International Journal of Life Cycle Assessment, Volume 15, Number 8, 2010, Pages 855-868

LCA Case Studies

Assessing ideas for reducing environmental Burdens of Producing Bread Wheat, Oilseed Rape and Potatoes in England and Wales using simulation and system modelling

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DOI: http://dx.doi.org/10.1065/lca2006.##.###

Abstract

Background, Aims and Scope. Food production is essential to life. Modern farming uses considerable resources to produce arable crops. Analysing the environmental burdens of alternative crop production methods is a vital tool for policymakers. The paper describes systematic procedures to calculate the production burdens of three key arable crops: bread wheat, oilseed rape and potatoes as grown in England and Wales using future alternative non-organic and organic systems. Resource use (e.g. abiotic and energy) and burdens from emissions are included (e.g. global warming potential on a 100 year basis, GWP, and eutrophication and acidification potentials).

Methods. Crop production was analysed, using systems models, so that the effects of factors like changing cultivations, N fertiliser application rates or irrigation could be examined using a life cycle analysis approach. Emissions of nitrate were derived from a simulation model in which soil organic N was driven to steady state so that all long term effects were properly accounted for. Yield response curves to N were similarly derived from long-term experiments. Crop nutrient inputs and plant protection applications were derived from national survey data and the literature. All major inputs were accounted for including fertiliser extraction, manufacture and delivery; pesticide manufacture; field fuel use; machinery and building manufacture; crop drying, cooling and storage. The current balance of production systems were found from survey data. The weighted mean national production was calculated from a combination of three rainfall levels and soil textures. The system boundary is the farm gate. The functional unit is 1 t marketable fresh weight of each product.

Results and Discussion. The current primary energy needs for producing the three main products were 2.4, 4.9 and 1.4 GJ/t for bread wheat, oilseed rape and potatoes respectively. When expressed in terms of dry matter, protein or energy, wheat incurred smaller burdens than oilseed rape, which incurred lower burdens than potatoes. The crops do, of course, all play different roles. The results are generally of the same order as those from other European studies. With the organic system of production, bread wheat needed about 80% of the energy, while potatoes needed 13% more energy because the lower fertiliser use (and hence energy use) is offset by more energy for fieldwork and lower yields and maincrop potato energy is dominated by cold storage. While pesticide use was always lower in organic production, other burdens were generally inconsistently higher or lower. and land occupation was always higher. With reduced N application production systems, bread wheat energy use and GWP are reduced, but also the proportion of the wheat achieving bread-quality is reduced. The optimum for energy is with N at about 70% of the current level. The optimum seems to be lower for GWP, but the sub-models used are beyond there range of reliability.

Conclusions. Arable crop production depends heavily on fossil fuel in current major production systems. The emissions causing GWP are very dependent on nitrous oxide, more so than fuel consumption. That, together with emissions of ammonia and nitrate, means that agriculture has a C-N footprint rather than the C footprint that typifies most industrial life. The reductions in burdens from alternative systems of production are less than their proponents suggest.

Recommendations and Perspectives. With the large influence of nitrous oxide on GWP, evaluation of nitrous oxide emissions by another method, e.g. crop-soil simulation modelling instead of the more rigid IPCC method would improve the robustness of the analysis. System modelling allows alternative production methods to be readily and properly explored and this greatly enhances LCA methodology.

Keywords: Arable; agriculture; system; simulation model; organic; GWP; nitrate; energy, nitrous oxide, environmental impact.

1 Introduction

A study of arable crop production in England and Wales was conducted as part of the government's programme on sustainability. It was conducted for the benefit of policymakers and stakeholders so that alternative production scenarios could be systematically examined such as: increasing the proportion of organic production, different tillage methods, reducing fertiliser application rates. This paper covers the major commodities of bread wheat, potatoes and oilseed rape and uses standard life cycle analysis (LCA) together with system modelling. Results are presented at the national level.

Other research has investigated crop production in Europe using LCA. Audsley et al. [1] used pan-European data in a study aimed at harmonising agricultural LCA methods and wheat was a case study. Cederberg [2] included wheat, maize and soya as feeds. Charles et al. (2006) studied wheat grown with different intensities of production [3]. Van der Werf [4] analysed wheat, barley, soya, maize, sunflower & more in a study of pig feed. Rape has been studied mainly with the perspective of the oil for use as a biofuel. Maize production has been analysed both as part of wider studies on animal feed in Europe [2,3] and as a bio-energy crop in the USA.

Previous studies have used specific data to study alternative systems. This limits the analysis to these systems. In this paper we adopt a different approach using system models. In the first instance national production is a combination of proportions of distinct systems – thus ploughing, minimum tillage, direct drilling – which can be altered. Secondly, systems models are used to properly represent responses to changes – thus level of nitrogen, irrigation or increased yield due to the breeding of new varieties of a crop. In this way new scenarios can be defined on continuous scales of change from the present.

The goals of the study were to calculate the environmental burdens of producing the commodities bread wheat, potatoes and oilseed rape in England and Wales at a national level, comparing current and future alternative production methods systematically.

2 Methods

2.1 Functional units

2.2 The functional unit is 1 t of fresh weight of each product, standardised to 86% dry matter (dm) for wheat, 92.5% for rape and 20% for potatoes. Bread wheat produced non-organically contained 13.5% crude protein (CP), but organic bread wheat cannot achieve that level and wheat for bread is accepted at 12.5% CP. Potatoes are grown in three main types: maincrop, 1st earlies and 2nd earlies, so that the commodity is defined as a basket of each type scaled by national proportions. System boundary

The system boundary is the farm gate, but all crop storage, cooling and drying prior to sale are included within the virtual farm gate (for example central grain storage facilities, but not processor's storage). Soil processes were included to a depth of 0.3 m.

2.3 Long term approach

The concept is to analyse the effect if all (or a substantial proportion of) farms in the UK replace their current systems of production and adopt new systems for the foreseeable future – for example 80% of optimum fertiliser or organic farming. In order to follow properly the fate of atoms into and out of the system boundary, a long term approach is needed in the analysis. Thus the output of N as emissions of ammonia, nitrate, nitrous oxide and as protein in crops, must be balanced by the input of N from the atmosphere, by nitrogen fixing, in manure organic matter and in fertiliser as ammonium, nitrate or urea, A build-up or depletion of nutrients in the soil is not permitted and offtake must be sustained by the long term nutrient supply. Every crop must bear the burden of supplying the nutrient it removes. Long-term also implies that the transition from one production system to another is not included, e.g. non-organic to organic conversion and the change in soil carbon status. In both organic and non-organic crop production, rotations, tillage and spray use were defined that would achieve technically sustainable yields. The arbitrary removal of, for example, a spray application or weed control cultivation step might incur no yield loss in one year, but would progressively lead to long-term yield loss.

2.4 National context

Crop production was represented at a national scale by considering a combination of nine soil texture and rainfalls: clay, loam and sand; 587, 675 and 776 mm. The national distributions were established by Williams et al. [4] to provide weighted average national production, including allowances for favoured soil types for particular crops.

2.5 Crop rotations

Crops are grown in a variety of rotations, while this project aimed to determine the burdens of producing specific commodities. The growth of the crops was analysed in the context of representative rotations, implying that the crop receives some benefits such as reduced disease incidence and rotational plant nutrient transfers. No change in rotation was analysed.

2.6 Crop production methods

The same approach was use to model all the crops, with differences in the detail. The full model can be downloaded from www.agrilca.com which allows access to all the details. The main sources of agricultural burdens for field crop production are: diesel for cultivation, chemical and fertiliser applications, irrigation and harvesting; drying and cooling crops; production of fertilisers, pesticides and machinery; construction and maintenance of buildings for crops and machinery; direct soil-crop emissions to air and water (like nitrate, nitrous oxide and ammonia) and land occupation. All except land occupation involve energy and abiotic resource use and involve some gaseous and aquatic emissions. Organic or non-organic production systems have significant differences and are analysed separately. The sum of non-organic methods represents contemporary conventional production. Full details are given in Williams et al. [6] and the main points are presented here.

In analysing the separate impacts of the integrated systems of livestock and arable production (conventional or organic), it is necessary to define appropriate system boundaries so that burdens of production are appropriately allocated. Feed and straw can be considered as co-products of arable and hence as inputs to livestock. Manure can similarly be considered as a (waste) product of livestock and as an input which displaces the need for fertiliser production in arable (with the burden of storage and spreading allocated to livestock). This definition is system independent.

This definition means that in analysing arable production it is not necessary to consider manure (or livestock), since its burden in the arable system is that of producing fertiliser and it is thus replaced by the equivalent fertiliser it provides. In the same way, in organic arable production, fertiliser input is by growing clover crops in a rotation (colloquially known as stockless organic). With livestock, the manure displaces the need for crops and thus receives a credit in terms of land occupied (rather than the MJ energy for fertiliser production credit for manure in non-organic systems). Thus if the system was expanded to a mixed farm consisting of a number of arable crops and livestock, the sum of the individual burdens would provide the correct burdens for the farm.

3 Data

3.1 Field operations

All arable crops require: seed bed establishment; crop protection (weeds and diseases); fertilisation; irrigation (potatoes only), harvesting and crop storage drying and/or cooling.

3.1.1 Seed bed establishment

Methods of soil cultivation were divided into three methods, namely plough-based, reduced cultivation and direct drilling. The number of passes of secondary cultivation operations depends on soil texture [7] and greater energy is needed for tillage of heavier soils [9]. The operations used in contemporary farming were derived from the Silsoe Whole Farm Model [8-10] and from details from a commercial farming group. Data on fuel used came from 13 sources (reviewed by Williams et al., 2006). These were linked with data on tractor and field machinery weights, work rates and life spans to derive overall primary energy requirements (and associated burdens) for field operations using the method of Audsley et al. [1]. Primary energy ranged from 470 MJ/ha for direct drilling on sandy soils to 5210 MJ/ha for ploughing on clay. Potatoes require deeper ploughing (25% extra energy) and only plough based tillage is used. This and the extra operations needed, increases the total energy for establishing potatoes on loam by 84%. In organic crops, ploughing is the norm, because reduced tillage and direct drilling require pesticides. However some crops in organic rotations are undersown.

3.1.2 Crop protection

Plant protection involves both rotations and some chemical applications. The numbers of passes with a sprayer and numbers of doses per crop were obtained from the Pesticide Usage Surveys [11]. Additional light cultivations for weed control are used in organic crops for weed and disease control. Potato blight control, using copper based products, is permitted in a derogation, otherwise pesticides are not used in organic crop production.

3.1.3 Fertiliser application and harvesting

Synthetic and mineral fertilisers are applied using relatively little energy (110 MJ/ha). If cereal straw is not being baled, then the combine harvester will also chop the straw (using more energy for this). The burdens of baling and carting straw are allocated to the straw, if harvested. Combine harvesting (with straw chopping) takes 1130 MJ/ha while potato harvesting needs 3140 MJ/ha.

3.1.4 Crop Storage, cooling and drying

All crop storage is considered to take place within the farm gate, even though in practice some takes place physically elsewhere. The energy for constructing, maintaining and demolishing a grain store were estimated using the method of Audsley et al. [11], but with their data supplemented by local expert opinion, using a typical mean storage requirement of 0.4 $m^2 t^{-1}$ (Table 2).

In the UK, grain is often dried after harvest. Wheat is dried to 86% dry matter (DM) and rape to 92.5% DM. During the harvest period the harvested grain DM varies with weather conditions. In good years, no grain needs drying. Data on long term harvested wheat grain DM came from Rothamsted's *Broadbalk* dataset for 1971 to 2001. These were used to calculate the energy needed for grain drying. The mean specific energy requirement for evaporating water in representative grain driers was estimated to be 4.7 MJ/kg water [12-13]. The drying requirements for other crops were calculated by relating their equilibrium moisture curves [14] to that of wheat so that the same distribution data from *Broadbalk* could be used as a proxy for DM at harvesting.

The results show that the energy needed for drying wheat from 1991 to 2001 was only 45% of that from 1971 to 2001, perhaps reflecting climate change or changed managerial practices resulting from higher fuel prices. Results from these 10 years were thus used (Table 2). Some crops are cooled by ventilating with ambient air and average values were derived from data in McLean [12] and Scotford et al. [15]. It was assumed that 1/12 of grain was sold direct from combine harvesters for immediate use and thus did not need storeing cooling or drying.

3.1.4.1 Potato storage

Earlies are harvested and sold directly. Maincrop potatoes may be stored for over a year [16]. The market price for maincrop potatoes falls in the spring and most are removed from stores by May, but some are stored for processing and catering through to next harvest. Most potatoes are stored in temperature controlled environments using ambient ventilation or refrigeration, while a small proportion is stored in clamps [17].

The energy needed to cool potatoes was estimated using a model of the expected rates of emptying of stores and the specific energy needs of store types [17-20]. Data suggests that 10% of organic maincrop is sold directly (e.g. vegetable boxes). This would not remain valid if organic became the main production system rather than its current niche. Cooling energy was thus scaled in proportion to the level of organic production so that the energy demands for all production organic and all production non-organic approach each other. This avoids the possibility of extrapolating a system that is currently a niche into a distribution system that operates in a different way.

3.2 Production of inputs

3.2.1 Pesticide manufacturing energy

The manufacturing energy for pesticides was derived from Audsley et al. [1] (which assign values for different types of pesticide (and growth regulators) and Garthwaite et al. [11]. The mean primary energy requirement for wheat, rape and potatoes were 144, 121 and 220 MJ/dose-ha respectively.

3.2.2 Fertiliser manufacturing

The four main plant nutrients (N, P, K and S) and soil pH adjustment through lime were included in the analysis. There are systematic differences between non-organic and organic methods. Organic nitrogen is derived directly (or indirectly as manure or compost) from nitrogen fixation by legumes. Non-organic N is mainly obtained from ammonia-derived materials using the Bosch-Haber process in which natural gas is used both as an energy source and feedstock. Both systems receive atmospheric deposition of N. In organic systems, P, K ad lime must be from sources such as rocks with a minimum of physical processing. We assumed lower rates of soil availability of the nutrients per tonne applied..

The burdens for producing, packing and delivering fertilisers (Table 4) were derived from 20 sources that were reviewed by Williams et al. [6]. The main burdens relate to energy use (e.g. for converting N_2 to NH_3 or quarrying and transporting minerals). A specific extra term is applied for N_2O emission from nitric acid production, which is used for nitrate based fertilisers.

3.2.3 Nitrogen supply in organic systems

A representative stockless organic rotation consists of two years of a fertility building clover crop, followed by wheat or potatoes, spring barley, winter beans, and spring oats. Forage rye is planted as a cover before the spring crops. If only one year of clover was grown, subsequent yields would be reduced owing to the lower N supply. Although land occupation would superficially fall (i.e. less land needed for fertility building) a lower N supply would reduce yields and could actually increase the land needed per t of crop. The additional burdens consist of additional ploughing and maintenance operations and land occupation including land for seed production. Overall the additional ploughing required per cash crop is a factor of 1.25 times the non-organic crop and the additional land required is a factor of 1.525. However the additional requirement should be applied per the nitrogen requirement of the cash crops.

It is estimated from data [21] that organic farms import compost annually into arable soils at a rate of 1.4 t/ha. The burdens of composting have two main sources: energy for collection and turning, and gases emitted during composting. A simplifying assumption was that no leaching takes place from compost heaps, and all N losses are gaseous. Energy and emissions were estimated (Table 5) using data from 15 sources as reviewed by Williams et al. [6]. However it is possible that if there were zero organic farms this compost would be applied to non-organic farms.

3.3 Use of inputs

3.3.1 P, K and S supply

Farmers supply P and K to maintain a particular soil status over time, but not necessarily to the specific crop. The model assumes that P, K and S are supplied equal to the offtake in the crop (and any losses to the environment). However, farmers add P to potatoes in excess of plant offtake because the crop needs (responds to) a higher level in the soil. The burden of this P production is born by potatoes and the surplus is allocated to other crops grown in such rotations in proportion to the national areas and yields. Atmospheric deposition of S was accounted for.

3.3.2 N supply

Short-term fertiliser experiments are confounded by previous cropping and fertiliser use so that low inputs reduce the fertiliser status of the soil and the yields achieved are not sustainable. Therefore the effects of fertiliser nitrogen on wheat yield (and protein content) were modelled using data from Rothamsted's long-term *Broadbalk* plots, where the fertiliser treatments have been applied for many years, so that true long term effects can be seen. N application rates range from 0 to 288 kg N/ha. The increase in the grain yield (Y) in response to applied N was well characterised by a linear-exponential curve: $Y = a - b\exp(-cN) - dN$. The nitrogen offtake in grain is characterised by a logistic growth curve: $Y = a + b/(1 + \exp(-c(N - d)))$. The same forms of equation applied to straw (Table 6). Using the expressions, yields and offtake change mechanistically in response to changes in N.

The *Broadbalk* data were for one type of feed wheat on one specific soil. Further adjustments were made to allow for differences between bread and feed wheat protein concentrations using NIAB (www.niab.com) variety data and for the effect of soil type on yield. Bread varieties typically yield 5 to 10% less than feed varieties, but contain more protein. Organic farmers (with lower soil nitrogen supply) need to choose the highest protein varieties to be able to achieve over 12% crude protein with any reliability and often grow spring wheat, which has a higher protein concentration, but is even lower yielding. Yield responses to soil texture were made using coefficients derived by Audsley [8]. Analogous relationships were derived for potatoes and rape (Table 6). The N supplies for crops grown organically were inferred from those needed to obtain the same yield non-organically.

3.3.3 Potato irrigation

Potatoes are often irrigated, with the amount depending on the weather and soil type. Weatherhead et al. [22] showed that irrigation increased yield by 25% for maincrop potatoes. Maincrop potatoes use more irrigation than first earlies, which may be harvested before the summer soil water deficit sets in. A relationship for yield in terms of proportion of the area irrigated was derived from Weatherhead et al. [22] and Weatherhead and Danert [23]. The yield at any level of irrigation, μ, is:

$$Y(\mu) = \frac{((\gamma_{100} - 1)\mu + 1)Y_m}{((\gamma_{100} - 1)\mu_m + 1)}$$

μ_m is the current level of irrigation, Y_m is the yield at the current level of irrigation (γ_{100}). . Parameter values and yield responses are given in Table 7. Long term yield data were obtained from government statistics [16], being 19.1 t/ha for earlies and 43.5 t/ha for maincrop. It was assumed that organic potato production uses 10% of the irrigation as non-organic as organic farmers try minimise any inputs.

3.4 Yield penalties

3.4.1 Sub-soiling

Sub-soiling is deep cultivation with narrow tines, used to break plough pans or to loosen compacted soils. It was assumed that if sub-soiling is too infrequent on some soils (one third of all), there is a yield loss. This happens when the interval (i) exceeds i_0 years. Below this interval, there is no yield loss or gain. Maximum yield loss was assumed to be 10%, with $i_0 = 3$ years.

3.4.2 Reduced tillage and direct drilling

There is controversy about the long term yields of crops grown without ploughing. Build up of some weeds such as blackgrass has been suggested as being detrimental, and may cause a move back to ploughing (maybe temporary), although Robertson et al. [24] found enhanced yields of wheat with direct drilling. It was decided to assume that long term yields reductions of 2% and 4% applied to crops grown with reduced tillage and direct drilling respectively, and with increased use of chemicals for weed control.

3.4.3 Marketable crop yield

Not all wheat intended for breadmaking achieves the quality required. HGCA [25] reported a survey of the crude protein (CP) concentrations in grain after harvest. For example, for the variety *Hereward*, the cumulative distribution of CP concentration was 1% at <11.3% CP, 21% at <13.5% CP, 71% at <15.5% CP (with 6% at >15.5% CP), suggesting a normal distribution. Both the *Hereward* and Rothamsted's *Broadbalk* data suggest a standard deviation of about 1% in protein concentration. Organic breadmaking wheat varieties show a standard deviation of 0.66% protein, with a mean of 12.5%. A standard deviation of 0.6% was thus used to calculate the proportion of the national crop that met the breadmaking protein criteria. Wheat can also fail to meet bread making quality by having a poor Hagberg Index or specific weight, due to growing conditions rather than N input. This is typically 4.4% of national yield and this also becomes feed (or non-bread milling) wheat. The burdens were allocated between the bread and feed fractions according to their economic value.

Potatoes may be not suitable for human food due to size, quality and damage. The typical non-organic loss rate is 15%. Loss was divided equally into stock-feed (12% burdens of human edible crop) and those returned to land (mostly via composting). The typical loss rate of organic potatoes (mainly from slug damage) is 30% [26-27] and can range as high as 50% [28].

3.5 Emissions to the environment

3.5.1 Emissions of N

The effects of soil and rainfall on leaching (nitrate to water) and denitrification (nitrogen as N_2 and N_2O to air) were established using the SUNDIAL simulation program from Rothamsted Research [29]. This simulates the nitrogen in the soil from year to year with N inputs from atmospheric deposition, fertiliser, fixing, seeds, returned roots, straw and haulm and N outputs to primary crop offtake (grain, tubers), secondary crop offtake (straw), returned offtake (roots, straw and haulm), leached nitrate-N, denitrified-N and N from senescing plants. A range of non-organic and organic rotations were defined that contained representative crops. Each rotation was simulated for nine combinations of soil type and rainfall (clay, loam and sandy soil with rainfall at 587, 675 and 776 mm) and with and without straw incorporation. Simulations were run for long enough to ensure that the simulated rotations were in steady state, as indicated by the soil organic N (SON) fraction being the same at the start and end of a rotation.

Yields, which are an input to SUNDIAL, were taken from national averages or standard texts, scaled according soil type using relationships previously developed by Audsley [8]. Organic crop yields for these simulations were taken from Lampkin et al. [26] and varied according to soil type.

Fertiliser inputs for non-organic production were established from RB209 [30] and use of the SUNDIAL (in the Fertiliser Recommendation System version). Individual crops were also simulated with N inputs increased or decreased by 20% from these standard values. For organically grown crops, the initial assumption was made that the yields should provide sufficient N and not deplete soil reserves, using fixed N from the clover ley (with beans in the 5th year). Preliminary runs assessed how well the rotation performed and most crops could achieve their target yields, except for the final crop, which only yielded 3.0 t/ha, rather than the 3.8 t/ha that was forecast. The N fixed was calculated by SUNDIAL as 300 kg/ha over the two years of clover, with more fixed in the second year than first year. This was based on standard values from the literature, and agreed as a possible value with the Elm Farm Research Centre.

Analysing the results, in the non-organic simulations the N leached at a rotational level was linearly related to the whole-rotation N-surplus (input as fertiliser or fixed minus offtake). Allocations were derived for the individual crops within each rotation on the basis of the proportion of the surplus due to each crop. The results were combined to generate linear relationships for each crop from which denitrification and leaching could be reliably calculated for each soil-rain combination from the N surplus for that crop. These coefficients were used in conjunction with crop husbandry data to predict denitrification, leaching and senescence for any given input of N. For field beans, it was concluded that denitrification and leaching losses were a constant for each combination of soil and rainfall.

Exactly the same methods could not be used with organic rotations, because there was not a simple surplus that could be calculated for each crop (most N being fixed at the start of the rotation by clover). Values for the offtake and N losses of field beans were taken from the non-organic rotations. The sum of all other losses from a rotation was then allocated to the remaining cash crops in proportion to the useful N offtake of each crop for each combination of rainfall and soil texture. Losses from senescence are generally low (about 2 kg N ha^{-1}) and were assumed to be an equal mixture of NH_3-N and N_2N.

3.5.2 Denitrification to nitrous oxide (N_2O) using the IPCC methodology.

SUNDIAL calculates total denitrification, but the major species of concern in global warming is N_2O. The Intergovernmental Panel on Climate Change IPCC 1997 method and emission factors, as reported in the UK greenhouse gas inventory [31] was adopted for land based emissions. This assumes that all direct inputs of N into soil are associated with an emission of N_2O and each is associated with an emission factor. Direct inputs include: synthetic fertiliser; N fixed by legumes; ploughed-in crop residues; land spreading of animal manures, compost or sewage sludge and direct deposition of manures by grazing animals. Indirect emissions arise from atmospheric deposition of N and leached nitrate.

3.5.3 Methane oxidation by soil

A credit arises to agricultural land from methane oxidation by methanotrophic soil bacteria. A value of 0.65 kg CH_4 ha^{-1} $year^{-1}$ for all non-organic land was established after an extensive examination of 24 papers literature reviewed by Williams et al. [6]. This was arbitrarily increased by 25% for organic land on the basis that N fertiliser is not used and some work has shown inhibition of methane oxidation from this. The field evidence for more methane oxidation in organic soil was not, however, found in the literature. The extra land occupied for grass-clover leys in organic arable crop production is also credited with methane oxidation capacity.

3.5.4 P and K losses

Losses of P and K by diffuse pollution (and erosion) from non-organic fields were set at 1.5 and 2 kg ha^{-1} respectively. These were reduced by 50% for organic fields in which a lower P and K status was assumed. P and K offtakes were derived from crop yields (including straw) and the nutrient concentrations [32].

3.6 Allocation of burdens between grain and straw

Grain is harvested by a combine harvester, but straw may be harvested or incorporated. If harvested, additional burdens are incurred by the straw baler, but the actual harvest energy is reduced slightly as a straw chopper is not required. Thus one can calculate the burden attributable to the grain.

The total burdens of producing grain and straw are: $T = H + (1 - p_s)I + p_s B + D$

Then the burden allocated to grain is: $G^* = (H + I)\ (Y_g/(Y_g + v_s p_s Y_s)) + D$,

and the burden allocated to straw is: $S^* = \dfrac{(H + I)\,(v_s p_s Y_s)}{(Y_g + v_s p_s Y_s)} + p_s(B - I)$,

where H is the vector of burdens of producing grain up to the end of combine harvesting per ha, I is the vector of burdens of chopping for incorporation for all straw produced, D is the vector of burdens of drying and storage of grain, B is the vector of straw baling burdens for all straw produced, p_s is the proportion of straw baled and harvested, Y_g is the net yield of grain per ha at standard DM content, Y_s is the yield of straw per ha (whether harvested or not) at standard DM content, and v_s is the relative value of the straw *prior to baling* versus the grain, typically 0.05.

3.7 Impact assessments

The impact assessment factors were taken from the Institute of Environmental Sciences of Leiden University (CML) found at (http://www.leidenuniv.nl/interfac/cml/ssp/index.html). The CML 1999 problem oriented approach baseline factors were used for eutrophication and acidification (not including fate) and abiotic resource use together with the IPCC 1997 factors for global warming potential. Land occupation was calculated explicitly from yield data.

4 Results

The gross fresh weight yields of the crops analysed are shown in Table 8 together with the proportions of each crop currently grown organically.

The results (FW basis) combine the current proportions of non-organic and organic farming and cultivation systems (Table 9). When compared on a DM basis, wheat captures about twice the DM per unit energy of the other crops (Table 10). Wheat is still about 25% more energy efficient in capturing protein than rape, but three times more efficient than potatoes. A similar trend holds for digestible energy (for pigs) of the whole crops (Table 10). Of course, the three crops fulfil very different functions and rape provides oil (for human food or bio-diesel) as well as a meal for animal feed. Once oil has been extracted from rapeseed, the protein in rapeseed meal incurs about the energy of that in wheat.

4.1.1 Bread wheat

The contrasts between non-organic and organic arable crop production are well illustrated by bread wheat (Table 11). Organic production uses about 20% less energy per tonne of product than non-organic, while occupying about three times the land area (including fertility building and cover crops). Although emissions per ha are sometimes lower from organic, yields are about halved and nitrogen fixing crops are needed, thus burdens in many cases are little changed. Fertiliser production, cultivations and harvesting are the main energy consumers, with fertiliser production dominating non-organic production (53%) and field work dominating organic production (60%). Field operations represents about a quarter of the total energy input to non-organic wheat, with equipment manufacture representing about one third of that energy input. Organic cultivations use more energy per ha than non-organic as direct drilling or reduced tillage are not used. This, together with lower yields and no artificial N fertiliser are why the proportion of energy used in field operations is so much higher. Organic wheat is produced without any pesticides.

Compared with combustion based industries, fossil fuel use is a minor contributor to global warming potential (GWP, on a 100 year basis) in arable agriculture. The main contributor (80%) is the N_2O-N emissions because they are 400 times more potent than CO_2 (mass basis). Nitrous oxide is emitted as a by-product of the nitrogen cycle in the soil as nitrogen is transformed between organic matter, ammonia and nitrate. The IPCC 1997 method estimates 1.25% of most soil N fluxes are emitted as N_2O-N. This emission is irrespective of whether the N source is as synthetic N or from N fixing, thus the proportions of N_2O emitted are closely related to the crop N supply and are not intrinsically different between organic and non-organic production. Arable methane emissions in the UK are trivial compared with those from animals, especially ruminants.

Scenarios

Scenarios of bread wheat production were investigated (Table 12). Because non-organic represents 99% of production, most of the following applies only to non-organic production.

Currently 20% of the fertiliser-N applied to bread wheat is urea. Increasing this to 100%, results in diverse effects. Primary energy (PE) remains effectively constant, but GWP falls by 21%, mainly because of the absence of the specific emission of N_2O associated with nitrate production. Eutrophication potential (EP) increases by 11%, but there is a 2.5 fold increase in acidification potential resulting from the large field ammonia emissions. Although urea has a lower specific energy requirement than ammonium nitrate, more has to be applied to maintain the same N supply as ammonium nitrate owing to the large field losses. So, potential gains in reducing PE are cancelled out by higher application rates.

If ploughing was reduced from the current 57% to 0 and replaced by 50% reduced cultivation and 50% direct drilling, PE use falls by 5%. Most other effects are small, but pesticide use is increased by 15% as herbicides are essential features of these lower energy tillage methods.

If plant breeding provides varieties with 1% more protein, the N supply to the crop must be increased, resulting in increases of all major burdens by about 4%. A greater proportion of domestic wheat could, however, be used for breadmaking, so replacing the need for imports. Importing grain from North America increases PE and GWP by about 28% and 14% respectively. The model assumes the same nitrogen utilisation efficiency for current and improved varieties.

Breeding new varieties with 20% higher yield, but with the same protein concentration, causes a reduction in all burdens (e.g. PE, GWP and acidification by 8-9% and eutrophication and potential land occupation by 17%). This happens even though 14% more N fertiliser is used. It should be noted that, there is normally a negative correlation between increased yield and increased protein in wheat breeds.

Growing wheat on heavier soils increases yields and despite requiring more energy for tillage, burdens are reduced (by a mean of 5%) as the proportion of clay soils used doubled.

If straw is baled rather than being incorporated, it incurs extra burdens for field operations and exported plant nutrients in straw. As straw is a co-product of grain, some of the burdens of grain production are passed to the straw. The effect is a linear decrease in the burdens of grain production (mean of 4%) as the proportion of straw baled increases (from 0 to 100%), reflecting the overall increase in useful produce exported from the field. The effect is similar for both organic and non-organic crops.

The effects of changing the N fertiliser rate are non-linear, reflecting at least partly the linear-exponential yield curve and the effects on protein concentration (Figure 1). The PE needed for bread wheat reaches a minimum at about 75% of the current rate. Other burdens show similar trends with different minima, but this is the most reliable value because the sub-models used to estimate leaching and total denitrification have been stretched beyond their original domain and the results become less reliable. The yield curve is well within a reliable range. Land occupation increases since both yield and protein concentration fall with less N. At 75% N rate, land occupation increases by 11%, but this increases rapidly with further reductions of N, increasing by 40%, 120% and 560% at 60%, 50% and 40% N rate respectively. This latter increase in land occupation reflects more the lower protein concentration than reduced yield.

4.1.2 Oilseed rape

The effects on N on rape were nominally similar to those for bread wheat, with a minimum energy need at about 75% of current N, but the absolute effect was much smaller than for wheat with a reduction of only 1% PE. Because rape is grown primarily for oil rather than protein, land occupation reflects yield reduction.

4.1.3 Potatoes

A large component of the energy (and other burdens) in potato production is cold storage. As it is a fresh crop and storage requires refrigeration the energy burden amounts to 50% of the total primary energy input (Table 13). However the GWP per unit energy of maincrop potatoes is less that from other crops, because the energy comes mainly from combustion of fuels to CO_2. Early potatoes have a similar ratio of GWP to PE use as other field crops, since there is no storage. 2nd earlies have only slightly lower yields than maincrop potatoes and so incur about half the burdens. 1st earlies yield about half that of maincrop, and, needing no storage, end up with about the same burdens as maincrop.

The burdens of organic and non-organic potato production are much more similar than for wheat, with energy and GWP_{100} being 2% and 13% higher, on average, in organic production (Table 14). Organic pesticide use is 19% of non-organic. This differs from wheat, where none are used, but this represents copper based products for blight control. The similarity of energy use is initially surprising, but results from the following: organic potatoes are lower yielding, but incur the same burdens for field machinery, which being a below-ground crop are relatively high; wastage of organic potatoes is twice as high as non-organic.

Because of the dominance of storage, reducing N input has a much smaller effect on total energy and GWP than with wheat or rape. The minimum energy use is at 92% of the current N rate, but the reduction is less than 0.1%.

Irrigation increases potato yield, but uses extra energy. Increasing the proportion of potatoes irrigated from 0 to 100% increases energy use per tonne by 4%, had no effect on GWP, but decreased land and pesticide use by 21%.

5 Concluding Discussion

The results presented (and the working model) allow the burdens of British arable production to be calculated in a flexible way that illustrates the environmental performance of alternative production systems. The analysis is more detailed than others for British crop production. Our results for non-organic production are broadly similar to those from other European studies (Table 15). The values for organic systems differ more widely, with ours being notably higher than Danish results for GWP. It is not clear, however, what systematic differences there are in terms of their farming systems or analysis methods as they do not provide full details. Our analysis does not allow for niche production that cannot be extrapolated to a national level. Our analysis is also based on long term technically sustainable systems.

The use of system modelling is designed to allow alternative production systems to be analysed, e.g. reduced tillage or N fertiliser use. Reducing N use on bread wheat by about 25% reduced several impacts per t. In general however the reductions in burdens from alternative systems of production are less than their proponents suggest.

Most alternatives increase the land occupation requirement per tonne of product. That is not a practical problem if land supply is not limiting (e.g. the existence of set-aside), but as demand for biofuels and human food increases, this may not hold for long. Solutions which export the problems of food production must be avoided.

The system modelling also shows how the burdens of crop production vary with soil type, for example, wheat grown on sandy soils uses about 20% more energy and causes about 40% more GWP than when grown on clay soils.

Large amounts of energy are used for storing maincrop potatoes. There could be potential for reducing energy use here, but it needs a detailed study in its own right.

The results show that greenhouse gas emissions from arable agriculture are far more dependent on N_2O than CO_2 in contrast to most manufacturing industry. That, together with the ill-effects of nitrate and ammonia emissions, leads to the observation that agriculture does not have a carbon footprint as much as a C-N footprint. The key to reducing burdens from agriculture thus lies in reducing the need for nitrogen in the production of the target product e.g. food protein or energy. However given with the large influence of nitrous oxide on GWP, evaluation of nitrous oxide emissions by a more situation dependent method, e.g. crop-soil simulation modelling, instead of the more rigid IPCC method would improve the robustness of the analysis. This would allow the possibility of alternatives that used the same amount of fertiliser input but with lower emissions.

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Table 1 Total numbers of pesticide applications for main crops

Crop	Details	Non-organic			Organic		
		Passes/ha	Dose-ha	Active ingredients, kg/ha	Passes/ha	Dose-ha	Active ingredients, kg/ha
Potatoes	Main	12	14	9.5	2.5	2.5	1.7
	1st Earlies	8.3	9.9	6.7	1	1	0.7
	2nd Earlies	12	14	9.5	2.5	2.5	1.7
Bread Wheat	Plough-based	5.2	6.5	4.4	2.5	2.5	1.7
	Reduced cultivation	6.0	7.5	5.1	N.A	N.A	
	Direct drilling	6.6	8.5	5.8	N.A	N.A	
Oilseed rape	Plough-based	4.8	4.4	3.0	N.A	N.A	
	Reduced cultivation	5.1	5.6	3.8	N.A	N.A	
	Direct drilling	6.4	5.8	3.9	N.A	N.A	

Each pass contains one or more active ingredients (a.i.) frequently at less than the full dose of that a.i. A dose is the sum of the fractions of full dose applied to the crop. Note that this independent of the toxicity of the ingredients. N.A = not applicable.

	Wheat	Oilseed rape	Maincrop	Earlies	2nd early
Mineral fertilisation, kgN/ha	208	195	170	170	150
Proportion of N applied as urea	0.2	0.31	0.04	0.04	0.04
Mass used as seed, t/ha-non-org	0.185	0.06	2.8	2.8	2.5
Mass used as seed, t/ha-org	0.225	0.06	2.8	3	2.5
Gross yield, t/ha - non-org	7.68	3.20	52.1	26.3	48.4
Gross yield, t/ha - org	4.12	1.71	35.2	19.1	35.0
Marketable Yield, t/ha - non-org	7.10	3.14	49.3	23.5	45.6
Marketable Yield, t/ha - org	3.03	1.65	32.7	16.1	32.5
Sprays, Dose-ha					
Plough-based	5.7(2.8)	2.8	17.3(12.1)	17.3(2.5)	1(2.5)
Reduced till-based	6.6(3.2)	3.2			
Direct drill	7.5(3.6)	3.6			
Fertiliser applications, passes	4	4	3		
Irrigation, m3-maincrop	0	0	672 (120)	0	576(120)
Cultivation systems					
Plough based	57%	50%	100%	100%	100%
Reduced tillage	41%	45%	0%	0%	0%
Direct drilling	2%	5%	0%	0%	0%
Proportion of crop wasted			7.5(5%)	7.5(3%)	7.5(5%)
Proportion of crop ending as stock feed			7.5%(25%)	7.5%(12%)	7.5%(25%)
Stock feed potatoes economic factor			0.117647	0.117647	
Soil types					
Clay	34%	43%	7%		
Loam	48%	29%	82%		
Sand	18%	28%	12%		
Protein content (Dry Basis), %	13.6(12.7)	21%	11%		
Straw incorporated (rest is baled)	75%(5%)	100%	100%		
Crop content (DB), %					
P	0.0035	0.006706	0.002		
K	0.0046	0.008486	0.0236		
Operations					
Subsoil (1 yr in 5)	x	X	x		
Plough	x	X			
Plough to 250 mm			x		
Destone			x		
Discing			o		
Roll	x	X			
Seedbed preparation	x	X			
Seedbed preparation	x	X			
Drill	x	X			
Ridge			x		
Plant			x		
Weeding			x		
Roll	x	x			
Spray	n	n			
Reduced cultivation operations					

Power Harrowing	x	x	
Discing	x	x	
Roll	x	x	
Subsoil tramlines	x	x	
Seedbed preparation	x	x	
Drill	x	x	
Spray	x	x	
Direct drilling operations			
Drilling	x	x	
Rolling	x	x	
Spray	x	x	
All systems			
Weeding			o
Irrigate			x
Sprayer fertiliser	n	n	n
Appy compost	o	o	o
Disk fertiliser broadcaster (12 m)	x	x	x
Lime spreader	x	x	x
Harvesting	x	x	x
Carting t/h	x	x	x
Waste potato disposal			x
Crop cooling, storage and drying	x	x	

Table 2 Primary energy used for crop storage, cooling and drying grain. All values relate to energy per unit mass fresh weight (after drying) at standard dry matter contents, MJ/t.

Item	Wheat	Rape
Building itself	11	11
Cooling	1.2	4.1
Drying	133	158

Table 3 Energy consumption during potato storage (primary energy per t)

Item	National total - for non-organic, %	Organic (estimated), %	Building, MJ (as primary energy)	Electricity (as primary energy), MJ	Weighted primary use, non-organic, MJ	Weighted primary use, organic, MJ
Outdoor clamps	0.2	0.7			0.0	0.0
Unventilated building	2.7	9.3	11		0.3	1.0
Ventilated building	35.8	33.2	11	224	84	78
Refrigerated building	61.3	56.8	11	929	576	534
Total	100.0	100.0			**660**	**613**

Table 4 Main burdens for producing, packing and delivering main types of fertilisers.

Item	Unit	Primary Energy, MJ	Global Warming potential, kg CO_2 equiv.]	Eutro-phication Potential, g PO_4^{3-} equiv.]	Acidifaction Potential, g SO_2 equiv.]	Abiotic Resource Use, g Sb equiv.]	N_2O-N, to air, g
Ammonium nitrate as N	kg N as N	41	7.2	0.50	4.7	23	9.4
Urea as N	kg N as N	49	3.5	0.54	5.3	23	0.025
Calcium ammonium nitrate as N	kg N as N	43	7.4	0.55	5.3	21	9.4
Ammonium sulphate as N	kg N as N	42	3.0	0.52	5.3	20	0.022
Triple super phosphate as P	kg P as P	19	1.2	0.74	8.1	15	0.012
Single super phosphate as P	kg P as P	13	0.60	0.57	6.6	16	0.0094
Rock P from 25% P_2O_5 Tunisian as P	kg P as P	15	1.1	0.97	13	17	0.012
K fertiliser (Muriate of potash) as K	kg K as K	5.7	0.53	0.30	7.2	3.9	0.0056
Rock K as K	kg K as K	15	0.86	1.40	8.8	17	0.0094
Gypsum (quarried) as S	kg S as S	5.5	0.35	0.58	3.7	5.9	0.0031
Gypsum from Flue gas desulphurisation as S	kg S as S	1.9	0.11	0.14	0.9	4.2	0.0020
Limestone as Ca (39% Ca in product) (*)	kg Ca	2.3	0.15	0.26	1.6	2.4	0.0014
Burnt lime (or chalk) (60% Ca in product) as Ca	kg Ca	8.5	0.23	0.20	2.4	5.1	0.0020
Weighted lime usage for non-organic crops as Ca	kg Ca	3.2	0.16	0.25	1.7	2.8	0.0015

(#) EP is Eutrophication potential, AP is acidification potential and ARU is abiotic resource use.

(*) Includes CO_2 emitted from soil once neutralised

Table 5 Main burdens of composting residues

Item	Unit	Primary Energy, MJ	Global Warming potential, kg CO_2 equiv.]	Eutro-phication Potential, g PO_4^{3-} equiv.]	Acidifactio nPotential, g SO_2 equiv.]	Abiotic Resource Use, g Sb equiv.]	N_2O-N, to air, g
Imported compost (fresh weight basis & energy based only)	t	80	5.10	7.1	43	170	0.094
Main compost nutrients in imported compost: N, P, K or S (energy based)	kg	8.6	0.55	0.76	4.6	18	0.010

Item	Unit	Primary Energy, MJ	Global Warming potential, kg CO_2 equiv.]	Eutro-phication Potential, g PO_4^{3-} equiv.]	Acidifaction nPotential, g SO_2 equiv.]	Abiotic Resource Use, g Sb equiv.]	N_2O-N, to air, g
Cattle manure composted – gaseous emissions	kg N		4.40	68	300		3.6
Pig manure composted – gaseous emissions	kg N		1.30	570	2500		2.0
Poultry manure (no bedding) composted – gaseous emissions	kg N		6.10	780	3400		11
Poultry manure (with bedding) composted – gaseous emissions	kg N		4.40	620	2800		9.2

Table 6 Fitted parameters for relating crop yields to nitrogen fertiliser application rate

Crop	a	b	c	d	Nominal mean N application rate, kg/ha
Wheat grain, t/ha	453.7	452.6	0.000626	0.237	208
Wheat straw, t/ha	461.6	460.8	0.000333	0.135	
Wheat grain N offtake, g/ha	-37.35	204.9	0.0131	83.64	
Oilseed rape	203.55	-203.03	0.000614	-0.104	200
Potatoes-main	3144.5	-3136.4	0.000760	-1.995	220
Potatoes-1st	1628.3	-1624.1	0.000832	-1.131	170
Potatoes-2nd	2976.5	-2968.9	0.000832	-2.067	200

Table 7 Mean irrigation rates, the proportions irrigated, the response to the current proportion irrigated and the average yield of potato growing areas in England. (Numbers in brackets are coefficients of variation, %. Y_{100} is the maximum factor by which yield increases through irrigation. Y_m is the mean yield at the current level of irrigation, μ_m)

Type of potato	Application rate, mm/year	Current proportion irrigated μ_m, %,	Y_{100} (*)	Y_m
First earlies	90 (18)	40 (11)	1.25	19 (21)
Second earlies	105	48	1.25	42
Maincrop	120 (23)	56 (24)	1.25	44 (4)

Table 8 Gross yields of crops at national level, t/ha. Values in parenthesis show the proportion grown organically.

Bread wheat (0.7%)		Oilseed Rape (0%)		Potatoes (1%)					
				Maincrop		First earlies		Second earlies	
Non-organic	Organic	Non-organic	Organic (*)	Non-organic	Organic	Non-organic	Organic	Non-organic	Organic
7.7	4.1	3.3	1.8	52	35	26	19	48	34

(*) estimated from the relative yields of organic and non-organic wheat as too little is grown organically to give valid data.

Table 9 Main burdens of production of each crop commodity (per t)

Impacts & resources used	Bread wheat	Oilseed Rape	Potatoes
Primary energy used, GJ	2.4	4.9	1.4
Global warming potential, t CO_2 equiv.	0.70	1.4	0.20
Eutrophication potential kg PO_4^{3-} equiv.	3.1	8.2	1.0
Acidification potential, kg SO_2 equiv.	3.3	9.0	0.8
Pesticides used, dose ha	0.9	1.5	0.4
Abiotic resource use, kg Sb equiv.	1.5	2.8	0.9
Land occupation, Grade 3a Equiv., ha	0.14	0.32	0.03
N losses			
NO_3-N, kg	4.3	12	1.7
NH_3-N, kg	1.2	2.4	0.25
N_2O-N, kg	1.0	3.0	0.08
N_2-N, kg	6.8	26	1.1
Irrigation water, m^3			21

Table 10 Primary energy used for crop production (grain or tuber only) on four bases (without any further processing)

Basis	Bread wheat	Oilseed Rape	Potatoes
GJ /t Dry Matter]	2.8	5.2	6.8
GJ /t Crude Protein]	20	25	63
GJ /GJ Gross Energy]	0.15	0.18	0.40
GJ /GJ Digestible Energy]	0.18	0.27	0.57

Table 11 Burdens of producing bread wheat non-organically and organically (per t produced)

Impacts & resources used	Non-organic	Organic
Primary Energy used, GJ	2.4	2.0

Impacts & resources used	**Non-organic**	**Organic**
Global warming potential, t CO_2 equiv.	0.70	0.80
Eutrophication Potential , kg PO_4^{3-} equiv.	3.0	9.3
Acidification Potential , kg SO_2 equiv.	3.3	3.6
Pesticides used, dose	0.92	0.00
Abiotic resource use, kg Sb equiv.	1.5	1.4
Land occupation grade 3a Equiv., ha	0.14	0.41
N losses		
NO_3^--N kg	4.2	18
NH_3-N kg	1.1	1.5
N_2O-N kg	1.0	0.91
N_2-N kg	6.7	12
Primary Energy Usage Proportions		
Field work: Cultivation	20%	60%
Field work: Spraying	3.6%	0.0%
Field work: Fertiliser or compost application	2.6%	2.7%
Field work: Harvesting	8.4%	21.6%
Crop storage, drying and cooling	5.2%	7.7%
Pesticide manufacture	6.9%	0.0%
Fertiliser manufacture	54%	7.8%
Contributors to Global warming potential		
CO_2	23%	16%
CH_4	0.8%	-0.4%
N_2O (direct)	70%	58%
N_2O (via nitrate)	6.9%	27%

Table 12 Effects of some scenarios on the burdens of bread wheat production (per t)

Impacts & resources used	**Original**	**All urea**	**Reduced cults**	**75% N fert.**	**90% clay**	**+1% protein**	**+20% yield**
Primary Energy used, GJ	2.4	2.4	2.3	2.3	2.3	2.5	2.2
Global warming potential, t CO_2 equiv.	0.70	0.56	0.70	0.61	0.64	0.74	0.65
Eutrophication Potential , kg PO_4^{3-} equiv.	3.1	3.4	3.1	2.5	2.7	3.2	2.5
Acidification Potential , kg SO_2 equiv.	3.3	8.5	3.3	3.1	3.1	3.5	3.0
Pesticides used, dose	0.9	0.9	1.1	1.0	0.8	0.9	0.8
Abiotic resource use, kg Sb equiv.	1.5	1.4	1.4	1.4	1.4	1.5	1.4
Land occupation grade 3a Equiv., ha	0.14	0.15	0.15	0.16	0.15	0.14	0.12
N losses							
NO_3^--N kg	4.3	2.8	4.4	3.0	3.6	4.5	3.4
N_2O-N kg	1.2	0.8	1.2	1.0	1.0	1.2	1.1
NH_3-N kg	1.0	3.3	1.0	0.9	0.9	1.1	0.9
N_2-N kg	6.7	4.5	6.9	4.7	6.4	7.1	5.4

Table 13 Comparison of the burdens of producing early, second early and maincrop potatoes (per t), with 1% produced organically

Impacts & resources used	**1st Earlies**	**2nd earlies**	**Maincrop**
Primary Energy used, MJ	1.3	0.74	1.5
GWP_{100}, kg 100 year CO_2 equiv.	0.29	0.13	0.17
EP, kg PO_4^{3-} equiv.	2.2	0.58	0.53
AP, kg SO_2 equiv.	1.0	0.62	0.78
Pesticides used, dose ha	0.48	0.35	0.33
ARU, kg antimony equiv.	0.65	0.38	1.1
Land occupation grade 3a Equiv., ha	0.043	0.022	0.021
Irrigation water, m^3	18	13	16
Primary Energy Usage Proportions			
Field work	57%	56%	28%
Crop storage and cooling	0%	0%	49%
Pesticide manufacture	8%	10%	5%
Fertiliser manufacture	34%	34%	18%

Table 14 Burdens of producing potatoes produced non-organically and organically (per t FW)

Impacts & resources used	**Non-organic**	**Organic**
Primary Energy used, MJ	1.4	1.6
GWP_{100}, kg 100 year CO_2 equiv.	0.19	0.20
EP, kg PO_4^{3-} equiv.	0.80	1.5
AP, kg SO_2 equiv.	0.81	1.0
Pesticides used, dose ha	0.36	0.10
ARU, kg antimony equiv.	1.0	1.2
Land occupation grade 3a Equiv., ha	0.024	0.058
Primary Energy Usage Proportions		
Cultivation	8.5%	15%
Spraying and fertiliser application	2.7%	1%
Irrigation	6.8%	13%
Harvest	10%	14%
Cold storage	49%	48%

Pesticide manufacture	4.8%	0.3%
Fertiliser manufacture	19%	8.0%
Contributors to Global warming potential		
CO_2	45%	49%
CH_4	2%	1%
N_2O (direct)	48%	42%
N_2O (via nitrate)	4%	7%

Table 15 Comparisons with other studies

	Primary Energy		**Global warming potential**		**Land occupation**	
	Non-organic	**Organic**	**Non-organic**	**Organic**	**Non-organic**	**Organic**
Wheat						
Denmark (1)			710	280	0.15	0.22
Germany (2)	2.4	1.5				
This study	2.5	1.7	804	786	0.14	0.44
Rape						
Denmark			1,510			
Germany	6.0	2.5			0.35	
UK other (3)	4.7				0.35	
This study	5.4	4.0	1,710		0.31	
Potatoes						
Denmark			160		0.03	
Germany	0.6	0.6				
This study	0.7	0.7	178		0.03	

Other data from [33-35]

Figure 1. Effects of changing N fertiliser on burdens of bread wheat production (PE: primary energy, GWP: global warming potential)