Water use implications of bioenergy cropping systems in Eastern England

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Food and fuel security in the face of population growth and climate change represent key societal challenges. Extending an arable farm-level bio-economic optimisation model 'MEETA' to include dedicated energy crops (DECs) and water metrics, we quantify water use implications and trade-offs between greenhouse gas emissions, net energy and farm profitability. Drawing upon the limited available water use data for arable and energy crops applicable for East Anglia in the UK, six different farm scenarios were investigated. Profit maximisation produces a conventional crop mix, while maximising net energy and minimising greenhouse gas emissions result in crop mixes which impose financial penalties and lower water use in comparison to conventional cropping; average financial impacts of the associated reduced water use under these respective scenarios range from £0.12 to £0.28 per m^3 of water. Confidence in these results and work on water use and management more generally would be improved through better data on inter-annual crop-water needs, temporal water availability relationships and water response functions. Water availability for UK crop production is largely perceived to be a non-limiting resource; however climate change predictions demonstrate that availability of water for UK crop production is of increasing concern for both farmers and society as a whole.

Keywords Food, Bioenergy, Water Use, Modelling, Greenhouse Gas Emissions.

JEL code Energy: Demand and Supply Q41

Introduction

The Foresight Report on the Future of Food and Farming (Beddington, 2011) eloquently captures the range of pressures on managed biological and environmental systems and the need for human interventions to alleviate these pressures if we are to meet increased global food demand. Particular problems highlighted by Beddington include soil degradation, over extraction of water, over fishing, too great a reliance on fossil fuel-derived energy and crop inputs and the release of greenhouse gases to the environment. Food pressures flow in part from projections for population change. In the UK current (2013) population levels of 63.7 million are projected to increase to 67-78 million by 2037 (Anon, 2013); in the EU projections for a 5% population increase between 2008 and 2030 have been cited, albeit with considerable variation between EU countries (Giannakouris, 2010). Globally population is widely projected to reach 9 billion by 2050, with some estimates providing an 80% upper confidence boundary for mid-century global population reaching 10 billon (Beddington, 2011). Environmentally, there is mounting evidence that climate change will have a substantial impact on EU agriculture (Anon, 2014a; IPCC, 2014); whether these impacts are positive or negative depends on location, with crop production in southern EU areas projected to be more vulnerable to reduced rainfall and higher temperatures (IPCC, *ibid*). While some estimates for northern latitude crop production under climate change are positive with respect to yields for major crops such as cereals (Anon, 2009; Olesen and Bindi, 2002; IPCC, *ibid*), projections are also for increased crop-yield variability. Moreover, climate predictions for the UK and France are for increased winter rainfall, summer temperatures and summer drought occurrences. Generally, variability of weather and the frequency of what are currently thought of as extreme events (precipitation within a set period, zero-rainfall days, floods and heat waves for example) are projected to increase. While a range of adaptations to farming systems would be required to meet these environmental changes, it is apparent that what might broadly be termed 'water management' will be an important consideration - and not just in southern EU countries. However, EU member states have multiple objectives for agriculture; indeed, the multifunctionality of agriculture has been a tenet of EU policy in recent years, with various interpretations as to what the different functionalities might include: food safety and security, animal welfare, rural development, biodiversity, environmental quality, cultural and landscape values are examples listed by Cahill (2001). From a more recent perspective, we can add energy production from biomass to this list. If water management is an important aspect of climate change, how do EU bioenergy production targets affect our ability to adapt while meeting a growing demand for food? Our focus in this paper is on water use and the implications of bioenergy policy on water use; however, there is a wider question relating to the 'multifunctionality' of agriculture and how we meet multiple objectives through what are often single-issue policy mechanisms - or policy mechanisms framed by single-issue discourse.

In the UK a renewable energy 'roadmap' outlines how the country will meet its energy targets: a legal commitment to derive 15% of energy from renewable sources by 2020 is now in place (Anon, 2014b). Incentives available include the renewable heat incentive, covering biomass boilers; feed-in-tariffs for electricity from low carbon electricity systems (Anon, 2014b); and establishment grants for energy crops. Policies introduced to increase the supply of renewable technologies also aim to help the UK meet 2050 greenhouse gas emission targets (Foxton and Pearson, 2007). Concerns over energy security and climate change have jointly driven interest in first generation bioenergy production (using food crops) and more recently, second generation bioenergy production (using agricultural co-products such as cereal straw and dedicated energy crops- 'DECs'). Within the wider EU, targets on energy use for 2020 have also included specific bioenergy targets, including those relating to biomass crops (EU Directive 2009/28/EU).

While there has been a growing interest in bioenergy crops and use of co-products for bioenergy, the impact of climate change on the potential for these crops to contribute towards meeting energy and climate change-mitigation targets has received less attention than the focus on their technical development and subsequent processing (an example in the UK is the BBSRC 'Sustainable Bioenergy Centre' [www.bsbec.bbsrc.ac.uk]) and renewable energy systems more generally (e.g. the Energy Technologies Institute [www.eti.co.uk]). Climate change will play an important role in determining the extent to which biological energy sources contribute to energy provision and GHG reduction targets. As we have noted, predictions of the impact of climate change on cropping systems include lower cereal and oilseed yields under conditions of increased temperatures that reduce growing periods (Olesen and Bindi, *ibid*) and also yield increases in northern latitudes (IPCC, *ibid*). Others have noted yield benefits will be observed under conditions of increased rainfall (Howden *et al*., 2007), albeit that regional differences due to flooding may also impact on productivity and cropping potential (e.g. as noted by Mokrech *et al*., 2008, in low-lying parts of East Anglia, or more recently - winter 2014 - in the south west of England). With respect to energy crops, drought stress conditions can lead to large yield reductions (40% has been reported for *Miscanthus*, Richter *et al.*, 2008). Data on water use and management for crops in Northern Europe is relatively scarce (substantially less than information on 'nitrogen use and management' for example). Mekonnen and Hoekstra (2010) provide information on green, blue and grey water use for various food (but not energy) crops and crop products; Gerbens-Leenes *et al*. (2009), examine the water footprint of 15 crops, including miscanthus and Borek *et al*. (2010) present water use for four crops including miscanthus and SRC (Short Rotation Coppice) willow. However, there is paucity of data on water use of crops and the sort of relationships that one would expect to be fully documented, such as input-response relationships, are lacking, particularly for bioenergy crops (Borek *et al*. 2010).

The desire to get a better understanding of water use and management issues in agricultural production is not new: a European Commission strategy document on sustainable water management was published over 15 years ago (European Commission, 1998). Some recent work has addressed the impact of agriculture on water quality (Wilson, 2014); however, in line with the limited data available, relatively little work has been done on water use and management in relation to bioenergy crops. In this paper we explore some of the data available and make a preliminary assessment of the impact of different cropping systems on water use within a UK context. Using an existing farm level optimisation model ('MEETA') we further develop our analysis by quantifying trade-offs and potential benefits between financial, net energy and greenhouse gas emission farm level outputs and water inputs.

Methods

The MEETA model

The MEETA model (Glithero *et al.*, 2012) is an arable farm level model which uses bio-economic linear programming and life cycle analysis techniques to investigate trade-offs between profitability, net energy and greenhouse gas emissions associated with a farm system. The model represents multi-year cropping rotational possibilities in a single year framework and includes the crops: winter wheat (with variations related to different nitrogen fertiliser applications and whether the straw is removed post-harvest), winter barley, spring barley, winter oilseed rape and winter field beans. The MEETA model of Glithero *et al.* (2012) has been extended to include annualised versions of the Dedicated Energy Crops (DECs) miscanthus (where the crop is grown for periods of 5 and 20 years) and SRC willow (where the crop is grown for periods of 9, 21 and 30 years) and recoded in GAMS (the General Algebraic Modelling System). The model takes account the establishment, growing, harvesting and removal phases of these DECs within a single year representation. The main inputs of the model are: work rates for the various crop operations, levels of chemical applications (both in the form of crop protection products and fertilisers), initial seed requirements, grain drying requirements and the associated diesel use for this operation, yield data for grain and straw for cereal crops, yields for DECs, contract costs and diesel use by machinery. The direct and indirect energy associated with the inputs of the model are included e.g. the energy contained within the diesel fuel and that embodied within the farm machinery. The model also accounts for the greenhouse gas emissions of nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) produced by the farm. The outputs from the model are the overall farm gross margin (our measure of profitability), the total greenhouse gas emissions, the net energy from the farm and the crop mix. The model can be optimised for one of three farm objectives; maximising the farm gross margin, maximising the net farm energy or minimising the total greenhouse gas emissions on farm (under the assumption that cropping occurs on all farmland). In addition to including DECs, the MEETA model has been extended to include water use metrics related to the yields of all the crops. Within this paper we represent a 400ha arable farm in East Anglia, building upon Glithero *et al.* 2012.

Water Use Data for the MEETA model crops

As argued in the introduction, data relating to water use is sparse in relation to arable crops, and in particular in relation to DECs, even though water use efficiency is more widely studied. Here, we focus on estimates from three different sources: Mekonnen and Hoekstra (2011), Borek *et al*. (2010) and Gerbens-Leenes *et al*. (2009) which each cover at least one western European country. Due to the differences in farm management and growing conditions throughout the world water metrics used in the MEETA model were limited to those applicable to western European countries as this would be most applicable in a UK context. Mekonnen and Hoekstra (2011) publish global water use data for a wide variety of crops and crop products, down to the sub-regional level within each country, but do not provide data for miscanthus and SRC willow. Water use data is recorded in m^3 t^{-1} of crop product, where production data refer to the actual harvested production from fields. The relevant subset of these data was used in the MEETA model to provide the water use results for the East Anglian region of the UK. Gerbens-Leenes *et al*. (2009) investigated the water footprint of fifteen crops in four countries of which one was the Netherlands. This study included some of the combinable crops used in the MEETA model but also included values for miscanthus, again in m^3 t^{-1} of crop. Borek *et al*. (2010) assessed the water implications of energy crops within Poland and considered winter wheat, miscanthus and willow. Data available include m^3 ha^{-1} water use, crop yields (t ha^{-1}) and water footprint m^3 t^{-1}. The Mekonnen and Hoekstra (2011), Borek *et al*. (2010) and Gerbens-Leenes *et al*. (2009) data for the UK for the combinable crops within the MEETA model can be seen in Figure 1. For miscanthus there are three values for the water use which are 126, 169 and 334 m^3t^{-1} and for SRC willow there are two values of 208 and 234 m^3 t^{-1}. There is a wide variation in the data for oilseed rape and miscanthus in comparison to the other crops, although data for miscanthus is limited.

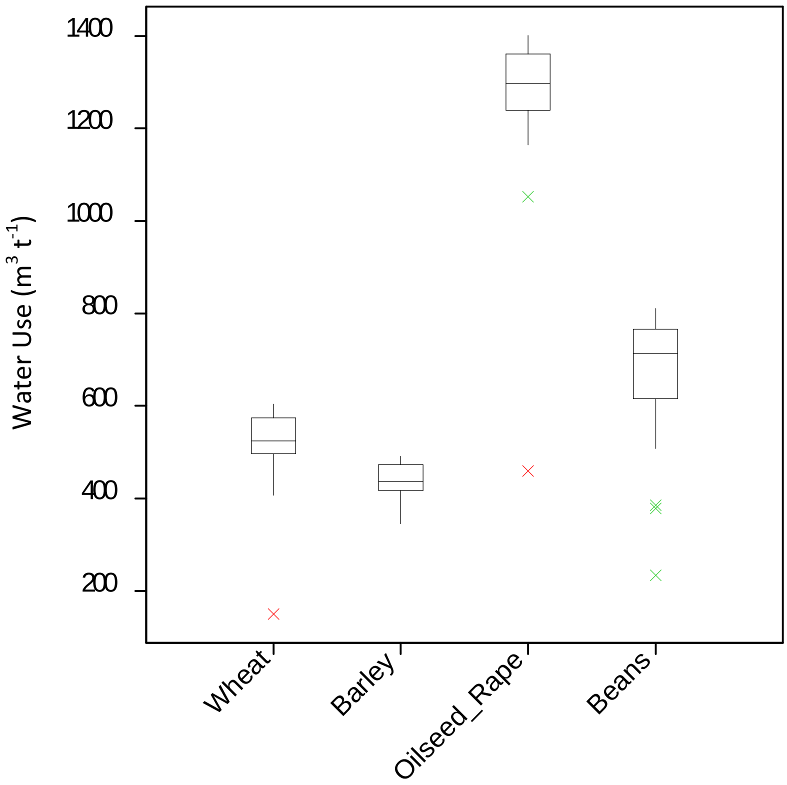

Figure 1: Water use data for each of the combinable crops (m^3 t^{-1}) taken from Mekonnen and Hoekstra (2010), Borek *et al*. (2010) and Gerbens-Leenes *et al*. (2009). Box shows the inter-quartile range with the horizontal line representing the median value. Whiskers extend to 1.5 times the inter-quartile range beyond the quartiles or the maximum value if this is smaller. The outliers are represented by crosses with the far outliers represented by the red crosses as they lie beyond 3 times the inter-quartile ranges beyond the quartiles. Beans refers to data for broad beans which is used to represent winter field beans. There are 86 data points for wheat, 83 for barley, 75 for oilseed rape and 88 for beans.

The water use values used in the MEETA model (based on East Anglia values where available) are shown in Table 1. Oilseed rape and winter field beans have much higher water use requirements on a per tonne basis in comparison to cereal crops although due to their lower yields this does not equate to high values on a per hectare basis. Miscanthus has a low per tonne water use, despite the wide max-min range of the data, and due to its low per hectare yield this also means that this crop has a low water use on a per hectare basis. SRC willow also has a relatively low per tonne water use but this crop is triennial so even though it has a high crop yield when this use is averaged over the three years it equates to a low per hectare water use. Overall DECs seem to have lower water use, on a per hectare or per tonne basis, compared to combinable cropping.

Table 1: Water use values for each of the crops taken from Mekonnen and Hoekstra (2010) for the combinable crops and Borek *et al*. (2010) and Gerbens-Leenes *et al*. (2009) for DECs.

Crop	Water Use ($m^3 t^{-1}$)		
	Min	Max	Median
Wheat	574	597	584
Barley	474	490	483
Oilseed Rape	1336	1402	1373
Field Beans	767	810	791
Miscanthus	126	334	169
SRC willow	208	234	221

Scenarios simulated using the MEETA model

The MEETA model was run under six different scenarios:

1. Farm maximises the gross margin and is able to utilise all types of crop
2. Farm maximises the net farm energy and is able to utilise all types of crop
3. Farm maximises the net farm energy and is allowed to utilise all types of crop except miscanthus
4. Farm maximises the net farm energy but is not allowed to grow any DECs
5. Farm minimises the total farm greenhouse gas emissions but is not allowed to grow any DECs
6. Farm minimises the total farm greenhouse gas emissions and is able to utilise all types of crop

Scenarios 1, 2 and 6 are applicable to farms where there are no restrictions on the types of cropping that can occur on the farm. Scenarios 3, 4 and 5 are applicable to farms where all or some DECs may not be grown due to constraints (e.g. restrictions imposed by tenancy agreements on rented land). Scenarios 5 and 6 also have the additional constraint that all farm land must be utilised.

Results

Simple water use and rainfall calculations

A simple calculation of the water use for each of the crops in the MEETA model was compared to annual average rainfall for East Anglia for two consecutive time periods, Table 2. Ignoring changes in both crop demand and precipitation over time, none of the crops considered would be water limited in East Anglia during either of the time periods, assuming an annualised representation of the perennial crops miscanthus and SRC willow.

Table 2: Water use calculations based on the water use for each of the crops in East Anglia, the yields for each of the crops taken from the MEETA model and comparison against available water in East Anglia during two consecutive time periods (1996 to 2005 and 2006 to 2013). As miscanthus and SRC willow are perennial rather than annual crops the yield values represent the yields of these crops in an annualised form (not including the establishment and removal phases); for miscanthus this is the yield from annual harvesting of the crop after the establishment phase is completed and for SRC willow, which is harvested triennially, the 3rd year yield is divided by 3 to provide an annual representation (3 year values provided in brackets).

Crop	Water Use[a] ($m^3\ t^{-1}$)			Yield ($t\ ha^{-1}$)	Water use per ha of crop ($m^3\ ha^{-1}$)			Rainfall (96 to 05) ($m^3\ ha^{-1}$)	Rainfall (06 to 13) ($m^3\ ha^{-1}$)
	Min	Max	Median		min	max	median		
Wheat	574	597	584	8.3	4766	4957	4849	6372	6248
Barley	474	490	483	7.0	3316	3428	3381	6372	6248
Oilseed Rape	1336	1402	1373	3.3	4407	4626	4530	6372	6248
Field Beans	767	810	791	4.0	3070	3241	3162	6372	6248
Miscanthus	126	334	169	13.0	1638	4342	2197	6372	6248
SRC willow	208	234	221	11.7 (35)	2427 (7280)	2730 (8190)	2578 (7735)	6372	6248

[a] Uses only Mekonnen and Hoekstra (2010) for the combinable crops.

MEETA model scenarios

The various metric outputs from the MEETA model under the different scenarios can be seen in Table 3 and Figure 2. A general result is that optimal solutions built around conventional, non-energy crop mixes produce a greater gross margin (£ ha^{-1} of total farm area) but are linked to greater water use. Of the model simulations that result in conventional cropping being optimal (max GM, max NE without DECs and min tGHG without DECs) a cropping pattern of winter wheat, winter barley and winter oilseed rape uses more water than that of a winter wheat and winter field beans crop mix. Differences in the yield of winter wheat given different levels of nitrogen applied can be seen in the max NE without DECs and min tGHG without DEC scenarios where the same cropping pattern, but with different nitrogen applications, shows differing water use. The largest water use can be seen in the max GM simulation which produces the cropping pattern: winter wheat, winter barley, winter oilseed rape. The smallest (using the median values) water use is associated with maximising NE where miscanthus (20 year) cropping occurs; however, note that this crop is subject to the greatest variation in the data for water. The second smallest water use is associated with short rotation coppice willow (30 year), achieved when maximising NE without allowing miscanthus cropping or when minimising tGHG. In practice, these runs may give the lowest water use: the variation in the water use data available for miscanthus (Figure 4) reduces our confidence in the results.

Table 3: MEETA Model results (calculated as a per hectare amounts) for the gross margin (GM), net farm energy (NE), total farm greenhouse gas emissions (tGHG), the water used on farm and the optimal crop mix given the scenario objective. The values '75% N' and '50% N' for winter wheat refer to the percentage of the recommended amount of nitrogen that is applied to the wheat crop. Miscanthus 20 ys is a miscanthus crop that is grown for 20 years and SRC willow 30 yrs is a short rotation coppice of willow that is grown for 30 years.

	Water Use (m^3 ha^{-1})			GM	NE	tGHG	Crop Mix
	Min	Max	Median	(£ ha^{-1})	(GJ ha^{-1})	(10's kg CO_2 eq)	
max GM	4200	4300	4200	710	64	440	1:1:1 Winter wheat 75% N wheat straw removed, Winter barley, Winter oilseed rape
max NE	1500	3900	2000	440	210	140	Miscanthus (20 yrs)
max NE (no miscanthus)	2200	2500	2300	340	190	110	Short rotation coppice willow (30 yrs)
max NE (without DECs)	3900	4100	4000	670	65	230	50:50 Winter wheat 75% N wheat straw removed, Winter field beans
min tGHG (without DECs)	3800	3900	3900	610	52	190	50:50 Winter wheat 50% N, Winter field beans
min tGHG (with DECs)	2200	2500	2300	340	190	110	Short rotation coppice willow (30 yrs)

The crop mixes from the max GM, max NE (without DECs) and min tGHG (without DECs) scenarios are the same as those in Glithero *et al.* (2012). The trade-offs between the gross margin, net energy and total greenhouse gas emissions can be calculated. These are the marginal changes between the solutions and hence give an indication of the incentives required to change production based on the assumptions of the MEETA model. Slight variations between the values from this GAMS version of the model and that published in Glithero *et al.* (2012) exist due to the differences in the optimisation routines. The GM-NE trade-off, where DECs are allowed, has a value of £2 GJ^{-1}, which represents the gross margin forgone per GJ of additional net energy produced when comparing the max GM and max NE scenarios; the trade-off value is £41 GJ^{-1} if DECs are not allowed. The water use implications between the max GM and max NE simulation (where DECs are allowed) is £0.12 per m^3 water: for every extra m^3 of water the farm uses, £0.12 (ranging from £0.09 to £1.10 using the max and min water use values) extra GM is earned if the farm maximises GM rather than maximising NE (with DECs): this increases to £0.16 per m^3 of water (ranging from £0.10 per m^3 to £0.53 per m^3) if maximising NE without allowing the production of DECs. The GM-tGHG trade-off, where DECs are allowed, is £0.11 per kg CO_2 eq which represents the GM forgone per kg of CO_2 eq emissions saved when comparing the max GM and min tGHG with DECs scenarios; the trade-off value is £0.04 per kg CO_2 eq if DECs are not allowed. The associated water use implications between the max GM and min tGHG scenarios (where DECs are allowed) is £0.19 per m^3 of water, thus for every extra m^3 of water the farm uses, £0.19 (ranging from £0.17 to £0.22 using the max and min water use) extra in GM is obtained if the farm maximises GM rather than minimising tGHG (with DECs): this changes to £0.28

per m^3 of water (ranging from £0.19 per m^3 to £0.51 per m^3) if minimising tGHG without allowing the production of DECs.

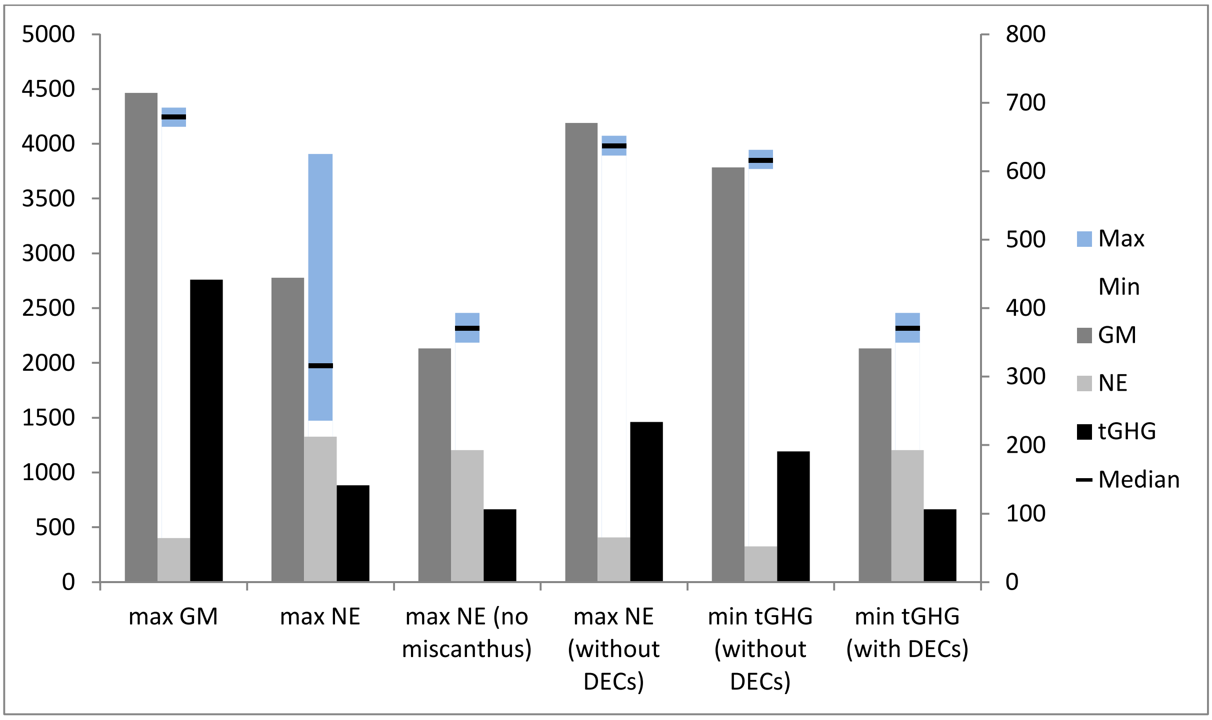

Figure 2: Outputs from the MEETA model in relation to the six scenarios. The black, dark grey and light grey columns (associated with the right hand axis) represent the total greenhouse gas emissions (tGHG, in 10s kg CO_2 eq ha^{-1}), the gross margin (GM, £ ha^{-1}) and the net farm energy (NE, GJ ha^{-1}) for the farm for each of the scenarios. The blue box represents the max-min range of the water result for the scenario (associated with the left hand axis, m^3 ha^{-1}) with the black line representing the median water use value for the scenario.

Discussion and Conclusions

The most notable feature of the results is that combinable cropping provides the optimal farm financial outcome and produces higher water use per hectare when compared to DECs - reducing water use by a change in cropping from food to bioenergy crops would impose financial penalties on the farm. The minimising tGHG and maximising NE (both without DECs) scenarios also have lower water requirements: here the reduction comes from altering crop mix, and reducing nitrogen input levels; the associated yield of the wheat crop also falls. The lowest combinable crop water use occurs with winter barley and winter field beans in rotation. DECs have the potential to use less water; however, while they may provide more energy and be associated with lower greenhouse gas emissions, financially they are sub-optimal. This in part explains the low current uptake of these crops (3,000ha of SRC and 8,000ha of miscanthus in 2011, Anon 2011) in the UK compared to traditional established cropping patterns.

On the basis of annual rainfall data, none of the crops investigated in this paper are water limited. However, this assumes that data available for SRC willow realistically represents water taken up over its growing cycle, with one harvest every three years (Table 2). The timing and amount of rainfall is of importance because crops utilise different amounts of water over the course of their growing cycles (Angus and Van Herwaarden, 2001), and so may be limited by the water availability during certain months even though they may not be water limited when considered on the basis of annual rainfall figures. Colloquial opinion has it that water use and availability is not important in the UK due to the perceived abundance of rainfall. However, parts of East Anglia are relatively dry by European standards. Kumar *et al*. (2011) suggest that water scarcity is already limiting winter wheat yield in some years, as a result of drought conditions post-anthesis (flowering). Understanding the link between water availability and crop water demands within particular timeframes is therefore of crucial importance. One proxy for crop water demand is the green area index (GAI; see Sylvester-Bradley *et al*., 2008) of the crop which represents the proportion of ground area occupied by the biomass coverage of that crop. For winter wheat the change in GAI is greatest in the months April to July inclusive; recent monthly rainfall data for East Anglia (2006-2013) from the UK Meteorological Office (Met Office, 2014) demonstrates that April has recorded the lowest average monthly rainfall over this time period, albeit also demonstrating the largest range in monthly rainfall. May to July inclusive have provided average monthly rainfall in line with annualised monthly data over 2006-2013. However, with only four months of crop growth representing the period within which substantial crop biomass growth occurs, greater understanding of inter-annual crop water demands against available water availability is required.

The variability and wide range of the underlying data on crop water use highlights the need for better information on crop–water demand in both the UK and wider European landscape. Ideally, information is needed on water-yield response functions, of the type presented by Richter *et al.* 2008. However, this is a generalisable point: despite much research effort and funding into the effects of fertilisers on yield, for different soil types and under different management practices, a centrally available source of data from field and other experimental work is lacking. Sources such as FADN (the Farm Accountancy Data Network) are also currently limited in the extent to which they capture water metrics, or attitudes of farmers towards water management, although in England additional information on attitudes towards water management has been collected for a sub-sample of farms for 2009/10 (Wilson, 2014). Predictions for warmer temperatures and greater frequency of extreme events (IPCC, 2014) will lead to more variable crop yields and water conservation will become more important. Total water use metrics are also important from a technology perspective; yield improvement focuses on improving yield from the total water used by the plant, rather than 'water use efficiency' (the ratio of above ground biomass to evapotranspiration) as WUE improvements are associated with lower yield traits such as stomatal closure (Kumar et al., 2011). Without improved data, targeting policies to reduce water use may not be the best approach - achieving water saving may have to be indirectly achieved through policies aimed at other aspects of the farm business. As shown here, targeting energy production or greenhouse gas emission savings which are - currently - more easily quantifiable at the farm level, may also result in lower water demands from farming systems.

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