all combinable crop yields at 90% of base-line, 100% miscanthus is the optimal crop mix. However, given yield penalties on DECs, in addition to combinable crop yield penalties, it is necessary to re-test for optimal crop mixes. With combinable crop yields at 90% of base-line, 100% miscanthus production remains optimal until the miscanthus yield is reduced to 80% of base-line yield. At this yield penalty level, the optimal crop mix returns to combinable cropping of 50%:50% WW:OSR; reducing the yield of SRC does not alter the optimal crop mix. Given yields of the combinable crops at 80% of base-line, optimal crop mix alternates between 100% SRC, 100% miscanthus and 50%:50% WW:OSR, depending on the yield reduction penalties assumed for miscanthus and SRC; this observed optimal crop mix 'switching' occurs when the miscanthus yield is 60% of base-line or lower, and the SRC yield is 70% of base-line or lower. Given yields of the combinable crops at 70% of base-line, optimal crop mix alternates between 100% SRC, 100% miscanthus and a third each of WW:SWW:OSR, depending on the yield reduction penalties assumed in miscanthus and SRC. The crop mix combination of WW, SWW and OSR occurs given miscanthus yields of 40% of base-line or lower, and SRC yields of 50% of base-line or lower. Given combinable crop yields at 60% of base-line or lower, optimal crop mix alters between 100% miscanthus and 100% SRC, depending on the relative yields of these two crops; however, given the 60% combinable crop yield penalties, the optimal crop mix never includes combinable crops, with the optimal outcome being no crop production of any kind, in preference to making a GM loss, Figure **3**. With combinable crop yields at 90% of base-line, miscanthus yield at 80% and SRC yields at 100% when there is no on-farm machinery the optimal crop mix is 100% combinable cropping: if combinable crop yields are reduced to 80% (holding other crop yields at previous levels) then the mix changes to 100% SRC. If the SRC yield is then reduced (crop yields being 80% for combinable crops, 80% for miscanthus and 90% for SRC) then the crop mix shifts to 100% miscanthus.

The GM varies between £149,470, given 100% miscanthus base-line yield and combinable crops at 90% of base-line yields, and £0 when no crops are produced. The net energy varies between 84,861GJ and 0GJ, the former occurring given 100% miscanthus production at 100% base-line yields, and the later when there is no cropping. The GHG emissions vary between 1,739,072 tCO_2eq and 0 tCO_2eq, the former occurring when the optimal crop mix is 100% combinable crops, and the latter under a no cropping scenario.



Without Machinery

		Combinable crops					
Miscanthus %	SRC %	90%	80%	70%	60%	50%	40% to 0%
100	100	🟥	🟥	🟥	🟥	🟥	🟥
	90	🟥	🟥	🟥	🟥	🟥	🟥
	80	🟥	🟥	🟥	🟥	🟥	🟥
	70	🟥	🟥	🟥	🟥	🟥	🟥
	60	🟥	🟥	🟥	🟥	🟥	🟥
	50	🟥	🟥	🟥	🟥	🟥	🟥
	40	🟥	🟥	🟥	🟥	🟥	🟥
	30	🟥	🟥	🟥	🟥	🟥	🟥
	20	🟥	🟥	🟥	🟥	🟥	🟥
	10	🟥	🟥	🟥	🟥	🟥	🟥
	0	🟥	🟥	🟥	🟥	🟥	🟥
90	100	🟥	🟥	🟥	🟥	🟥	🟥
	90	🟥	🟥	🟥	🟥	🟥	🟥
	80	🟥	🟥	🟥	🟥	🟥	🟥
	70	🟥	🟥	🟥	🟥	🟥	🟥
	60	🟥	🟥	🟥	🟥	🟥	🟥
	50	🟥	🟥	🟥	🟥	🟥	🟥
	40	🟥	🟥	🟥	🟥	🟥	🟥
	30	🟥	🟥	🟥	🟥	🟥	🟥
	20	🟥	🟥	🟥	🟥	🟥	🟥
	10	🟥	🟥	🟥	🟥	🟥	🟥
	0	🟥	🟥	🟥	🟥	🟥	🟥
80	100	🟦	🟨	🟨	🟨	🟨	🟨
	90	🟦	🟥	🟥	🟥	🟥	🟥
	80	🟦	🟥	🟥	🟥	🟥	🟥
	70	🟦	🟥	🟥	🟥	🟥	🟥
	60	🟦	🟥	🟥	🟥	🟥	🟥
	50	🟦	🟥	🟥	🟥	🟥	🟥
	40	🟦	🟥	🟥	🟥	🟥	🟥
	30	🟦	🟥	🟥	🟥	🟥	🟥
	20	🟦	🟥	🟥	🟥	🟥	🟥
	10	🟦	🟥	🟥	🟥	🟥	🟥
	0	🟦	🟥	🟥	🟥	🟥	🟥
70	100	🟦	🟨	🟨	🟨	🟨	🟨
	90	🟦	🟨	🟨	🟨	🟨	🟨
	80	🟦	🟥	🟥	🟥	🟥	🟥
	70	🟦	🟥	🟥	🟥	🟥	🟥
	60	🟦	🟥	🟥	🟥	🟥	🟥
	50	🟦	🟥	🟥	🟥	🟥	🟥
	40	🟦	🟥	🟥	🟥	🟥	🟥
	30	🟦	🟥	🟥	🟥	🟥	🟥
	20	🟦	🟥	🟥	🟥	🟥	🟥
	10	🟦	🟥	🟥	🟥	🟥	🟥
	0	🟦	🟥	🟥	🟥	🟥	🟥
60	100	🟦	🟨	🟨	🟨	🟨	🟨
	90	🟦	🟨	🟨	🟨	🟨	🟨
	80	🟦	🟨	🟨	🟨	🟨	🟨
	70	🟦	🟦	🟥	🟥	🟥	🟥
	60	🟦	🟦	🟥	🟥	🟥	🟥
	50	🟦	🟦	🟥	🟥	🟥	🟥
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50	100	🟦	🟨	🟨	🟨	🟨	🟨
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	80	🟦	🟨	🟨	🟨	🟨	🟨
	70	🟦	🟦	🟨	🟨	🟨	🟨
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	0	🟦	🟦	🟦	⬜	⬜	⬜
20 to 0	100	🟦	🟨	🟨	🟨	🟨	🟨
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	50	🟦	🟦	🟦	⬜	⬜	⬜
	40	🟦	🟦	🟦	⬜	⬜	⬜
	30	🟦	🟦	🟦	⬜	⬜	⬜
	20	🟦	🟦	🟦	⬜	⬜	⬜
	10	🟦	🟦	🟦	⬜	⬜	⬜
	0	🟦	🟦	🟦	⬜	⬜	⬜

With Machinery

		Combinable crops					
Miscanthus %	SRC %	90%	80%	70%	60%	50%	40% to 0%
100	100	🟦	🟪	🟥	🟥	🟥	🟥
	90	🟦	🟪	🟥	🟥	🟥	🟥
	80	🟦	🟪	🟥	🟥	🟥	🟥
	70	🟦	🟪	🟥	🟥	🟥	🟥
	60	🟦	🟪	🟥	🟥	🟥	🟥
	50	🟦	🟪	🟥	🟥	🟥	🟥
	40	🟦	🟪	🟥	🟥	🟥	🟥
	30	🟦	🟪	🟥	🟥	🟥	🟥
	20	🟦	🟪	🟥	🟥	🟥	🟥
	10	🟦	🟪	🟥	🟥	🟥	🟥
	0	🟦	🟪	🟥	🟥	🟥	🟥
90	100	🟦	🟪	🟪	🟥	🟥	🟥
	90	🟦	🟪	🟪	🟥	🟥	🟥
	80	🟦	🟪	🟪	🟥	🟥	🟥
	70	🟦	🟪	🟪	🟥	🟥	🟥
	60	🟦	🟪	🟪	🟥	🟥	🟥
	50	🟦	🟪	🟪	🟥	🟥	🟥
	40	🟦	🟪	🟪	🟥	🟥	🟥
	30	🟦	🟪	🟪	🟥	🟥	🟥
	20	🟦	🟪	🟪	🟥	🟥	🟥
	10	🟦	🟪	🟪	🟥	🟥	🟥
	0	🟦	🟪	🟪	🟥	🟥	🟥
80	100	🟦	🟩	🟩	🟨	🟨	🟨
	90	🟦	🟦	🟪	🟥	🟥	🟥
	80	🟦	🟦	🟪	🟥	🟥	🟥
	70	🟦	🟦	🟪	🟥	🟥	🟥
	60	🟦	🟦	🟪	🟥	🟥	🟥
	50	🟦	🟦	🟪	🟥	🟥	🟥
	40	🟦	🟦	🟪	🟥	🟥	🟥
	30	🟦	🟦	🟪	🟥	🟥	🟥
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	0	🟦	🟦	🟪	🟥	🟥	🟥
70	100	🟦	🟩	🟩	🟨	🟨	🟨
	90	🟦	🟦	🟩	🟨	🟨	🟨
	80	🟦	🟦	🟪	🟥	🟥	🟥
	70	🟦	🟦	🟪	🟥	🟥	🟥
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	50	🟦	🟦	🟪	🟥	🟥	🟥
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	80	🟦	🟦	🟩	🟩	🟨	🟨
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	0	🟦	🟦	🟦	🟪	🟥	🟥
40	100	🟦	🟩	🟩	🟨	🟨	🟨
	90	🟦	🟦	🟩	🟨	🟨	🟨
	80	🟦	🟦	🟩	🟩	🟨	🟨
	70	🟦	🟦	🟦	🟩	🟨	🟨
	60	🟦	🟦	🟦	🟩	🟩	🟨
	50	🟦	🟦	🟦	🟪	🟪	🟥
	40	🟦	🟦	🟦	🟪	🟪	🟥
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	10	🟦	🟦	🟦	🟪	🟪	🟥
	0	🟦	🟦	🟦	🟪	🟪	🟥
30	100	🟦	🟩	🟩	🟨	🟨	🟨
	90	🟦	🟦	🟩	🟨	🟨	🟨
	80	🟦	🟦	🟩	🟩	🟨	🟨
	70	🟦	🟦	🟦	🟩	🟨	🟨
	60	🟦	🟦	🟦	🟩	🟩	🟨
	50	🟦	🟦	🟦	🟪	🟩	🟨
	40	🟦	🟦	🟦	🟪	🟪	🟥
	30	🟦	🟦	🟦	🟪	🟪	🟥
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	10	🟦	🟦	🟦	🟪	🟪	🟥
	0	🟦	🟦	🟦	🟪	🟪	🟥
20 to 0	100	🟦	🟩	🟩	🟨	🟨	🟨
	90	🟦	🟦	🟩	🟨	🟨	🟨
	80	🟦	🟦	🟩	🟩	🟨	🟨
	70	🟦	🟦	🟦	🟩	🟨	🟨
	60	🟦	🟦	🟦	🟩	🟩	🟨
	50	🟦	🟦	🟦	🟪	🟩	🟨
	40	🟦	🟦	🟦	🟪	⬛	⬜
	30	🟦	🟦	🟦	🟪	⬛	⬜
	20	🟦	🟦	🟦	🟪	⬛	⬜
	10	🟦	🟦	🟦	🟪	⬛	⬜
	0	🟦	🟦	🟦	🟪	⬛	⬜

🟥	100% Miscanthus
🟨	100% SRC
⬜	No crops
🟩	100% Combinable crops & SRC
🟪	100% Combinable crops & Miscanthus
🟦	100% Combinable Crops
⬛	<100% Combinable Crops

Figure 3: Crop mixes seen under assumption 2, with and without on-farm machinery. Combinable crops are all held at the same yield reduction and then the DEC yields are altered. The resultant cropping mixes are shown here. If only combinable crops are grown this is shown as 100% combinable crops. If only miscanthus is grown then this is 100% miscanthus. If miscanthus and combinable crops are grown this is shown as 100% combinable crops and miscanthus. There are 1210 simulations for each of the machinery scenarios.

3.4 Assumption 2: Reductions in yields of combinable crops and DECs, with own on-farm machinery

Given the presence of own on-farm machinery, combinable crop yields have to fall below 90% of base-line yield before DECs enter the optimal crop mix, Figure **3**. Where miscanthus yields are 90% of base-line, or higher, then SRC is not produced, and depending on the combinable crop yield penalties, optimal crop mix graduates between 100% combinable crops and 100% miscanthus. Below 80% of miscanthus base-line yield, SRC willow enters the optimal crop mix, in increasingly large amounts, as the miscanthus yield decreases. Given miscanthus yields of at least 20% of base-line yields, the land is cropped with combinable crops, miscanthus or SRC. When the miscanthus yield is reduced below the 20% of base-line yields, combinable crop yields are 40% of base-line or below, and SRC yields are less than 50% of base-line yields, the optimal farm plan is to not produce any crops.

The GM varies between £231,601, given a 100% combinable crop mix at 90% base-line yields, and £0 when no crops are produced. The net energy varies between 84,860GJ, given optimal cropping of 100% miscanthus, and 0GJ, when no crops are produced. The GHG emissions vary between 1,761,300 tCO_2eq under a 100% combinable cropping scenario, and 0 tCO_2eq, when no crops are produced.

4. Discussion

Modern biomass in the early part of the 21st century accounts for less than 2% of world energy supply [2]. Set against this, some authors projects that bioenergy will account for 15% of energy supply by 2050 [5]. The discrepancy clearly signals that we need greater understanding of what drives land use change at the farm-level; indeed we would argue that this understanding is a necessary condition if we are to put increased bioenergy production on a sustainable pathway. Within the UK context, previous studies have typically estimated aggregate level impacts or potential for the production of DECs [15,16,17,18,19,20] producing estimates that range from 140k ha [20] to 3.4m ha [19] against current production levels of less than 10k ha [22]. However as identified by Glithero et al. (2013) [20], Bocqueho and Jacquet (2010) [29] and Alexander and Moran (2013) [30], farm-level drivers, relative crop profitability and variation in relative crop yields can lead to significant impacts on optimal farm-level cropping plans. Our results reinforce Alexander and Moran's (2013) [30] finding that changes in relative crop yield have a substantial influence on optimal cropping. In addition, the results presented above indicate that strategic farm-level decision making with respect to the level of on-farm machinery owned by the business will have a substantial impact on both overall optimal cropping decisions and the potential flexibility of crop choice over time. UK policy incentives to increase the area of DECs have thus far not led to large scale increases in DEC areas in the UK. The results presented above therefore provide novel policy messages for those seeking to incentives DEC production; we develop this idea further below.

Modelling a farm business scenario in the absence of own farm machinery shows that only modest combinable crop yield reductions are required to result in a financially optimal cropping switch to 100% miscanthus production, assuming miscanthus does not suffer a yield penalty. Specifically, with winter wheat yields at 90% of baseline and winter barley and oilseed rape at less than 100% baseline yields, the financially optimal miscanthus only cropping strategy represents a gross margin reduction from baseline of 14%, with an increase of 227% in net energy produced from the farm, and a decrease in GHG emissions of 68%. Hence, where farmers have de-invested in own farm machinery, growing conditions which result in modest yield reductions in combinable crops lead to large scale changes to financially optimal cropping plans, with substantial net energy and GHG emissions improvements. However, in the presence of own farm machinery, winter wheat yield penalties equivalent to 70% of baseline are required before 100% miscanthus becomes financially optimal, albeit that miscanthus enters the crop mix in lower percentages when winter wheat yields are set to 90% of baseline; hence given own farm machinery a more graduated introduction of miscanthus occurs as combinable crop yields are reduced, in comparison to the whole-sale changes to optimal crop mix observed under the without own farm machinery scenario.

However, the modest yield reductions in combinable cropping that lead to large switching to miscanthus assumes that miscanthus will not suffer yield penalties under these conditions. Under sensitivity testing for yield reductions in DECs, when yield penalties for miscanthus are observed, combinable crops re-enter, or increase in magnitude, in the rotation. Only under circumstances when yield reductions are assumed for both combinable crops and miscanthus does SRC (without yield reduction) enter the optimal crop mix under both the presence and absence of own farm machinery scenarios. Given an *absence* of own farm machinery, the financially optimal cropping plan contains either: i) combinable crops, ii) miscanthus or ii) SRC; however, the flexibility introduced from not owning farm machinery leads to these three crops types not being jointly present in any proportion as optimal switching occurs across the whole farm area; such an approach to 100% cropping of DECs will however be incompatible with future Common Agricultural Policy (CAP) cross compliance restrictions in that it will result in financial penalties [43].

Given the presence of own farm machinery a more graduated cropping pattern occurs as relative crop yield penalties are assumed, and typically the optimal crop mix contains a more varied cropping pattern across the farm. The results that demonstrate miscanthus is the optimal DEC choice, given combinable crop yield penalties, reinforces Glithero et al.'s (2013) [20] findings that interest in growing miscanthus is greater than interest in SRC production, albeit that only modest proportions of English arable farmers would consider growing either crop; miscanthus (17.2%) and SRC (11.9%). In more extreme cases of reduced yields for all crop types, including reduced yields for DECs, the optimal model solution is to not crop the land; given the *absence* of own farm machinery, non-cropping is optimal at more modest yield reductions than the yield reductions which lead to abandoning cropping given the *presence* of own farm machinery.

There is a lack of data that ties the yields of crops to the quality of land on which they are grown, especially in relation to DECs. A range of studies investigate the impact of management practices on both soil quality and crop yield combined but this is often carried out on agricultural land that is already used for food crops [44]. Alternatively, differences in crop yields between areas of different land quality are simulated in models to give yield maps [26;27]. The approach used in this paper is a more comprehensive and theoretical approach, in that all potential yield reductions for crops on marginal land in comparison to current arable farmland are included, so that precise yield reduction data is not initially needed in order investigate how cropping on marginal land could be affected by yield reductions.

The results differentiate between optimal cropping plans under the presence and absence of own farm machinery. This approach is more comprehensive than BEFMs which either exclude the possibility of the use of contractors in production (akin to Søgaard and Sørensen, 2004 [35]) or only allow the use of contractors once own farm machinery resource has been fully utilised within a particular time-frame [33;34] and complements Annetts and Audsley's (2002) [32] approach where different levels of machinery ownership can be examined. While our approach explicitly tests for sensitivity of results with respect to relative yield (and hence financial return) variation that may exist, a number of potential caveats should be noted. Specifically to ensure tractability of the MEETA model, we represent perennial cropping within a single-year time-frame and hence do not account for the dynamic variation in costs and revenues that flow from perennial crop production in contrast to annual crops. In addition, our extension to the MEETA model draws upon input data which represents typical, contemporaneous (and therefore competing) production alternatives, from standard farm management data sources; consequently within our approach we do not test for sensitivity of variation with respect to the input data, however in commercial practice and planning farmers and their advisors would typically draw upon the sources of data we utilise within our approach.

Accepting the above caveats, we argue that our findings provide direct industry and policy relevance to those seeking to secure sustainable bioenergy pathways. Previous work notes the need for policy makers seeking to incentivise DEC production via introduction of alternative policies to the establishment grant [20]. The results presented here suggest that while modest yield penalties in combinable crops will lead to financially optimal cropping plans that include DECs, the presence or absence of own farm machinery will be a key short term factor for farmers seeking to optimise financial returns. Policies which therefore encourage farmers to de-invest in own farm machinery (e.g. reductions in capital gains tax, increased targeting of agricultural support to environmental stewardship activities involving non-cropped land), or incentivise the purchase of specific DEC machinery may therefore play an important role in assisting the development of DEC production.

The focus of much policy attention of producing DECs on ‘marginal land’, while a necessary consideration for the future of DEC production, is argued here to be incomplete given that such analyses only consider one aspect of a complex mix of issues facing farmers and land managers with respect to production possibilities. While previous work has identified the potential for particular geographic regions of the UK to be converted to DECs (e.g. Alexander et al (2013) [45], these do not take into account farmer attitudes towards DEC production, which has been highlighted by Glithero et al. (2013) [20] as of key importance. Moreover, it is important for analyses to consider the asset fixity aspects that influence farmer decision making with respect to the introduction of DECs [46]. Specifically, the results presented herein highlight the contrasting financially optimal crop mixes observed under the presence and absence of own on-farm machinery, which have been demonstrated to have a greater impact on financially optimal DEC plans than the relative crop yield penalties that may result from production of combinable crops on marginal land.

5. Conclusion

While calls for the production of energy crops on marginal land have been repeatedly made, and provide a convenient policy message, farm-level decisions over the use of land are complex and dynamic. We find that relative crop yield, machinery ownership decisions, the wider policy environment and farmer attitudes towards the production of energy crops combine to influence the potential uptake of DEC production. In order to incentivise the production of DECs further, government will need to develop more innovative policies which demonstrate a greater understanding of the complexities of farm-level decision making. These policies should also allow for the inevitable trade-offs that exist in promoting one type of production over competing alternatives, even where ‘marginal land’ has been identified as being suitable for bioenergy production.

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Footnotes

[1] The area of set-aside in the UK as a percentage of arable area between 1996 and 2005 [21],

Appendix A:

A.1. Labour and Machinery Use:

The machinery added to the model to perform the additional crop operations (Table A1) for the dedicated energy crops can be seen in

Table A**2**. The additional machinery incorporated into the MEETA model were treated in the same was as Glithero et al. (2012)[34]. Additional details relating to the machinery area available from the authors on request.

Table A1: Work rates for field operations and the frequency of these for the dedicated energy crops. The number of operations for these crops taken from the best practice guides for these crops [38,40]. Work rates taken from Glithero et al. (2012)[34] and the ABC book [39].

	Field Operation	hr ha^{-1}	Miscanthus		SRC	
			Establishment & Removal (2)	Harvest (1)	Establishment & Removal (3)	Harvest (3)
Cultivations	Plough (6 furrow) – heavy land	1.18	1		1	
	Power harrow m – heavy land	1.11	1		1	
	Subsoiling 3 leg - heavy land				1	
	Roll	0.71	1		1	
Planting	Miscanthus planting machine	1.10	1			
	SRC planting machine	1.37			1	
Crop maintenance	Spraying 24m	0.14	4		4	1
	Fertilising - spinning	0.17		1	1	1
Crop harvest	Miscanthus harvester (mower conditioner)	0.36		1		
	SRC harvester	1.56				1
	Baler (take to be same as straw one)	0.5		1		
	Straw carting (2 men tractor loader and trailers)	0.5		1		1

Table A2: Farm machinery added to the MEETA model specifically for the dedicated energy crops.

Machines	Weight (kg)	Diesel use (l h^{-1})	Direct energy (GJ h^{-1})	Indirect energy (MJ h^{-1})	Direct emissions (kg CO_2 eq h^{-1})	Indirect emissions (kg CO_2 eq h^{-1})	Contract cost (£ h^{-1})
SRC step planter	1400			10.73		0.73	297.08
SRC adapted forage harvester	11560	56.5	2.08	371.4	183.71	21.46	425.85
Roller	1500			11.5		0.78	
Miscanthus precision planter	4512			34.6		2.35	347.53
Miscanthus mower conditioner	500			3.83		0.26	63.41

A.2. Fertilisers:

Due to the soil type included in the model applications of P and K for either crop are not required [40] although it is recommended that P and K levels in the soil are regularly checked. Miscanthus requires no applications of N during the establishment of the crop but it is recommended that 60 kg ha-1 of N is applied annually after this period [40] which has been included in the MEETA model despite the best practice guide stating that there is no yield response (at Rothamsted Research, UK) from N applications over 13 years of research. It is recommended that 30 kg ha-1 N is applied to SRC after the establishment although due to the difficulty of application during the growing period of the crop then this can be applied triennially as 90 kg ha-1 post harvest [47].

A.3. Pesticides:

SRC and Miscanthus only need applications of herbicides [38;40]. The best practice guide for SRC [38] states that fungicides and insecticides are not recommended for a range of economic, practical and environmental reasons. Table A3 shows the number of pesticides applied to the DEC's along with the costs and the embodied energy. Further details about the types of chemicals applied available on request from the authors. The costs and energy for these chemicals are treated in the same way as Glithero et al. (2012) [34].

Table A3: Number of pesticides applied to miscanthus and SRC willow.

		Miscanthus[a]	SRC	
		Establishment & Removal	Establishment & Removal	Harvest
Herbicides	Chemicals	4	4	1
	Cost	69.09	108.5	27.53
	Energy	1249	2337	625

[a] No chemicals are required during the harvest phase of the crop.

A.4. Other inputs to the crops

The planting rates for the two crops are taken from the best practice guides for these crops [38;40] and [39]. Miscanthus rhizomes are planted at a density of 14,000 per hectare at a cost of 8.5p per rhizome [39]. SRC cuttings are planted at a density of 15,000 per hectare at a cost of 5p per cutting [39]. There is no data on the energy used to produce these cuttings and rhizomes and so no energy data for this was used in the model.