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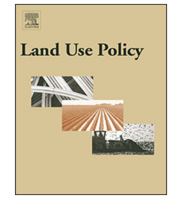

Modelling the production impacts of a widespread conversion to organic agriculture in England and Wales

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ABSTRACT

We assess the production impacts of a 100% conversion to organic agriculture in England and Wales using a large-scale linear programming model. The model includes a range of typical farm structures, scaled up across the available land area, with the objective of maximising food production. The effects of soil and rainfall, nitrogen (N) supply/offtake and livestock feed demand are accounted for. Results reveal major reductions in wheat and barley production, whilst the production of minor cereals such as oats and rye increase. Monogastric livestock and milk production also decreased considerably, whilst beef and sheep numbers increased. Vegetable production was generally comparable to that under conventional farming. Minimising the area of fertility building leys and/or improving rates of N fixation increased the food supply from organic agriculture at the national level. The total food output, in terms of metabolisable energy, was 64% of that under conventional farming. This would necessitate substantial increases in food imports, with corresponding expansion of cultivated agricultural land overseas. Significant changes in diet and reductions in food waste would be required to offset the production impacts of a 100% conversion to organic farming.

1. Introduction

The continuing expansion and intensification of global agriculture presents a clear need to develop modes of production that can supply sufficient amounts of food for growing populations with more efficient use of resources (Godfray et al., 2010). At the same time there is a pressing need to move populations of western countries towards more balanced diets to promote public health, with particular regard to increasing the share of fresh fruit and vegetables in the diet (Macdiarmid et al., 2011; Wellesley et al., 2015). Organic farming has the potential to contribute to developments in the first of these areas through a focus on reduced input intensity and the maintenance or enhancement of ecosystem functions and various studies have identified and quantified the benefits of organic production, in areas such as fossil-energy use, biodiversity and on-farm employment (Lampkin et al., 2015). The significantly higher soil carbon sequestration rates observed in organically managed soils have also led to suggestions that wider use of this production system could help to delay the onset of damaging climate change (Gattinger et al., 2012) although others have noted that these benefits would be offset by the requirement to increase the area of land in agricultural production to meet food demand (Leifeld et al., 2013).

The benefits provided by organic agriculture in areas such as soil protection and rural development also align with the dimensions of sustainability proposed by the United Nations following Rio + 20 through the Sustainable Development Goals (SDGs) and EU action plans such as the Biodiversity Strategy (European Commission, 2010) and Soil Thematic Strategy (European Commission, 2006).

While acknowledging these sustainability benefits and the potential for further growth in the market for organic products (Willer and Lernoud, 2016) some commentators (for example Connor, 2008) have suggested that the lower yields observed in organic agriculture would mean that widespread conversion to organic production could be detrimental to food security. Because the land area devoted to organic farming globally currently remains very small (i.e. organic farmland constitutes approximately 1% of the total global agricultural area, Willer and Lernoud, 2016), it is also difficult to extrapolate from this low baseline to assess the impacts of much larger scale adoption.

Despite this limitation, a few studies have attempted to explore the production and food security impacts of a widespread conversion to organic farming, the most recent of which, with a focus on the UK, was undertaken in 2009 by Jones and Crane. In this study, two different approaches were used to estimate how much food might be produced

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under an assumed 100% organic conversion of agriculture in England and Wales. The results indicated that full organic conversion would lead to major reductions in wheat, barley, and oilseed rape production. Pig and poultry numbers would also fall markedly, while there would be significant increases in the production of minor-cereals (e.g. oats, rye) and ruminant livestock. Although the Jones and Crane (2009) study projected credible trends, levels of production were not adjusted in line with N availability (i.e. the nitrogen availability constraints that impact organic farming, Berry et al., 2002). Feed availability and the nutritional requirements of livestock were also not assessed in detail. Prior to this 2009 study, Badgley et al. (2007) assessed the implications of a 100% conversion to organic production at the global level using FAO-derived data. Organic yield adjustment coefficients (i.e. organic versus conventional) were estimated for 10 groups of crops and livestock products, based on a review of 293 studies drawn from the peer-reviewed literature. Badgley et al. (2007) estimated the average organic yield ratio for all crop types at the global level as 1.32 (i.e. organic would produce 132% of the conventional yield). In the Badgley et al. (2007) study the total N supplied by leguminous cover crops in organic systems was estimated to be 140 million Mg which, according to the study authors "is 58 million Mg greater than the amount of synthetic N currently in use". The authors therefore suggest that the rates of biologically fixed N under widespread organic conversion could support yields equivalent to high-yielding conventional agriculture. Although the Badgley et al. (2007) study included estimates of N availability, the authors base these on the erroneous assumption that 100% of arable land could accept an additional legume crop, following the main crop in the same year. In making this assumption, the authors failed to account for the fact that much of the world's most productive land is already required to carry multiple food crops in a single year to meet food demand. Additionally, no account was taken of areas where climatic conditions and water supplies limit the possibility of a second crop in the same year (Connor, 2008). In consequence of the methodological limitations of recent studies, there is still an absence of reliable data on the food security implications of upscaled organic agriculture.

The study presented here builds on these earlier studies to make a significant contribution to these data needs, through estimating the production and food security impacts of a 100% conversion to organic farming in England and Wales. A modelling approach was adopted that was able to account for yield differences between conventional and organic production, as well as yield variation due to local environmental conditions, plus supply constraints imposed by the availability of N, the need to maintain agronomically rational crop rotations, and the availability of livestock feeds. A multi-scenario approach was adopted to explore the impact of variation in the assumptions underpinning these constraints. In addition, a healthy eating framework developed in the UK was used to assess the ability of a fully organic domestic agriculture to supply optimal human nutritional requirements (i.e. the Eatwell Plate, Macdiarmid et al., 2011)

2. Materials and methods

2.1. The OLUM model

A linear programming model was developed – the Optimal Land Use Model (OLUM) – in the GAMS programming language (GAMS Development Corporation, http://www.gams.com/), to explore the impacts of 100% conversion to organic farming in England and Wales. Fig. 1 summarises the model. At its core is an objective function, Z, to maximise the output of food (expressed as metabolisable energy – ME), defined as:

$$Z = \sum_{ij=0}^{n} C_{ij} \cdot x_{ij} \quad \text{subject to} \quad Rx_{ij} \leq \mathbf{b},\ x_{ij} \geq 0 \tag{1}$$

where C_{ij} is ME output per unit of agricultural products i (i.e. tonnes of crop or livestock product) on soil × rainfall class j, *while* x_{ij} is a scalar, i.e. areas of crops in hectares and numbers of livestock on each soil x rainfall class.Rx_{ij} is the resource (R) requirement for producing enterprises (x_{ij}) and b is the resource endowment and input availability vector. Constraints are specified as linear inequalities and equalities and employed to determine the following:

1. Availability of land by farm type and soil × rainfall class.
2. Maximum and minimum stocking densities (livestock units per ha).
3. Annual feed requirements of different livestock, expressed as metabolisable energy (ME) and crude protein (CP) requirements.
4. Maximum/minimum crop areas by crop groups (i.e. rotation constraints).
5. Soil N availability reflecting cycling of nutrients, plus N inputs and outputs through crop and livestock offtake, atmospheric deposition and biological N fixation.
6. Upper limits on the total permissible production volumes of individual crop and livestock products set at 150% of the current supply, on the assumption that increases beyond this volume could not be absorbed by the market. Evidence suggests that most consumers are unwilling to make major changes to diet (Traill et al., 2008) and this constraint ensured that national levels of production would remain broadly in-line with current dietary choices at a national level, preventing the model from returning unrealistic solutions (e.g. with regard to the over-production of oats and other minor cereals commonly found in organic rotations). Geographical constraints on sugar-beet production were also imposed to restrict the expansion of this crop away from major processing centres in eastern regions.

The components of the model are as follows.

2.1.1. Farm Types

The model's functional units are farms, i.e. production systems consuming various inputs, including land and other resources, to produce multiple crop and livestock outputs. Nine farm types are defined based on the Defra Robust Farm Types (Fig. 2). The mix of enterprises available to each farm type was fixed, although the model was permitted to vary the relative scale of these. This constraint was based on the observation that the dominant enterprises on farms under conventional agriculture is usually maintained post-conversion, because these are the activities that suit existing farm infrastructure and local conditions (Howlett et al., 2002; Langer, 2002).

2.1.2. The land base

Land availability was fixed, at the national level, within NUTS1 region and within farm type. Within each farm type, the allocated land area was fixed at the area observed under each Robust Farm Type in the 2010 Defra June Survey of Agriculture. It was assumed that the total land area under each robust farm type would not change following organic conversion. The land base was disaggregated into 16 classes based on soil type and rainfall (next section). Yield potential was determined for each of these classes. Within each farm type and NUTS1 region, the areas of these 16 land classes were fixed according to their observed spatial distribution.

2.1.3. Land classes

Heavy, medium and light soil classes were specified, each with estimated organic matter content and pH values based on data from long-term organic cropping trials (Smith et al., 2016). A fourth soil class was specified for 'humose', i.e. cultivated soils with an organic matter content and pH typical of the Downholland soil series of the Soil Survey of England and Wales (www.LandIS.org.uk). The spatial distribution of each soil class in 5 km × 5 km grid squares across England and Wales was obtained from the National Soil Inventory (www.LandIS.org.uk). Four rainfall classes were specified, based on 30-year Meteorological

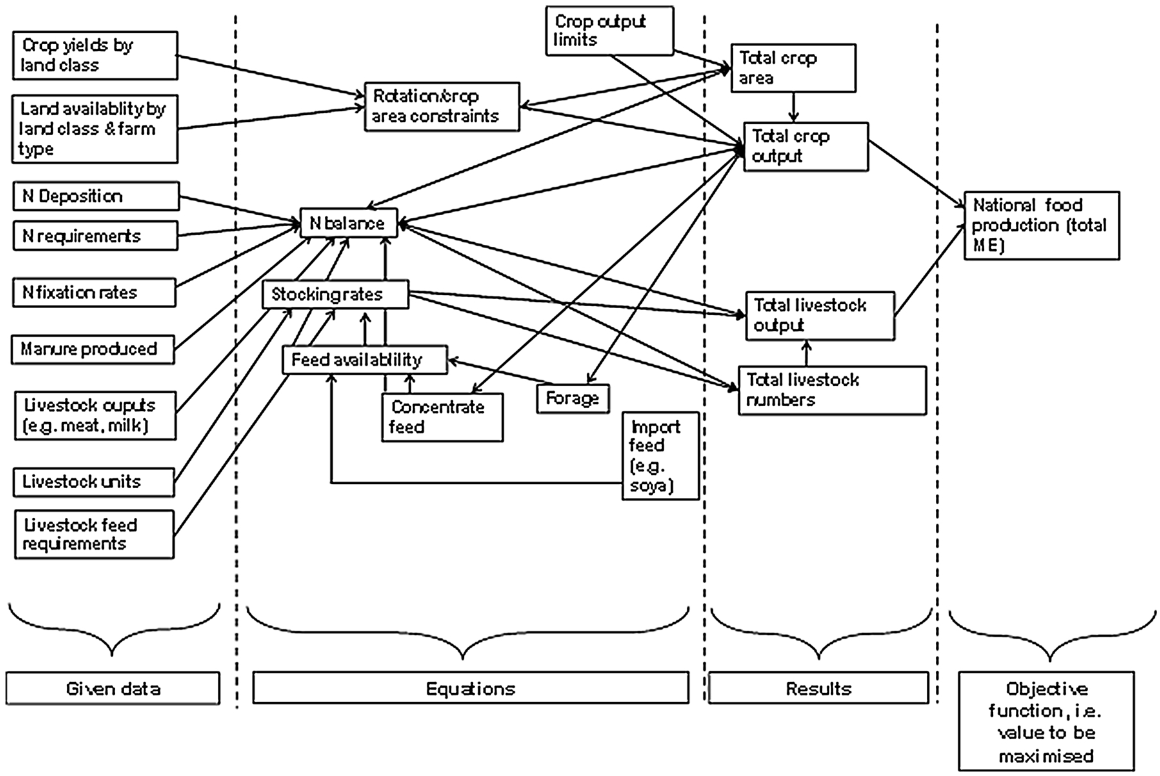

Fig. 1. Schematic of the Optimal Land Use Model (OLUM).

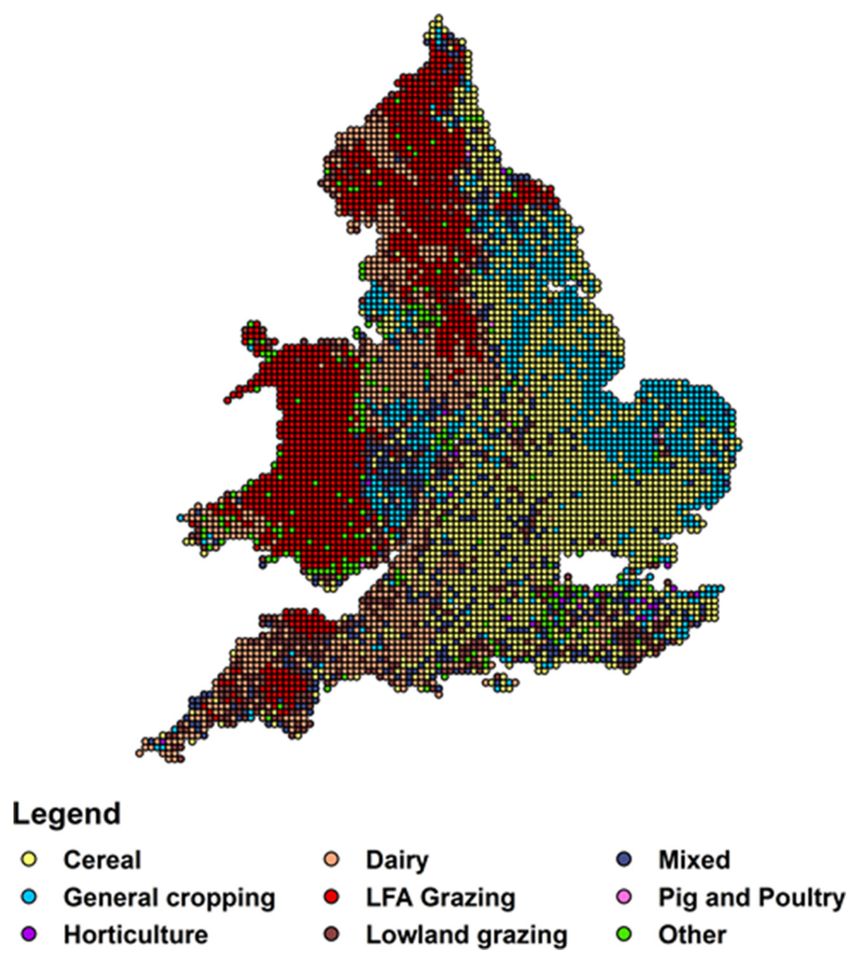

Fig. 2. Dominant Robust Farm Types on a 5 km × 5 km grid across England and Wales. Data are from the Defra June Agricultural Census (Defra, 2011).

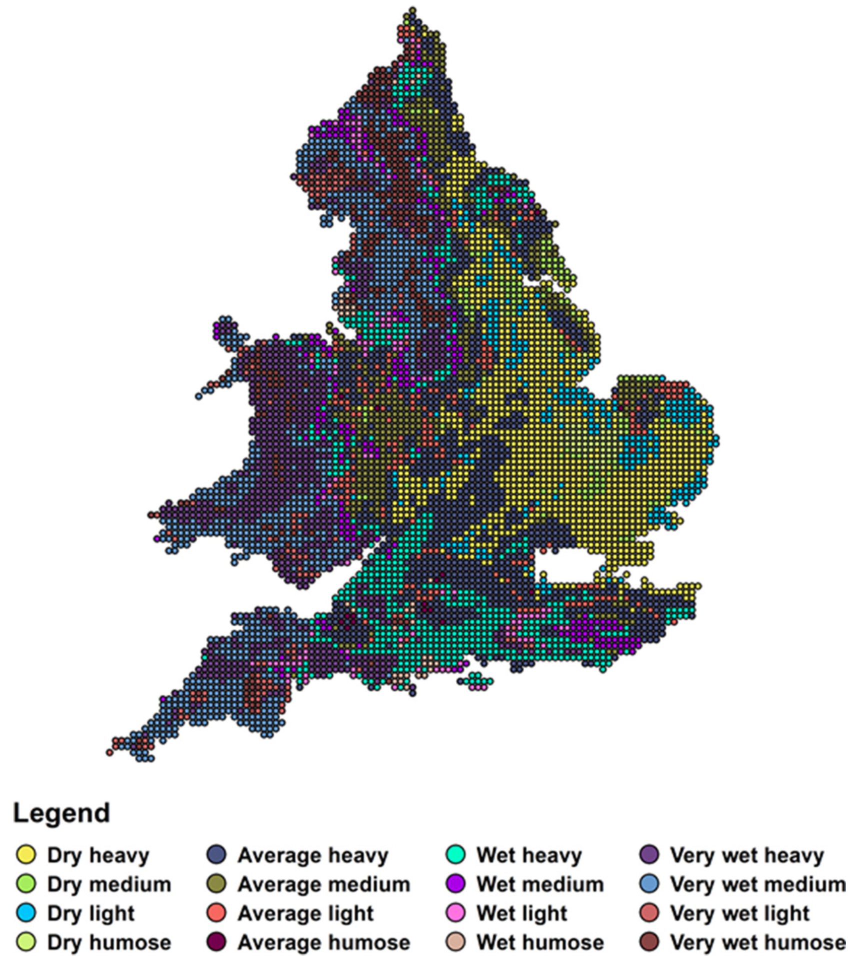

Fig. 3. Dominant land classes based on soil type and rainfall on a 5 km × 5 km grid. Data sources are described in the main text.

Office annual rainfall data. These were, dry 539–635 mm, medium 636–723 mm, wet 724–823 mm and very wet 824–2500 mm. To determine the total areas of each soil × rainfall combination (hereinafter 'land classes'), the dominant combination was identified in each of the 5 km × 5 km grid squares of the National Soil Inventory, and then the sum of the areas of each square, less any non-agricultural area, was allocated to that land class (Fig. 3).

The areas of each land class within each farm type and NUTS1 region were estimated, to generate constraints on land availability at these levels. The sum of these areas provided the constraint on land availability at the national level:

$$\sum_{c=0}^{n} a_{c,t,s,r} = L_{t,s,r} \quad \forall\ t,\ s,\ r \tag{2}$$

where $a_{c,t,s,r}$ is total production area, summed over each crop (c), farm type (t), land class (s) and NUTS1 region (r), and $L_{t,s,r}$ is total land availability.

2.1.4. Crop yields

Potential crop yields for each land class were estimated using the Nitrogen Dynamics in Crop Rotations in Ecological Agriculture (NDICEA) model (Van der Burgt et al., 2006). Smith et al. (2016) showed that NDICEA gives sufficiently accurate estimates of N availability for our purposes in a range of UK soil types and rainfall zones, using data from long-term organic trials. NDICEA has three modules as follows:

- *soil water dynamics*, which accounts for irrigation, rainfall, evapotranspiration, capillary rise and percolation;
- *N mineralisation*, which accounts for N availability from soil organic matter and organic manure; and
- *inorganic N dynamics*, which accounts for N inputs from mineralisation, atmospheric deposition, fertilisers, irrigation and biological fixation, and N losses through denitrification, leaching and crop uptake.

NDICEA is target-oriented, meaning target yields are entered by the user and adjusted manually. Yields are therefore iteratively adjusted according to N supply in each land class for the rotations in Table 1. Points in the rotation where N availability was greater or less than crop requirements were identified, and yields were adjusted accordingly up to a maximum yield potential based on data given in Appendix A in the Supplementary material.

Example results from the NDICEA yield estimation and adjustment exercise are shown in Appendix A in the Supplementary material. Due to the lack of yield data for organic oilseed rape and sugar beet in the UK, as a consequence of very limited organic production of these crops, yield data from a national survey of organic farmers in France and a UK-based modelling study were used (Tzilivakis et al., 2005; Valantin-Morison and Meynard, 2008). The yields for these two crops were adjusted for each of the 16 soil/rainfall classes on the same basis as crops considered similar in terms of their likely position in the rotation (i.e. wheat and potatoes).

2.1.5. Grass yields

A regression-equation model, based on the grass site class system of Brockman (1995), was used to estimate organic permanent pasture

Table 1
Rotations assessed within NDICEA to derive crop yields for each soil and rainfall class.

	Course									
Rotation	1	2	3	4	5	6	7	8	9	10
Stocked 'complex'	G/WC	G/WC	G/WC	WW	WO	RC/G	RC/G	P	SB	SW
Stocked 'simple'	RC/G	RC/G	WW	P	WW	WR				
Stockless 'complex'	RC/G	RC/G	P*	WO	SB	SW				
Stockless 'simple'	RC/G	WW	PE	SO						
Field vegetable	RC/G	RC/G	P	BR	L					
Market garden	RC/G	RC/G	CB	O	B	C	SB	BR	PE	CG
Dairy	G/WC	G/WC	G/WC	G/WC	G/WC	G/WC	G/WC	FB	WS	SB
Cattle and sheep	G/WC	G/WC	G/WC	G/WC	G/WC	G/WC	G/WC	G/WC	FB	WW
Mixed	G/WC	G/WC	G/WC	RC/G	WW	WO	SB	WB	WR	

(G/WC = Grass/white clover, WS = wholecrop silage, WB = winter barley, WW = winter wheat, WO = Winter oats, RC/G = red clover, SW = spring wheat, SB = Spring beans, P = potatoes, WR = Winter rye, FB = Fodder beet, PE = peas, SO = spring oats, BR = broccoli, L = leeks, CB = cabbage, O = onions, B = beetroot, C = carrots, CG = courgettes, SB = spring barley)

yields based on annual rainfall, soil type and altitude (Williams et al., 2006). The model was validated by comparison with yield data from grassland-dominated organic conversion trials at the University of Wales, Aberystwyth (Haggar and Padel, 1996) and Scotland's Rural College (SRUC,Taylor et al., 2006). Appendix A (in the Supplementary material) describes the regression model and the calculated yields.

2.1.6. Crop rotation constraints

Crop rotation is a necessary component of organic systems to break pest and disease cycles, control weeds and maintain soil N through biological fixation (Lampkin, 2002). It was therefore important to include rotational constraints in the OLUM to limit the area of each crop type that could be grown. The rotational constraints were applied at the level of crop group, where these groups were defined in terms of common growth characteristics, i.e. similar nutrient requirements and pest/disease susceptibility (see Appendix A in the Supplementary material). The minimum area constraints on these crop groups were derived from the rotational data described in Table 1 and specified in the model by:

$$\sum_{g=0}^{n} a_{g,t,s,r} \geq L_{t,s,r} \cdot R_{g,t} \;\; \forall\, t,\, s,\, r \tag{3}$$

Where a is the total land-area produced by crop group (g), in each farm type, soil/rainfall class and region (t, s, r), $L_{t,s,r}$ is total land availability by farm type, land class and region and $R_{g,t}$ is a coefficient reflecting the minimum proportion of total utilisable agricultural area (UAA) that must be allocated to this crop group. Maximum areas of each crop-group were defined with the same equation structure, using a "less than or equal to" sign (i.e. $\leq$in place of the $\geq$shown above) and replacing $R_{g,t}$ with a coefficient defining the maximum UAA proportion for each group.

2.1.7. Constraints on livestock numbers

Total livestock numbers were constrained both within farm type and at the national level. At the farm-type level, permissible maximum and minimum stocking rates were set, reflecting constraints inherent in CAP cross-compliance measures. These stocking rates were derived from actual practice, as observed in the organic sub-sample of the Defra Farm Business Survey (Moakes et al., 2012, 2014). Using this data minimum and maximum stocking rates, averaged over a three-year period were calculated by dividing total livestock units by total land area. At the national level, maximum permissible livestock units of each stock type were set, and a separate constraint was set through a maximum manure-N production of 170 kg-N per hectare averaged over the entire land base (i.e. the limit set for organic production within Council Regulation No 889/2008, 2008). As the data provided by Moakes et al. (2012, 2014) excludes information on organic poultry and pig farms, alternative sources were used (Browning pers. comm., 2016, Leinonen et al., 2012a,b) to derive stocking rate limits for these livestock types.

In the OLUM model minimum stocking rates were defined by:

$$\sum_{l=1}^{n} lu_l \cdot l_{l,t,s,r} \geq \sum_{c=1}^{n} c_{c,t,s,r} \cdot smn_t \;\;\; \forall\; t,\, s,\, r \tag{4}$$

where lu_l is a standard livestock unit conversion factor, $l_{l,t,s,r}$ is livestock numbers, $c_{c,t,s,r}$ the total agricultural area and smn_t the minimum stocking rate per ha within each farm type, soil/rain class and region (t, s, r). Minimum stocking rate constraints were removed for specialist cereals, field vegetables, market gardens and general cropping farms to allow for stockless production. Maximum stocking rates were defined using the same equation structure, using $\leq$ in place of the $\geq$ shown above and replacing $R_{g,t}$ with a coefficient defining the maximum stocking rate per hectare within each farm type, soil/rain class and region.

The numbers of young stock, replacements and other stock (e.g. pigs and poultry) required by the model were calculated as a fixed ratio of the numbers of adult animals in the dominant livestock type on each farm type (i.e. the stock type with the highest number of livestock units as a proportion of the total livestock presence). An example of the approach used is:

$$\sum_{bc=1}^{n} \sum_{lg=1}^{n} \sum_{s=1}^{n} \sum_{r=1}^{n} l_{bc,lg,s,r} \cdot pl_{fc} = l_{fc,s,r} \;\;\; \forall\;\; l,\, lg,\, s,\, r \tag{5}$$

where $l_{bc,lg,s,r}$ is the number of adult animals of the dominant livestock type (in this example beef suckler cattle bc) pl_{fc} is a fixed proportion reflecting the number of replacements required to maintain the adult herd. The term $l_{fc,s,r}$ represents total store cattle numbers and lg is the area of the farm-type "lowland-grazing" in each soil/rain class (s) and region (r).

2.1.8. Feed availability

Livestock numbers were also limited by total feed availability. The ME requirements of the livestock being produced were offset against the ME availability in the feedstocks produced. Data on the ME requirements of the different types of livestock and the energy and protein contents of different types of crops and grasses, plus purchased feeds, were drawn from a range of industry sources and technical guides (Soffe, 2003; Lampkin et al., 2014; The Professional Nutrient Management Group, 2015). Livestock concentrate feed composition data were obtained from Vitrition Organic Feeds, Newcastle University (Edwards, 2002) and a recent study on the feasibility of replacing soy in UK livestock production with UK-grown protein crops (Jones et al., 2014). Feed supply constraints and minimum feeding requirements for different types of livestock were defined using the following feed-groups:

Table 2
Scenarios assessed within the sensitivity analysis, defined in terms of their adjusted parameters.

Scenario name	Parameters adjusted
Low N fix	Low crop yields and N fixation rates from NDICEA modelling
High N fix	High crop yields and N fixation rates from NDICEA modelling
Low Clover area	10% reduction in area of grass/clover leys as% of total utilisable area (UAA)
High Clover area	10% increase in area of grass/clover leys as% of total utilisable area (UAA)
High stocking rate	Upper/lower bounds on stocking rates per ha increased
Low Stocking rate	Upper/lower bounds on stocking rates per ha decreased
No fallow	Non-productive land (fallow) added to cultivatable area
Combined	Imported food residue added to livestock feed and fallow added to cultivatable area

- forage (e.g. grass/clover, fodder beet, fodder maize);
- concentrates/straights (e.g. cereals, beans, peas); and
- compound feeds (processed feeds incorporating straights, plus other supplements including, soybean and oilseed meals, crop processing residues, and other imported feed including molasses).

The proportion of the total livestock ME requirement supplied by each feed group was predetermined for each robust farm type, using data reported in Moakes et al. (2012, 2014). Due to the dominance of forage crops within most organic rotations (e.g. grass, clover and other leguminous crops) a maximum forage ME supply was applied at the farm type level in each region to reflect the fact that most organic farms still feed some concentrate and compound feed for finishing. This constraint also ensured that the ME from forages demanded by ruminant livestock did not exceed the ME available from the forage crops. This constraint was applied within each farm type and region to reflect the fact that forage is unlikely to be transported between farms due to costs and impracticalities associated with the transport of such high bulk, low value products. More details on the livestock feed constraints applied are contained in the detailed model description (Appendix B in the Supplementary material).

2.1.9. Livestock outputs

Outputs of beef, sheep meat and milk were constrained, to reflect current yield potential, on a livestock headage basis for each farm type and region using output value data from Moakes et al. (2013), financial and physical output data from the Organic Farm Management Handbook (i.e. total output value for each livestock type divided by price/head, Lampkin et al., 2011) and a recent study by the Agriculture and Horticulture Development Board (AHDB Dairy, 2012). Eggs, poultry meat and pork production were also constrained per head of livestock based on rearing periods and liveweights recorded by Leinonen et al. (2012a, 2012b) and Soffe (2003). These data were applied in the OLUM using equations which expressed total volume/value of output as a proportion of the headage of livestock on each farm (more on this approach is provided in Appendix B in the Supplementary material).

2.1.10. Nitrogen balances of crops and livestock

As the supply of N can be a limiting factor for the maintenance of productivity in organic systems (Berry et al., 2002), N supply and offtake equations were incorporated within the OLUM. Total N supply and crop/livestock offtake were accounted for at the regional level to allow for transfer of manure between farms within the same area, as in Eq. (6):

$$\sum_{c=1}^{n}\sum_{t=1}^{n}\sum_{s=1}^{n} co_{c,t,s,r}\cdot a_{ch,t,s,r} + \sum_{l=1}^{n}\sum_{t=1}^{n}\sum_{s=1}^{n} livn_l\cdot l_{l,t,s,r} \le \sum_{c=1}^{n}\sum_{t=1}^{n}\sum_{s=1}^{n} fx_{c,t,s,r}\cdot a_{c,t,s,r} + \sum_{l=1}^{n}\sum_{t=1}^{n}\sum_{s=1}^{n} lu_{l,t,s,r}\cdot l_{l,t,s,r}\cdot Nin_t + \sum_{l=1}^{n}\sum_{t=1}^{n}\sum_{s=1}^{n} imp_{ltsr}\cdot compn + \sum_{c=1}^{n}\sum_{t=1}^{n}\sum_{s=1}^{n} a_{c,t,s,r}\cdot dp_{c,t,s,r}\ \forall\ r \tag{6}$$

where $co_{c,t,s,r}$ is a coefficient of crop-N offtake,$a_{ch,t,s,r}$ is the scalar, i.e. the area of crops destined for human consumption (ch),$livn_l$ is a coefficient of livestock N-offtake per head and $l_{l,t,s,r}$ is the scalar of livestock numbers by stock type (l). The term $fx_{c,t,s,r}$ represents N fixation per hectare of crop $a_{c,t,s,r}$, $lu_{l,t,s,r}$ is total livestock units, $l_{l,t,s,r}$ is livestock numbers and Nin_t is N contained within imported concentrate (i.e. cereals and beans). Imported compound feed (e.g. soy cake) is represented by $imp_{l,t,s,r}$ and $compn$, i.e. the total compound feed tonnage and the N content/tonne, based on feed values provided by Watson et al. (2010). The term $dp_{c,t,s,r}$ represents average atmospheric N deposition, values for which are derived from national pollution data downloaded from the Centre for Ecology and Hydrology (CEH) website (http://www.pollutantdeposition.ceh.ac.uk/). N supply and offtake values for crops and livestock products were derived from Defra Fertiliser Recommendations (Defra, 2010) and the nutrient budgeting software PLANET (Dampney and Sagoo, 2008). To capture manure requirements for individual crops, a separate manure supply and demand constraint was applied within each region (see Appendix B in the Supplementary material).

2.2. Scenario testing

A base run of the model was produced, applying the data sources, assumptions and constraints described above, in order to generate a “best-guess” of what a wholly organic England and Wales agriculture would look like. The results of this base run were used as a comparator for additional scenarios in which parameters and constraints were adjusted to explore the sensitivity of the base run to changes to key assumptions. The scenarios are summarised in Table 2 and explained below.

2.2.1. N fixation rate

As biological fixation by legumes is the main N input to organic systems, and reliable estimates of the amount of N fixed by different N-fixing crops under different conditions are difficult to obtain (Herridge et al., 2008), two scenarios were run to explore the effect of higher and lower fixation rates, where the base run represents an ‘average’ fixation rate. The amounts of N fixed at these high and low rates were derived from Peoples et al. (2009), Schmidt et al. (1999) and Herridge et al. (2008). These altered N-fixation rates were also used to generate new crop yield estimates within NDICEA (see ‘crop yields’ section above).

2.2.2. Clover ley area

Organically managed arable land must be periodically diverted to fertility-building leys. This reduces the area that is cultivated compared with conventional systems. To explore the sensitivity of the base run to this requirement, two scenarios were run with high and low clover-ley rates, with the average used for the base scenario.

2.2.3. Stocking rates

The effects of varying stocking rate constraints on livestock outputs were also assessed to capture intensive and non-intensive organic livestock production, using high/low stocking rate ranges based on data derived from AHDB Dairy (2012) and Moakes et al. (2012, 2014).

2.2.4. Fallow land

A significant area of fallow (non-productive) land was enforced in the base run reflecting average historic organic practice (up to 13% of the total area in the case of cropping farms was fallow). A separate scenario explored the impact of removing this constraint, i.e. allowing fallow land to be cultivated, as a means to reduce supply shortfalls.

2.2.5. Combined scenario

In a final scenario, two constraint settings were adjusted simultaneously. First, a new source of feed stocks (processing residue from imported cereals) was included in the livestock feed availability equation. Second, fallow areas were added to the cultivatable land area. Results for each scenario were compared with three points of reference: (i) the OLUM base run; (ii) the observed situation in 2010 under conventional agriculture, as recorded in the June Survey of Agriculture (Defra, 2011; Welsh Government, 2011); and (iii) the projections of Jones and Crane (2009) for a wholly organic agriculture. The latter was undertaken for validation purposes. We consider the ‘Combined’ scenario to be the most likely outcome of 100% organic conversion, as it does much to address the supply shortfalls seen in the base run. The results from this scenario were therefore used to assess the potential impacts of a 100% conversion on human nutrition. This was done by assessing the scenario outputs of each food group within a healthy eating framework developed in the UK, i.e. the Eatwell Plate (Macdiarmid et al., 2011). This comparison addressed the question of whether the mix of products produced by a wholly organic agriculture is more closely aligned with the requirements of the Eatwell Plate than conventional agriculture, for example by supplying more fruits and vegetables than can currently be supplied by domestic sources.

3. Results

3.1. Cereals

Under all the organic scenarios, wheat and barley production was considerably reduced compared to the conventional, non-organic baseline (Fig. 4). Averaged across the scenarios, organic production of these crops was only 42% of the 2010 non-organic baseline production. For wheat, the greatest reductions were for the low stocking rate, high clover area and low-N fixation scenarios, due to combination of lower manure availability, cropland availability and crop yields. Reductions in output were less severe for barley, although the levels of production were more variable, ranging from 26% of the non-organic baseline under the low-N fixation scenario to 73% in the low clover scenario. Reductions in barley output were less severe for the low clover area, and high N fixation scenarios, as a result of both higher cropland areas and higher yields. The production of oats was relatively stable over the scenarios, reaching the upper limit of 150% of the baseline area in some scenarios. Production (and production areas) of oilseed rape (OSR) were also relatively consistent, in showing significant losses in all scenarios with an overall average production of 2.5% of the 2010 baseline (data not shown). Production estimates for wheat and barley are similar to those reported by Jones and Crane (2009), whereas the projections for beans and peas are higher, probably as a result of their increased representation in rotations. Oat production was much lower than reported by Jones and Crane (2009), probably as a result of the imposition of upper limits on production area in the OLUM.

3.2. Other crops

Potato production was generally higher than in the non-organic baseline (Fig. 5). This is reasonable because potatoes are common in organic rotations due to their beneficial impacts on soil structure and weed control. Potato production was lower in the low-stocking rate scenario due to the lower livestock-manure-N availability. However, output volumes under all other scenarios exceeded the conventional baseline and the estimates of Jones and Crane (2009). Production of sugar beet was more variable than potatoes across the scenarios, as the high-N offtake per hectare greatly affected the amount that could be produced under the low-N fixation and low stocking rate scenarios.

Brassica and protected vegetable production varied considerably across the scenarios, with the highest production found under the high-N fixation scenario (Fig. 6). With higher stocking rates production was reduced, as additional land and manure-N was required for feed crops. Production of root crops (onions, leeks, carrots) reached the upper constraints in most of the modelled scenarios, illustrating their relatively high energy values and resource-use efficiency (Carlsson-Kanyama et al., 2003).

3.3. Grazing livestock

Increases in beef cattle and sheep numbers above the 2010 conventional baseline were observed across all scenarios (Fig. 7). This was particularly so for the “Combined” scenario, due to increases in feed availability from recycled residues. The lowest rates of sheep meat production occurred under the low-stocking rate and low-N fixation scenarios, in the latter case due to lower cereal yields and consequent reduced feed availability. Dairy cattle numbers and milk production were more sensitive to changes in N availability, cropping area, and cereal yield, due to a higher reliance on concentrate feeds compared to beef and sheep. Milk production reached between 40% (low N fixation scenario) and 90% (high stocking rate scenario) of the 2010

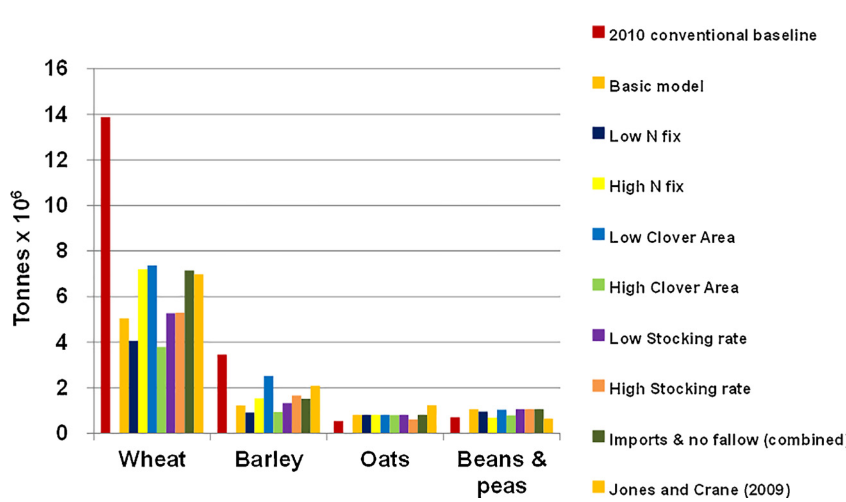

Fig. 4. Production of arable crops in England and Wales under organic management scenarios compared to a 2010 conventional baseline and results from Jones and Crane (2009).

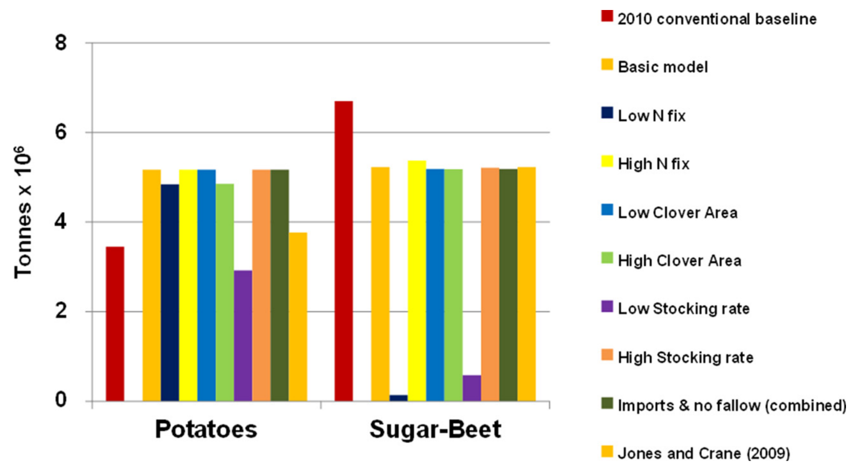

Fig. 5. Production of potatoes and sugar beet in England and Wales under organic management scenarios compared to a 2010 conventional baseline and results from Jones and Crane (2009).

conventional baseline. Despite the increase in beef and sheep livestock numbers in all scenarios, total carcass production for these livestock types was comparable to the conventional baseline as a result of longer finishing periods and lower carcass weights in organic systems (Fig. 9).

3.4. Pigs and poultry

A major reduction in monogastric livestock production was observed in all the organic scenarios compared to the conventional baseline (Figs. 8 and 9). Laying hen numbers were particularly affected, with total numbers reduced to 25–30% of the non-organic baseline, and considerably lower than the estimate by Jones and Crane (2009). The difference with Jones and Crane (2009) is likely due to the limits on feed supply reflected in the OLUM, as evidenced by the increase in monogastric numbers when dependence on home-grown feed supply was reduced under the Combined scenario. A similar effect is observed for pig production systems, although the values were closer to those projected by Jones and Crane (2009).

3.5. Metabolisable energy supply by food group

Conversion of the output volume results to output ME by Eatwell food group enables an assessment of the ability of a wholly organic agriculture in England and Wales to provide the food required by the populations of these countries (Fig. 10 and Appendix C in the Supplementary material). The results show that fruit and vegetable production could almost match the 2010 conventional baseline levels under the Combined organic scenario (i.e. with increased feed availability and a reduced fallow area) with increases in outputs in eastern and south-west regions offsetting reductions in other regions. This illustrates the relatively small difference between organic and non-organic yields for field vegetables and the relatively small production areas required. However, the ME output of fruit (in particular apples and strawberries) was considerably less than the conventional baseline (data not shown), in part because of the failure of much organic produce to meet the cosmetic standards set within the retail sector (Smith et al., 2015). The relatively high organic productivity seen in the fruit and vegetable food groups results from the high yields and outputs of ME per hectare for many of these crops (e.g. carrots and potatoes). The losses in output and food energy in starchy crops (e.g. wheat and barley) are a result of low yields, plus the requirement to divert land to clover/grass leys in arable rotations. Smaller reductions for this food group were found in western, livestock-dominated areas, which tend to have lower yields under conventional agriculture.

Milk ME was substantially reduced under the Combined scenario, at just under two thirds of 2010 levels (see Appendix C in the Supplementary material) although introduction of dairy herds results in a small production increase in the eastern counties of England. In terms of total protein production, the reduction in meat and egg supply is somewhat offset by the increase in grazing livestock and peas and beans, although there is still an overall reduction in protein supply, in particular resulting from a decrease in poultry-meat and pork production under organic management.

Fig. 11 shows that the decrease in wheat production projected by

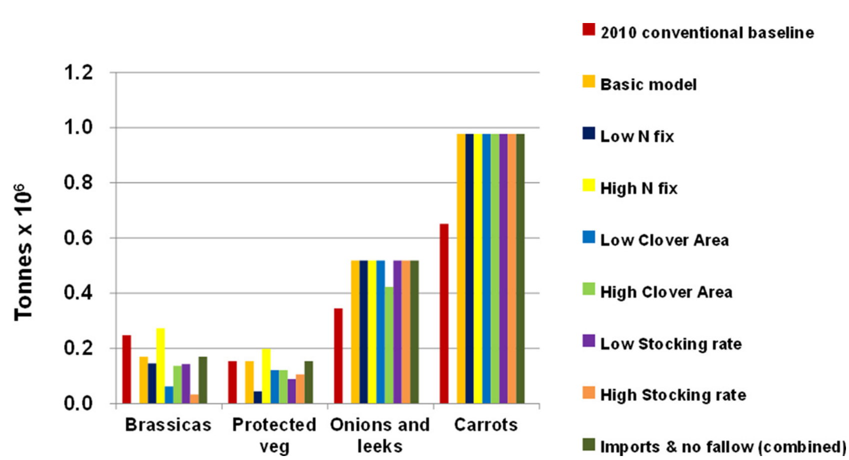

Fig. 6. Production of vegetable crops in England and Wales under organic management scenarios compared to a 2010 conventional baseline.

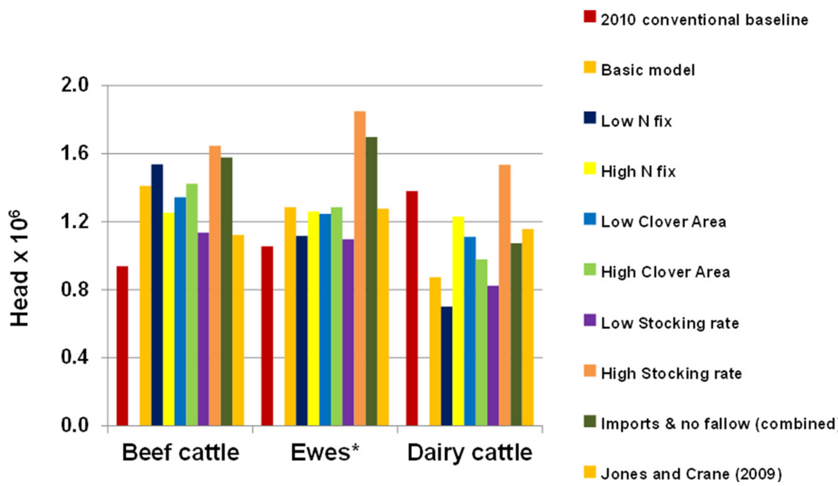

Fig. 7. Ruminant livestock numbers in England and Wales under organic management scenarios compared to 2010 conventional baseline and results from Jones and Crane (2009). Beef cattle = beef breeding herd. * = head × 10.

the Combined scenario is a result of reductions in both area cultivated and crop yield (organic yields are only 51% of non-organic production). Oats and rye have smaller yield losses under organic production, but the projected increases in production under organic scenarios are largely due to increases in the area cultivated. The low productivity of organic oilseed rape is compounded by a much smaller cultivated area (which itself probably results from the low yield). The increase in bean production under the organic scenario is a result of the increase in production area, this being driven by the need to maintain fertility (as reflected in the rotation constraints). It is also the case that such N-fixing crops produce yields under organic management very close to conventional. The production area of potatoes is also substantially increased under the organic scenario, whilst sugar beet areas hit the upper constraint on production area.

4. Discussion

4.1. Reprise of modelling outcomes and comparison to outputs from previous work

The results showed that converting agriculture in England and Wales to organic management would result in a major drop in food production, with total food output (expressed as metabolisable energy, ME) falling to 64% of non-organic baseline levels (Appendix C in the Supplementary material). The reductions in crop output would be most severe for major cereal crops, sugar beet and oilseed rape, as a result of reduced yields, the need to divert land to fertility building leys, pest, disease and weed susceptibility and high N demands in the spring (Schneeberger et al., 2002; Tzilivakis et al., 2005; Valantin-Morison and Meynard, 2008).

Carrot yields are also lower under organic management than conventional, due to susceptibility to weeds and carrot fly attack. Despite this, the relative efficiency of this crop, in terms of energy output relative to N requirements, resulted in a potential overproduction compared to 2010 levels (see Fig. 6) and a substantial increase in the production area. However, in the case of most vegetables, including potatoes and leguminous crops, production could meet or exceed the non-organic baseline due to smaller yield losses for these crops within organic systems and overrepresentation of these crops in organic rotations. Beef and sheep numbers could also increase overall, as a result of increased stocking levels in arable dominated areas, whereas poultry and pig production and output would decrease, due to the requirement for more extensive production practices under organic certification. Dairy cattle numbers and total milk production would also decrease as a result of lower stocking rates and lower milk yields under organic management.

The similarity of the results reported here to outcomes from the study by Jones and Crane (2009), which used a different methodological approach, suggests that the estimates are robust and therefore realistic as far as such an extreme scenario can be predicted. There are

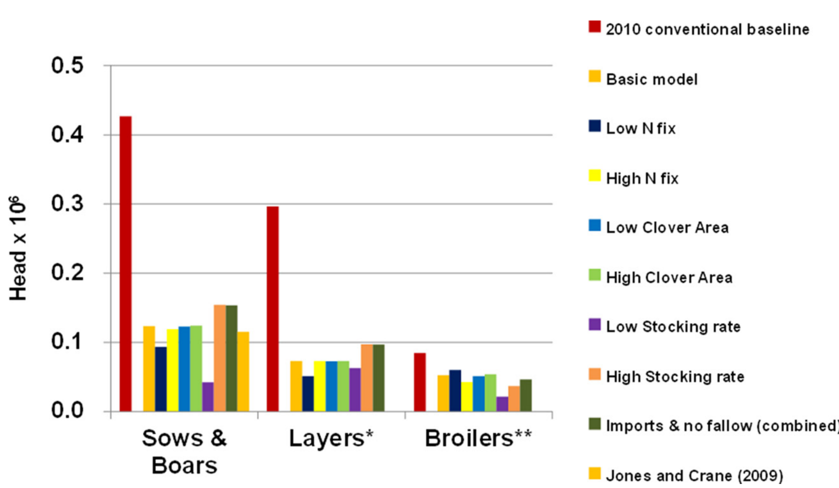

Fig. 8. Monogastric livestock numbers in England and Wales under organic management scenarios compared to 2010 conventional baseline. * = head x 10^2, ** = head × 10^3.

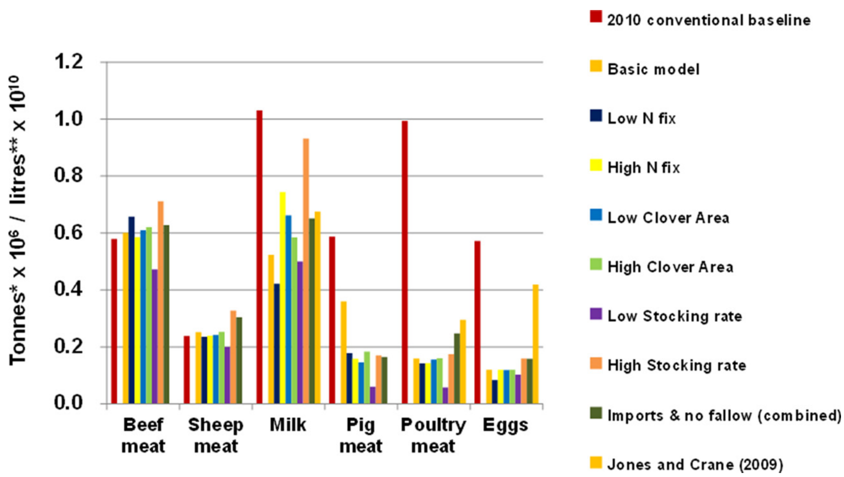

Fig. 9. Output of livestock products in England and Wales under organic management scenarios compared to 2010 conventional baseline. * = meat and eggs, ** = milk.

some interesting areas of divergence, however, in particular the projection, in this study, of much lower volumes of egg production than projected by Jones and Crane (2009). This divergence has been caused by limits on domestic feed availability present in the OLUM model, reflecting constraints on the amount of feed that can be imported and upper constraints on the stocking rate per hectare. Estimates of total wheat and barley production were also considerably lower than Jones and Crane (2009), and it is possible that Jones and Crane (2009) overestimate organic yields of major cereals due to sampling error, i.e. the Farm Business Survey, which was the sole-source of the organic yield data used in the 2009 study, is known to over-represent larger, more commercial farms (Jones and Crane, 2009). Conversely, pea and bean production estimates are higher in this study, driven by rotational requirements (nearly all of the rotations applied included a legume crop). Production of sugar beet was comparable with Jones and Crane (2009), except in the scenarios with reduced N supply (i.e. the "low stocking rate" and "low N-fixation" scenarios). Milk production levels were similar to the 2009 study, although production volumes exceeded those projected in Jones and Crane (2009) under the higher stocking rate scenario.

4.2. Disparity between demand and supply

The results suggest that a widespread conversion to organic farming would have major implications for domestic food supply, i.e. not only supplying less food than conventional agriculture, but also supplying a different balance of foodstuffs. While conventional agriculture does not by any means achieve a perfect supply balance in-line with domestic consumer demand, it supplies a much greater amount of food in supporting national diets within England and Wales. Obviously, without redress, this would present a major impediment to the large-scale expansion of organic agriculture, i.e. consumers would react negatively to supply shortages of wheat, milk, pork and poultry, and consequent higher prices, politicians would not want to support a system of agriculture that led to higher levels of food imports and farmers would not want to produce crops, such as legumes and minor cereals, that were already being oversupplied within an organic scenario.

This begs the question of how supply and demand could be adjusted

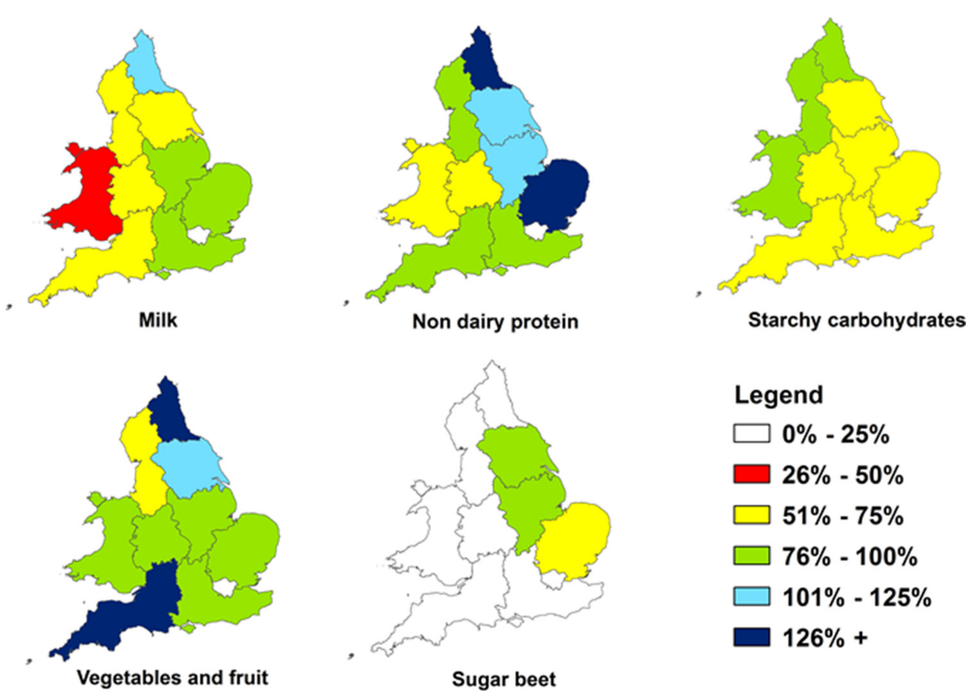

Fig. 10. Food production (expressed by Eatwell group) in England and Wales under organic management as a percentage of a 2010 conventional baseline, expressed as total ME by NUTS I region (100% level = conventional production in 2010). The output by group refers to *production* only (e.g. wheat and potatoes in the case of starchy carbohydrates) as opposed to processed foods. Commodities allocated to each group within this study are shown in Appendix C in the Supplementary material.

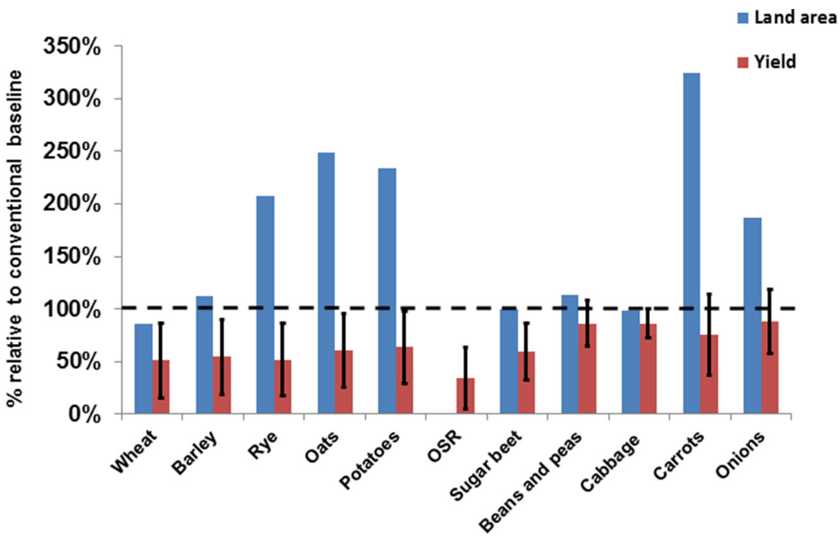

Fig. 11. Crop area and yield under a 100% organic England and Wales agriculture, expressed as a percentage of the 2010 conventional baseline. Conventional yield data are from Nix (2009), the Farm Business Survey (2010) and Defra Horticultural Statistics (2010). Organic yield data are derived from the NDICEA-based adjustments described above. OSR = oilseed rape. Error bars indicate standard deviation.

to make a large-scale transition to organic production more feasible. Changes might conceivably be made on both sides. On the supply side, adjustments could be made to farm structures, individual practices or certification scheme requirements. On the demand side changes to the national diet, and reductions in food waste could help to increase the feasibility of an organic scenario. In the sections following, both of these possibilities are explored.

4.2.1. Changes to the national diet

A detailed analysis of the extent to which diets would need to change in order to accommodate a 100% organic supply is beyond the scope of this study. However, some qualitative conclusions can be drawn. The results suggest dietary changes would need to include a reduction in the consumption of poultry meat and eggs, increased consumption of beef, lamb and non-meat protein (in particular beans and peas) and increased vegetable consumption in some regions. Although an increase in bean, pea and vegetable consumption would be relatively consistent with the changes to western diets currently being recommended by health professionals, an increase in red meat and a drop in poultry meat consumption could represent a conflict. A requirement for a reduction in wheat consumption could also present major difficulties, and this would need to be compensated for by an increased consumption of other forms of domestically-produced starchy carbohydrate (e.g. potatoes and oats), or increased imports of crops like maize and rice. It should also be noted that the impacts of large-scale organic conversion on the supply and demand of fish, either from wild or farmed sources, was not addressed in this study. However, it is worth noting that current organic certification requirements predicate against the intensification of fish farming, with implications for fish supply, while dietary recommendations call for increased fish consumption in the UK, especially oily fish (Macdiarmid et al., 2011).

4.2.2. How feasible are dietary changes on this scale?

There would be two possible routes to achieving dietary change on the scale needed to significantly reduce the gap between what organic agriculture can supply and what consumers demand. The first is proactive policy intervention, while the second is endogenously-driven (i.e. market-led) changes to dietary habits, often associated with changes to lifestyles.

It would seem unreasonable under present market and social conditions to expect policy makers to develop a programme of policies to drive food consumption towards organic supply. However, some of this gap might be closed adventitiously through policies that encouraged healthier diets. Currently there are no policy mechanisms in place that might drive such a change and there is a notable lack of political will to invest the time and resources needed to transition to healthier and more sustainable diets (Wellesley et al., 2015). Encouraging greater consumption of vegetable crops is therefore likely to require a significant overhaul of policy support measures in the UK and Europe, which has in the past tended to promote the (over) production of meat, sugar and dairy products, thereby driving down market prices, leading to over consumption, particularly in low income households (Birt, 2007; Bailey et al., 2016). With the recent decision to leave the European Union, the UK has an opportunity to change the balance of support for agriculture and reduce the environmental and health impacts of the food system, whilst providing additional jobs in a labour-intensive sector (Schoen and Lang, 2016).

Changes to lifestyles could also lead to an increased uptake of ‘sustainable diets’ under a 100% organic scenario, particularly as recent evidence suggests that typical ‘organic consumers’ exhibit preferences for fresh vegetable consumption and vegetarian food, i.e. diets that can lead to lower environmental impacts compared to those rich in livestock products (Pelletier et al., 2013). A shift to organic consumption habits could therefore lessen the environmental impacts of widespread organic conversion and yield human health benefits (Baroni et al., 2006; Macdiarmid et al., 2011). The increased costs to consumers associated with organic production and consumption could present a major challenge, particularly in view of the current lack of willingness amongst consumers to pay more for sustainable diets (von Koerber et al., 2017). It should also be considered that regular ‘organic consumers’ (i.e. those who buy and consume mainly organic products) are a small, self-selecting population, and how the whole population would respond to being offered only organically produced food is currently unknown.

The third possible route to over-coming demand side constraints to large-scale organic conversion is the reduction of food waste. With over 27% of the food purchased in the UK wasted in 2015 there are still considerable opportunities for offsetting supply losses through improving: management practices in the retail sector (e.g. avoiding overstocking); technological innovations (e.g. smart-fridges); and educating consumers (e.g. the Love Food Hate Waste Campaign introduced by the Waste and Resources Action Programme (WRAP) in 2007 (Priefer et al., 2013). If such measures could be implemented on a wider scale, they could not fail to reduce overall food demand, thereby reducing the significance of the supply shortfalls projected under extensive organic conversion and in so doing allow for the wider adoption of this agricultural system, accruing the lower resource use benefits that would accompany it.

4.2.3. Overcoming supply-side constraints

There are three possible routes to overcoming supply-side constraints to large-scale expansion of organic production. First, to bring more land into agricultural cultivation; second, overcome some of the agronomic challenges that lead to lower yields and rigid rotational requirements in organic systems; and third, circumvent some of the certification impediments to the development of more flexible organic systems. The feasibility of these options is explored in the following section.

4.2.4. Bringing more land into cultivation

While UK Government could, theoretically, adopt policies to encourage an increase in the area under cultivation, in political terms, except under crisis conditions, this would be prohibitively difficult. To illustrate with just one constraint, converting non-productive land (e.g. parklands, or non-arable land, such as woodland or low input permanent grassland) to arable production would result in changes to landscape character, loss of amenity and potentially severe environmental impacts. There would be widespread societal resistance to this. Additionally, such a move would run counter to multiple environmental protection policy objectives, such as set-out in the UK Climate Change Act, the UNFCCC Paris Climate Change agreement, the UN convention on biodiversity and the EU Biodiversity Strategy. Some increased production from urban farms and gardens could be envisaged however.

4.2.5. Adjusting organic standards and farm structures

Potentially more feasible, as a means to reducing supply-side constraints to large-scale organic conversion, would be a relaxation of some organic standards. Obvious targets here would be the current maximum permissible stocking rates and flock sizes and the ban on certain manufactured inputs (e.g. synthetic fertilisers and pesticides). Adjustments in such areas could allow organic farming to supply more food at prices which are more competitive, by allowing some of the resource efficiency and scale benefits currently enjoyed by conventional agriculture. In this context it could be argued that organic rules and regulations are outdated, whereas a more flexible approach, i.e. one that takes into account new technological developments, could help to address some of the key challenges that are faced by organic producers, with particular regard to N availability and pest and disease incidence (Trewavas, 2004). A "ranked" or "graded" approach to organic certification could also help to improve the supply of food under a 100% organic scenario, by allowing the use of currently-prohibited inputs, but at lower levels of intensity than currently found in conventional practic. Such a 'best of both world's' approach could allow for substantial improvements in the resource-use efficiency of farming, through a combined approach of organic production methods and application of the best available technology

Far less contentious, but potentially more challenging in practical terms, would be overcoming some of the agronomic challenges inherent in organic systems, such as, for example, the requirement for a significant area of grass/clover ley for fertility-building purposes. The 'low clover area' scenario in the modelling exercise has demonstrated the benefits that reducing the fertility-building area would have on the land availability for the productive phase of rotations. However, while such a strategy would yield benefits in the short term, in the longer term it is likely to result in decreased N availability and increased occurrence of pests, diseases and weeds, as use of grass/clover-leys in organic systems is a primary method of controlling these factors (Lampkin, 2002). A balance would therefore be required in terms of the optimum amount of ley relative to the cropping phase, although this is likely to vary with climate, soil and other conditions, such as labour availability post-harvest for ley establishment. Difficulties associated with the prediction of N supply from grass/clover leys can also present major challenges, in particular for stockless systems, which rely on biological fixation for the supply of N and can struggle to maintain a positive N balance over the course of a rotation, particularly in wetter areas and on lighter soils (Smith et al., 2016). In addition, reducing the grass/clover ley percentage in organic rotations may offset some of the purported benefits of organic approaches in terms of enhanced C sequestration and biodiversity (Lampkin et al., 2015). P supply could also become critical, in due course, and a change in organic standards to permit the use of sewage sludge would promote the circular economy and produce a valuable supply of P and N, along with organic matter.

4.2.6. A combined food systems approach to make 100% organic feasible

A combined approach of adapting agricultural practices and reducing food waste could also help to "manage and not just meet demand" (Ingram, 2017) under a 100% conversion to organic farming. A recent study has illustrated that a global conversion to organic management could lead to improvements in sustainability when combined with reduced food waste and adjustments in the amount of grain fed to livestock (Muller et al., 2017). With the right societal-level changes, it may therefore be possible to ensure that a widespread adoption of organic production becomes feasible. These adjustments would require a long-term dialogue with the public on the future of farming and the importance of dietary change, from a range of environmental and human health perspectives. Retailers, as the main route to market in the UK, will need to play a key role in ensuring the effective implementation of sustainable food systems (Doherty et al., 2017).

4.3. Methodological critique

Although the modelling approach used in this study extends the approaches deployed by Jones and Crane (2009), i.e. by increasing the range of factors taken into consideration in estimating organic production volumes (e.g. accounting for yield variation by land class and constraints on livestock feed availability), the approach is still somewhat restricted. The primary limitation is that the objective function of the OLUM is maximisation of food output, and so does not fully reflect the business goals of farmers, which can be diverse and multifaceted. An economic approach to the upscaling of organic agriculture, i.e. the use of a profit maximising model, may yield considerably different results, although the input costs and price differentials under a 100% organic scenario are likely to be highly spurious given uncertainty over product prices and changes to the costs of inputs in such an extreme situation. It should also be considered that in this modelling exercise, organic systems in their *current form* were scaled up to the national level, but constrained by biophysical factors. Under a 100% organic scenario it may be reasonable to expect a significant change in demand patterns and a major restructuring of the agricultural industry to avoid some of the supply shortfalls observed here. Although it is likely that the broad structure of agriculture in England and Wales will remain the same, due to immutable agronomic and possibly also certification, constraints (e.g. cropping dominating in the eastern areas and ruminant livestock dominating in the west) there will be some loss of specialisation, i.e. a shift towards greater arable production in livestock dominated areas (e.g. Wales and the south west of England) and expanded ruminant livestock production in the Eastern Counties, where specialist arable farms currently predominate.

It is also quite possible that a widespread switch to organic methods would have a much greater impact on food production than estimated within this study. For example the approach employed here assumed that the organic industry would maintain the current (conventional) mix of farm-types by region, however the current trend within organic agriculture in the UK is for a high proportion of farms, including arable farms, to host ruminant livestock, i.e. producing beef, lamb and dairy products (Defra, 2015). If this arrangement were scaled up to the national level, i.e. if the model were not permitted to maintain such a high percentage of stockless arable farms, as these are currently rare in the UK, the impacts on food security in the UK could be even more severe, at least for arable production, although the output of beef and sheep would be likely to increase dramatically. One way in which stockless arable farms can make economically rational use of grass and clover leys is to use the forage produced for other purposes. For example grass and clover can be an efficient feedstock for anaerobic digestion (AD) plants, if these can be situated on the farms where the feedstock is produced, or at a reasonable distance to them (Halberg et al., 2008). The economic impact of AD on the modelled scenarios projected here is beyond the scope of this study to assess. However, such approaches could contribute to making the application of stockless ley/arable systems more viable on a wider scale. The digestate fertiliser provided by the wider application of AD on arable farms could also help to enhance organic crop yields by providing a source of readily-available N to meet crop requirements at times of peak demand (Stinner et al., 2008).

In future developments of the OLUM model it would be possible to construct a scenario where forage can be used for heat and/or electricity generation. Careful consideration would of course have to be given to constraints limiting the extent to which the model can deploy this option, reflecting the fact that the development of farm-scale AD has been, and continues to be, slow in the UK, as a result of perceived risks, and relatively poor economic returns for smaller scale plants (Jones and Salter, 2013). It is therefore likely that the use of forage as AD feedstock, on a large scale, would depend on the use of centralised AD plants, with a number of organic farms providing feedstocks from a distance.

The results from this study also illustrate the dependence of organic systems on N supplied within the farming system, in particular on the supply of manure. In this study the assumption was made that manure would not be transported outside a given region. However it would be reasonable to expect that transfer might occur over larger distances (e.g. from livestock-dominated areas in the south west of England to arable areas in the east) although transport costs, increased disease transmission risk and odour may make long-distance transport infeasible (Sims et al., 2005). Some successes have been achieved in installing central manure processing plants in the Netherlands, to help deal with N surpluses at a local level, although the financial viability of such systems has been difficult to maintain, even in cases where the final product is 'dewatered' to facilitate transport (Zwart, 2015).

The approach taken to reflecting N availability and its influence on yields in the OLUM model is also fairly rudimentary, i.e. through focussing on N availability under a limited range of environmental conditions (i.e. soil type and rainfall). A more complex model of organic crop yields could take account of factors such as pests and diseases, water stress and annual variations in areas of grass/clover ley, whether caused by environmental (e.g. average temperatures within each region) or economic (e.g. availability of labour) factors. The effect of climate change on the production scenarios could also be considered, for example, allowing for the predicted northward expansion of sunflower production and possibly soybean into the UK (Olesen and Bindi, 2002). Crop productivity estimates could also be adapted to account for the effects of annual or seasonal variation in temperature and/or rainfall at regional or national scales. Expanding the model to consider a broader range of livestock nutritional requirements, i.e. accounting for supply values in crop and livestock products (e.g. iron, calcium) and/or environmental criteria (e.g. greenhouse gas emissions per tonne) could also allow for an increased range of scenarios to be modelled, for example to estimate the optimum balance between healthy food choices and environmental sustainability, as reported in Macdiarmid et al. (2011). Finally, future modelling exercises should seek to explore the constraints to large-scale expansion of organic production that have been discussed in this study, as a means to identifying which are the most limiting. The OLUM provides an invaluable framework for the assessment of such scenarios by providing a model that emulates the current national structure of the agricultural industry and current practices on typical farms.

5. Conclusion

In summary, the results from our study suggest the impact of full conversion to organic farming on food production in England and Wales would be severe. The losses would be greater for some commodities (e.g. cereals, oilseeds, monogastric livestock) than others (e.g. vegetables and milk). The relative similarity of organic vegetable yields to conventional make this the most likely cropping sector to be able to sustain widespread adoption of organic practices. The results also suggest that certain organic practices could be expanded within some non-organic systems to improve resource use efficiency, without jeopardising production. This could include greater use of clover in grassland and/or introducing livestock to field vegetable cropping systems. To lessen the need for large increases in imports to replace lost production resulting from large-scale organic production, a combination of adjustments would be necessary, including relaxation of some certification constraints, new solutions to agronomic constraints, significant reductions in food waste and, perhaps most challenging of all, significant changes in the national diet. Further research is now required to understand the feasibility of these adaptations, if a clear picture of the route to major expansion of organic production is to be developed.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.landusepol.2018.02.035.

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