CLIMATE CHANGE AND AGRICULTURE PAPER

Greenhouse gas emissions and energy use in UK grown short-day strawberry (*Fragaria xananassa*) crops

Short title: *GHG emissions & energy use in strawberries*

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SUMMARY

Reducing greenhouse gas emissions and optimizing energy consumption is important for mitigating climate change and improving resource use efficiency. Strawberry (*Fragaria xananassa* Duch) crops are a key component of the UK soft fruit sector and potentially resource-intensive crops. This is the first study to undertake a detailed environmental impact assessment of all methods of UK strawberry production. A total of 14 systems with six additional sub-systems grown for between 1 and 3 years were identified. They were defined by the growing of short-day (Junebearer) or everbearer varieties, organic production, covering with polytunnels or grown in the open, soil-grown (with or without fumigation) or container-grown (with peat or coir substrate) and summer or spring planted. Pre-harvest, the global warming potential

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varied between 1.5 and 10.3 t CO_2 equiv/ha per crop or 0.13 and 1.14 t CO_2 equiv/tonne of class 1 fruit. Key factors included use of tunnels, mulch and irrigation, sterilization of soil with fumigants, and use of peat substrate. Seasonal crops without covers grown where rotation of sufficient length reduced *Verticillium* (System 4) were the most efficient. System 4a (that did not use mulch) emitted 0.13 t CO_2 equiv/t of class 1 fruit. A second or third cropping year in soil grown systems prolonged the effect of mulch and soil fumigants. Greenhouse gases from System 4 (with mulch) averaged 0.30 t CO_2 equiv/t of class 1 fruit after 3 years of cropping compared to 0.63 and 0.36 t CO_2 equiv/t after 1 and 2 years respectively.

INTRODUCTION

Strawberries (*Fragaria xananassa* Duch) are an important component of the UK soft fruit sector. The value of UK strawberry production has risen from £94 million in 2002 to £213 million n 2008 (Department for Environment, Food and Rural Affairs (DEFRA) Agricultural Statistics 2009a). Production in the UK is predominantly from 'short-day' (Junebearer) crops, harvested during June and July, of which the main cultivar is cvar Elsanta. Most UK growers extend the growing season by sequential planting of short-day crops and growing under covers (polytunnels). Production may also be extended beyond the main season with everbearer cultivars, plants able to flower at least twice per season (Hancock 1999), such as cvar Bolero and cvar Everest, which crop between August and September (Simpson *et al*. 2002).

Climate change, one cause of which is increased atmospheric concentration of greenhouse gases (GHG), is predicted to increase mean surface temperature and alter precipitation patterns (Jenkins *et al*. 2007; Murphy *et al*. 2009). The Kyoto Treaty of 1997 committed industrialized nations to reduce GHG emissions by 5.2 % below their 1990 levels during the first commitment period (the Quantified Emission Limitation or Reduction Commitments (QELRC)) between 2008 and 2012 (DEFRA 2005). The UK Climate Change Act (2008) commits the UK to an 80 % reduction in GHG emissions compared to 1990 by the year 2050. Carbon dioxide (CO_2) is one of six GHG covered by the Kyoto Protocol (IPCC 2006); others include nitrous oxide (N_2O), methane (CH_4) hydrofluorocarbons (HFC), perfluorocarbons (PFC) and sulphur hexafluoride (SF_6). Each GHG has a different potential to cause global warming but may be standardized on a single scale as CO_2 equivalent (CO_2 equiv), its global warming potential (GWP). The time elapsed affects the GWP of a GHG and in this case it has been calculated after 100 years (GWP_{100}). Methane and N_2O have a GWP of 25 and 298 respectively.

Detailed life cycle analyses (LCA) pre-farm gate of current UK arable, livestock and glasshouse horticultural production methods have been undertaken by a number of authors (Blanke & Burdick 2005; Edwards-Jones *et al*. 2008, 2009; Hülsbergen & Kalk 2001; Tzilivakis *et al*. 2005*a, b*; Williams *et al*. 2006; Milà i Canals *et al.* 2007). Assessments of crops produced overseas include Ligouri *et al*. (2009) and Maraseni *et al*. (2009). Foster *et al*. (2006) and Garnett (2006, 2007) have examined the entire supply chain.

Strawberries may be grown by several different methods; 14 primary systems were identified, nine of which used short-day varieties, with six additional sub-systems. The analysis focuses on short-day varieties since everbearer crops are grown concurrently as opposed to alternatively. The GWP_{100} and primary energy (PE, in giga-joules (GJ)) were quantified per hectare (ha) and per tonne (t) of class 1 fruit (berries that growers stated were suitable for sale fresh) for each system. It is the first study to undertake a detailed environmental impact assessment (EIA) of all methods of UK strawberry crop production. The results are discussed with respect to minimizing two environmental burdens, GHG emissions and PE per unit area grown while maintaining yields to optimize efficiency per tonne of output.

MATERIALS AND METHODS

Description of scenarios

A questionnaire devised by East Malling Research (EMR) obtained detailed management descriptions from 20 individual farm enterprises of the strawberry growing methods used on that farm (Table 1). The interviewees were either existing EMR contacts or introduced via the suppliers K. G. Fruits Ltd and Berriworld Ltd. They included several of the major English strawberry producers and enterprises were situated within the three main strawberry growing regions of England. Each management description included information on crop protection and fertilizer (product, rate and timing), cultivations (type, timing and depth), water volume, if covered with a polytunnel, type of growing media and typical yield of class 1 fruit/ha. A system was not representative of an individual farm enterprise but was defined by the following variables: use of short-day (Junebearer) or everbearer varieties, conventional or organic production, covered with polytunnels or grown in the open, soil-grown (with or without fumigation) or container-grown (with peat or coir substrate) and summer or spring planted. Most systems cropped for 1 or 2 years, systems 1, 2 and 4 cropped for up to 3 years. Individual farm enterprises often used more than one system of production to enable sequential planting of crops.

Three geographic locations were chosen from key strawberry growing areas, the spatial boundaries of which were defined using the Nomenclature of Units for Territorial Statistics (NUTS) level 1 (Government Office Regions) (DEFRA 2009a).

It included the South-East (1006 ha) represented by Kent (0.59 of the production within the South East region), the East of England (602 ha) represented by Norfolk (0.55 of the East of England production) and the West Midlands (512 ha) represented by Herefordshire (0.62 of the West Midlands production). Production occurred on a range of soil types (sand, sandy clay loam (to represent loam soils) and clay) and within areas that receive different quantities of rainfall annually (low, <600 mm per annum; moderate, <600 – 700 mm; and high, >700 mm).

Global warming potential$_{100}$ and primary energy

System boundaries accounted for upstream indirect (Scope 3) emissions of all products used on the farm. The analysis was conducted up to and including controlled atmosphere (CA) storage post-harvest. In 2008 the British Standards Institute (BSI) introduced the Publicly Available Specification (PAS 2050) (BSI 2008) as a standardized method for calculating the carbon footprint of a commodity. The present study was undertaken before its publication and instead follows ISO 14044:2006 LCA protocols (ISO 2006). Emissions from fuel consumption have been derived from the Carbon Trust (2004) and Choudrie *et al*. (2008) and include the following:

1. Manufacture of crop protection chemicals, fertilizers, polyethylene and galvanized steel for tunnels and mulch (including packaging and transport to the farm). Materials such as low density polyethylene (LDPE) tunnel covers whose lifetime is longer than one season were calculated on a per year basis.
2. Execution of field operations to account for type and working width of machine, speed, operating depth and soil type.
3. Manufacture of machinery and its maintenance based on estimates of operating lifetimes and depreciation.

Where only PE was available (for example pesticide manufacture), GHG emissions have been calculated per MJ from the proportion of the given type of fuel used multiplied by the CO_2 equiv/MJ of that fuel. This calculation was done for each component fuel and then summed.

Crop protection

The product, rate and timing of application for each system were provided by EMR, S. Raffle (formerly of ADAS) and the grower interviews (Tables 2 & 3). Since completion of the present study, review of EC Directive 91/414 has excluded paraquat (a component of the herbicide PDQ) from Annex 1 and it is now no longer approved for use in the UK. Chloropicrin has been voluntarily withdrawn (withdrawal date December 2010) although it may be used until December 2011. The PE to manufacture each pesticide has been calculated where possible by active ingredient (Pimentel 1980; Green 1987) or an active ingredient (ai) from the same pesticide class (Tzilivakis *et al*. 2005*a*, *b*). Where PE data representative of a particular class was not available, the mean of herbicides, fungicides or insecticides was used. Primary energy consumption during pesticide manufacture was between 67 MJ/kg ai (halogenated hydrocarbons) and 460 MJ/kg ai (paraquat) (Pimentel 1980; Green 1987) excluding packaging, storage and transport equivalent to an additional 23 MJ/kg ai (Hülsbergen & Kalk 2001). The GHG emissions were calculated per MJ in the following proportions: 0.40 electricity, 0.22 natural gas, 0.05 fuel oil and 0.33 naptha (Green 1987). Application by spraying used 1.7 litres/ha of diesel with a further 29 MJ/ha to account for machinery depreciation (Hülsbergen & Kalk 2001). Diesel released 39.6 MJ/l including extraction and transport (Hülsbergen & Kalk 2001). Where products were tank mixed they have been calculated as one spray operation. Chloropicrin, applied at a rate of 200–400 litres/ha (The Assured Produce Scheme 2009), was used as a fumigant and a mean application rate of 300 litres/ha has been assumed.

Cultivations

Soil-grown systems were sub-soiled (350 mm), ploughed (200 mm) and lightly cultivated (50 mm) before bed formation. Crops grown in containers on tables had no soil tillage operations. Where containers were placed on beds the beds were ploughed and lightly cultivated only. The PE consumed as a result of ploughing and sub-soiling operations on various soil types were derived from regression equations described in Kalk & Hülsbergen (1999), other operations from Hunt (1995) and Donaldson *et al*. (1994) (Table 4). Bed formation and laying mulch cultivated 0.625 ha per ha of crop (1.0 m and 0.6 m per bed and alley, respectively). Indirect PE of 143 MJ/ha to include manufacture and maintenance of machinery (Hülsbergen & Kalk 2001) was used.

Nutrition

Crop nutrition is summarized in Table 5. A base dressing of phosphorous (P) and potassium (K) was applied to soil-grown crops in response to soil testing (MAFF 2000). Additional nutrients including nitrogen (N) were applied through the irrigation system during the summer in response to leaf analyses. The chemical composition, GHG emissions and PE during manufacture of each fertilizer product are given in Table 6. The most modern ammonium nitrate fertilizer manufacturing plants have an accumulated production cost of 30.5 MJ kg/N (Jenssen & Kongshaug 2003; Brentrup & Pallière 2008). The present day ‘average Europe’ value (38.7 MJ/kg N) used in the current study incorporates production from older plants. Diesel consumption (l/ha) during application has been derived from regression equations (Kalk & Hülsbergen 1999) plus 28 MJ/ha to account for machinery depreciation (Hülsbergen & Kalk 2001). Farmyard manure (FYM) was assumed to be a by-product whose production incurred no energy cost to the strawberry crop (it was attributed to the livestock system from which it was generated). Its application used 20.8 litres/ha directly, 813 MJ/ha indirectly (Hülsbergen & Kalk 2001), 0.5 litres/t diesel to load (Dalgaard *et al*. 2001) and a mean 2.2 MJ/t/km to transport (Fealy & Schrőder 2008) over an estimated 10 km.

Crop culture

A 0.05 mm thick polyethylene mulch 1.4 m wide was used to cover the beds of the soil-grown crops before planting in both fumigated and non-fumigated crops. The low density polyethylene (LDPE) used for tunnel covers, mulch and container bags required 78 MJ/kg and emitted 0.0019 t CO_2 equiv/kg (mean for European polyethylene production) during its manufacture (Bousted 2003). The PE includes the feedstock; however the feedstock carbon (C) is not emitted until disposed of permanently. This will either be immediately as CO_2 if burnt or gradually as CO_2 and CH_4 during biodegradation within a landfill (Eggels 2001). Since the Waste Management (England and Wales) Regulations 2006: Statutory Instrument (SI) 2006/937 prohibits on-farm burial or burning, disposal of the LDPE was assumed to be via landfill. An estimated 0.05 of polyethylene decomposes after 100 years, releasing 101 kg CO_2/t and 14 kg CH_4/t plus 2.7 kg CO_2/t from fuel consumed during processing (Eggels 2001). Fuel consumption during transport was estimated as an additional 0.086 kg CO_2 equiv/t/km (DEFRA 2009b) for two journeys of 133 km, the average haulage distance by road for 'miscellaneous manufactured goods' in the UK (National Statistics 2009) by a 38 t gross weight truck. The mulch lasted for the lifetime of the crop (1–3 years).

Polytunnel dimensions were supplied by Haygrove Ltd. The hoops and legs consisted of galvanized steel tube manufactured from a combination of primary and secondary steel (UK mix, 24.4 MJ/kg) plus 7.5 MJ/kg for galvanizing (Hammond & Jones 2008). The LDPE cover was attached by nylon rope (120 MJ/kg; Bousted 2000) with a 10-year lifespan.

The container systems used up to 6200 growbags/ha (grower interviews) with an average lifespan of 2 years. The GWP_{100} and PE associated with their manufacture were calculated on an annual as opposed to a per crop basis. Tables were constructed from scrap or were 'second hand' and not reprocessed specifically for the purpose; 0.5 of the original 24.4 MJ/kg has been estimated for their manufacture. A high density polyethylene (HDPE) trough (926 kg/m^3, 77 MJ/kg; Bousted 2003) was situated below the bags to act as support and trap drainage water.

Irrigation of soil-grown crops used a double line of T-tape (lifespan 3 years), while table-grown crops used a permanent pipe (lifespan 10 years). Irrigation water was applied for 154 days (grower interviews) and 0.5 h/day (EMR, personal communication) (Table 1). It is acknowledged that some growers may irrigate for longer periods each day but this data was not available from the interviews. An estimated 52 MJ/mm/ha (Dalgaard *et al*. 2001) was consumed as diesel.

Post-harvest operations

Punnets were manufactured from HDPE. Strawberries were chilled then stored in a CA for 12 h before despatch to the retail outlet. Energy consumption was based on descriptions given in Mila i Canals *et al.* (2007). Transportation from packhouse to retail outlet was calculated for 114 km (average haulage distance by road for 'agricultural produce' in the UK (National Statistics 2009)) by a 38 t gross weight truck.

Emissions from soil

Two environments exist within a strawberry crop: (1) an area of exposed soil between the crop rows (the alleys, 0.38 of the area), which in most systems does not receive any further N; and (2) the soil beneath the mulch in which the strawberry plants root and to which N is applied in most systems via trickle irrigation during the late spring and summer months only. Two mechanisms are responsible for most of the N_2O emissions from soils: microbial nitrification and denitrification (Machefert *et al*. 2002). A proportion of N within nitrate leachate (NO_3^-) and volatilized ammonia (NH_3) may also be emitted as N_2O (Williams *et al*. 2006; Choudrie *et al*. 2008).

In the alleys, the N balance model SUNDIAL (Smith *et al*. 1996) was used to simulate the quantity of N that is nitrified, denitrified and leached for a fallow soil without the application of N as a base dressing. The model calculates weekly inputs and outputs of N and an overall N balance which was adjusted to 0.38 ha, except when no mulch was present. The organic crops to which FYM was applied received the equivalent of 40 t/ha FYM within the alleys. The fraction of total N nitrified and denitrified that formed N_2O-N was 0.0125 and 0.035 respectively (de Vries *et al*. 2003). The proportion of N leached as NO_3^--N that subsequently formed N_2O-N equalled 0.00075 (Choudrie *et al*. 2008) Where a polytunnel was present and prevented rainfall from reaching the soil, the proportion of water-filled pore space (WFPS) within the alleys was estimated to be below 0.55, such that emissions were predominantly from nitrification (Machefert *et al*. 2002). The NH_3 volatilized due to application of FYM, assumed to be incorporated within 6–12 h, was quantified with MANNER (Chambers *et al*. 1999). A mean 0.01 formed N_2O-N (Choudrie *et al*. 2008). The widths of bags used in the container-grown systems were smaller than the mulch and the area occupied by the alleys adjusted accordingly.

The second environment within the crop is beneath LDPE mulch (0.62 of the area). Rainwater does not tend to penetrate the mulch (EMR personal communication) so its movement through the soil profile was assumed to be negligible. The WFPS is likely to be classed as low to intermediate (a proportion of < 0.55 WFPS) and so favour nitrification (Machefert *et al*. 2002). During the late spring and summer (for 154 days) the soil beneath the mulch within the root zone is irrigated to field capacity (D. Simpson, personal communication), to a proportion of *c*. 0.60 WFPS for most soils (Davidson & Schimel 1996). Water sensors may be used to control irrigation such that field capacity within these areas is not exceeded. At a WFPS of 0.60 there is potential for both nitrification and denitrification to occur (Machefert *et al*. 2002) but this is at the lower range for denitrification and considered by Skopp *et al*. (1990) to be optimal conditions for aerobic processes (nitrification). Emission of N_2O beneath the mulch was estimated using the modelled nitrification values for within the alleys and adjusted to 0.62 ha.

Peat extraction in Great Britain and Northern Ireland for horticultural use is estimated to cause a mean loss of 49.9 kg C/m^3 extracted (Choudrie *et al*. 2008). This represents the sum of 'on-site' emissions (from the peatland in response to extraction) and 'off-site' emissions (from the extracted peat used in growbags). In peat container systems, each 1 m long bag contained 5 litres (0.005 m^3) of dry peat, the equivalent of 31 m^3/ha crop.

RESULTS

Crop protection

Fumigated second year crops without covers had the largest PE and GWP_{100} associated with crop protection. Chloropicrin (1.66 kg/l bulk density (Green *et al*. 2009)) persists for the lifetime of the crop. The total PE for an assumed 300 litres/ha application decreased from 45.9 to the equivalent of 22.9 and 15.2 GJ/ha per crop respectively for 1, 2 and 3 cropping years. Over-wintering of strawberry crops (maincrops) necessitates treatment of crown rot during the spring and additional herbicide treatments in the autumn and winter. Covering a crop with a polytunnel reduces incidence of *Botrytis* and number of fungicide sprays.

Nutrition

The crop N requirement was determined by type of growing media (soil grown and type, peat or coir) (Table 5). Container-grown crops with coir (system 9) received the largest dose of N, followed by systems that used peat (system 7 and 8). Field-grown strawberry crops have a relatively low N demand (MAFF 2000). Nitrate fertilizer releases N_2O during manufacture (Jenssen & Kongshaug 2003) and GHG emissions are proportionally greater than the PE (Table 6). In total, 0.57 t CO_2 equiv/ha or 4.3 GJ/ha were attributed to nutrition (inclusive of P and K) of each soil grown crop, 1.14 t CO_2 equiv/ha or 8.5 GJ/ha over 2 cropping years. Most growers applied mineral N through the irrigation system with no further PE necessary for product application. Loading, transport and application of 40 t/ha FYM emitted 0.38 t CO_2 equiv/ha and needed 5.7 GJ/ha but was distributed over the crop lifetime (2 cropping years).

Cultivations

The PE consumption for bed formation ranged from 2.4 GJ/ha for container crops on raised beds to 5.1 GJ/ha for soil-grown crops on clay. Deeper tillage operations on heavier soils consumed greatest quantity of fuel. Soil grown systems with raised beds were sub-soiled to improve rooting depth, whereas for those crops grown in containers tillage of the top soil layer to enable bed formation was sufficient. The bed remains until the crop is grubbed out therefore PE per crop decreased with each cropping year. For example, on clay soil PE was 5.1, 2.6 and 1.7 GJ/ha for 1-, 2- and 3-year crops, respectively, from ploughing the field before bed formation up to and including crop removal.

Crop culture

Use of plastics in many aspects of strawberry production contributes significantly to the GWP_{100} and PE as highlighted in covered soil-grown crops that used both mulch and polytunnels. Mulch lasts for the lifetime of the crop, up to 3 years. The bags in container systems last for 2 years, but they may be re-used after the crop is removed (e.g. for two different crops of 1 year each). The equivalent PE to manufacture mulch is reduced with each additional year the crop is in the ground.

Emission from soil

Emissions of N_2O from soil were estimated to range from 1.1–1.8 kg N_2O-N/ha/year. A base dressing of N was not applied pre-planting but delivered gradually via irrigation. Residual N remaining in the alleys is vulnerable to loss but is determined in most systems by the previous crop and soil N supply (SNS) index. Application of FYM to the entire field in System 5 resulted in emissions of 2.9 kg N_2O-N/ha/year.

System 4a (no crop 1st year) was grown on a sandy soil, given a base dressing of mineral N fertilizer and did not use LDPE mulch. The first crop was grown over 2 years for which an estimated 3.0 kg N_2O-N/ha resulted in total.

Global warming potential$_{100}$ and primary energy per ha and per tonne of class 1 fruit

Short-day strawberry varieties had a GWP_{100} per ha pre-harvest of between 2.2 and 10.3 t CO_2 equiv/ha per crop for 1 cropping year and a mean of 1.5 and 10.3 t CO_2 equiv/ha per crop for 2 years. Systems were distinguished by use of peat substrate, soil fumigants, and materials such as polyethylene and galvanized steel for mulch for the tunnels. Other potentially significant emission sources included manufacture of nitrate fertilizer, applied in greater quantities to coir systems, and N_2O from soil in fallow alleys to which FYM had been applied. The GWP_{100} pre-picking was smallest in systems not covered and not fumigated. Emissions were greatest from covered peat container grown systems (10.3 t CO_2 equiv/ha) to which the oxidation of C in peat (Choudrie *et al*. 2008) contributed significantly. Emissions were calculated on a per year basis for an average container life-span of 2 years and as such a reduction in the CO_2 equiv/crop did not occur during the second year of cropping in contrast to soil grown systems. Per tonne of class 1 fruit, the GWP_{100} was smallest in System 4a (0.13 t CO_2 equiv/t) as a result of low emissions/ha (1.5 – 2.2 t CO_2 equiv) and a yield of 23.8 and 11.0 t/ha during the first and second year, respectively. The GWP_{100} was also small in the summer-planted system 2 (fumigated and grown in the open) (0.22 t CO_2 equiv/t) high yielding during both years, 27.0 and 23.0 t/ha respectively (Figs 1*a*, *b*). Yields of 6.4, 13.5 and 13.5 t/ha during years 1–3 in System 4 meant relatively low mean emissions of 0.30 t CO_2 equiv/t after 3 years of cropping. Over 2 years the GWP_{100} of the covered organic System 5 with FYM (0.37 t CO_2 equiv/t) was similar to the covered and non-fumigated System 3 (0.36 t CO_2 equiv/t). The lower yielding non-covered peat container System 8 (7.1 and 11.2 t/ha) had the largest emissions of all the systems considered (1.14 t CO_2 equiv/t).

Per crop the mean PE per ha (excluding post harvest operations) ranged from 15.8–194.0 GJ/ha to one crop and 11.0–156.0 GJ/ha for two crops. The main constituents of PE overall was the manufacture of polyethylene for polytunnels, mulch, container bags and irrigation pipe, the manufacture of galvanized steel for tunnel supports, soil fumigants and fuel consumed by delivery of irrigation water. Systems that did not use covers or fumigants, such as System 4a (11.0–15.8 GJ/ha) and System 4 (42.9–65.2 GJ/ha), had the smallest input of PE/ha, while the summer-planted, covered and fumigated System 1 on clay soil had the largest, due to bed preparation on heavier soil and crop protection applied to an over-wintered as opposed to spring planted crop, in addition to covers and fumigants. Coir systems needed 136.8–158.6 GJ/ha, a significant factor being their demand for additional nutrients. Primary energy use per tonne of class 1 fruit ranged from 0.6–14.3 GJ/t and was greatly reduced in all soil grown systems when two or three crops were produced (Fig. 2). System 4a was the most energy efficient, followed by Systems 4 and 2 (summer planted) after 2 years.

DISCUSSION

Strawberries may be grown under a variety of different production methods within the UK. They include soil-grown (with or without fumigation), soil-grown under organic production and container-grown (with a peat or coir substrate). With the exception of the organic production systems, crops may be grown with or without cover by a polytunnel. The present report focuses on two environmental burdens, GHG emissions and PE consumption. The former ranged, pre-harvest, from 1.5–10.3 t CO_2

equiv/ha/crop and the latter 11.0–194.0 GJ/ha/crop. For most systems this was significantly greater than crops such as sugar beet (15.7–25.9 GJ/ha, Tzilivakis *et al*. 2005*a*), winter wheat (10.1–23.3 GJ/ha, Hülsbergen & Kalk 2001) and winter oilseed rape (15.8 GJ/ha, Ingram *et al*. 2003), to which mineral N fertilizer manufacture has tended to make the greatest contribution. Soil-grown strawberry crops have a relatively low N requirement in comparison (MAFF 2000). Significant GHG emissions and / or use of PE resulted from the post-extraction use of peat substrate, the manufacture of soil fumigants, LDPE in polytunnel covers and mulch, galvanized steel for tunnel supports and fuel consumed during the delivery of irrigation water. The low input System 4a does not use any of these strategies and as such has GWP_{100} and PE similar to that of arable crops, significantly less than all other systems considered.

System 4a was the only system that did not use a mulch to prevent weed growth but applied additional herbicides during the first year instead. The non-cropping of fruit during year 1 allowed the application of products with longer harvest intervals. The GWP_{100} and PE associated with this herbicide programme were significantly less than for the manufacture of LDPE mulch. It was the only example on sandy soil and while effective on this soil type, crops grown on a clay soil may encounter greater weed populations and require additional herbicide treatments, illustrated in other row crops such as sugar beet (Tzilivakis *et al*. 2005*a*, *b*). The revision of EU Directive 91/414 involves withdrawal of selected herbicide active ingredients, which may alter the effectiveness of agrochemical weed management. An area of land that allows sufficient time between crops to prevent *Verticillium* is also necessary; however, in contrast to the fumigated systems, this system will not be vulnerable to the voluntary withdrawal of chloropicrin as part of Directive 91/414. All other systems used LDPE mulch, the removal of which causes tearing and soil contamination that prevents re-use. Mulch lasts for the lifetime of the beds, 1–3 years. As such, the embodied environmental burdens are reduced significantly per ha with each additional cropping year. System 4 with mulch was also one of the most efficient methods of production, particularly when the yields of three crops were taken into account.

Polytunnels are used to protect crops from frost (in early crops produced out of season) or rainfall during fruit set when damage to the flower causes misshapen fruit (class 2) that most growers stated they did not sell. Tunnels allow production of fruit earlier in the season and the sequential planting of crops. Further, they reduce the risk of the pathogen *Botrytis* and the quantity of fungicide applied (S. Raffle, personal communication). The use of tunnels may be critical in organic systems where chemical treatment of *Botrytis* is not possible. Overall, the covered systems required fewer chemical crop protection interventions since biological control with predatory mites (*Phytoselius*) was also more effective. The materials needed to cover crops make a notable contribution toward the GHG and PE balance of strawberry production. The GWP_{100} and PE/t of class 1 fruit did, however, tend to be lower in covered crops during the first year of production and favourable in container systems that may crop for 1 year only (for example System 7 compared to 8). Systems grown in the open had yield improvements after year 1 such that burdens/t of class 1 fruit were smaller, particularly in year 3. Crops produced in season may be covered (although none of the growers interviewed stated that they did so during the years analysed) in order to protect crops from heavy rainfall, again to reduce the proportion of class 2 fruit. The predicted increase in risk of extreme climatic events, particularly summer storms (Jenkins *et al*. 2007; Murphy *et al*. 2009) may require more frequent covering of crops for this purpose. Covered crops used greater volumes of irrigation water although the impact on fuel use was reduced by many growers extracting 'grey water' from boreholes and reservoirs instead of the mains. Mains water is estimated to use 2.95 MJ/m^3 (Wessex Water Ltd 2004), equivalent to 4.4 and 6.8 GJ/ha/year, in non-covered and covered soil-grown crops, respectively. Soil water sensors offer potential to maximize water use efficiency, decrease fuel used in its application and reduce risk of N leaching and indirect emissions of N_2O beneath the mulch. More widespread adoption is recommended. Use of gutters to collect rainfall run-off from tunnels for subsequent use in irrigation, although currently not widely adopted, would also be beneficial not only to preserve grey water but prevent other environmental impacts such as soil erosion.

Crop protection makes relatively minor contributions to the overall GHG and PE balance in many crops due to small quantities of ai (Hülsbergen & Kalk 2001; Tzilivakis *et al*. 2005*a*, *b*). Soil fumigants applied at 200–400 litres/ha with 0.94–1 ai (Lainsbury 2009) are an exception. Fumigation is necessary where soil-borne pathogens such as *Verticillium* wilt, caused primarily by *V. dahliae* in the UK (Talboys *et al*. 1975), is established. Fumigation with chloropicrin requires 29.8–59.7 GJ/ha to manufacture including packaging, storage and transport (Pimentel 1980; Green 1987). The fuel consumed by its application using a shank is greater than a typical spray due to the number of field passes needed and the slow speed at which the operation occurs (Hunt 1995; Hülsbergen & Kalk 2001). *Verticillium* is able to survive for periods of up to 20 years as either dormant microsclerotia within the soil or through its ability to infect a broad host range, involving weed species, between rotations (Woolliams 1966; Green 1980). Its severity may depend on geographical region and soil type (Talboys *et al*. 1975). Long rotations are usually required to eliminate the need for fumigation (e.g. System 4), but where limited areas of land are available there may be no alternative. Many growers already test the soil for *Verticillium* and target fumigation as necessary, reducing the quantity applied without compromising productivity; this is an important strategy. The voluntary withdrawal of chloropicrin due to the review of EU Directive 94/414 means that infected areas require alternative methods of soil sterilization. Steam sterilization consumes large quantities of diesel (C. Mullins, personal communication) while the effectiveness of biofumigation is currently unproven.

Predicted emissions of N_2O from soil (1.1–3.0 kg N_2O-N/ha) lay within the range attributed to cultivated land by previous studies, from 0.7–2.4 kg N_2O-N/ha/year (Dobbie & Smith 2003), 1.4–3.7 kg N_2O-N/ha/year (Kaiser *et al*. 1998) and 0.99–3.75 kg N_2O-N/ha/year applicable to 0.69 of UK counties (Brown *et al*. 2002). The greatest release (3.0 kg N_2O-N/ha) came from the fallow alleys of systems to which 40 t/ha FYM was applied, since its precise targeting is difficult. Emissions of N_2O from soil in response to FYM application have been assigned to the strawberry crop since the benefit of the N it contains is realized here. Nitrogen from FYM within the alleys (approximately 0.38 of the total applied) is not utilized by the crop and remains within the soil. This results in an increase in nitrification and denitrification (Smith *et al*. 1996; Machefert *et al*. 2002), risk of N leaching and emission of N_2O from soil. The notable yield improvements from FYM increased efficiency through provision of additional K (MAFF 2000) as well as N. The recommendation to apply 25 t/ha FYM made by Lampkin (2004) would reduce the fuel consumed by its application and haulage and in all probability the emission of N_2O from soil within the alleys. The impact on crop yield is unknown, but since the limiting nutrient is likely to be K as opposed to N, the K could be supplemented with, for example, sylvinite (0.24 K_2O). Application of FYM tends to be during the summer pre-planting. This risks greater volatilization of ammonia, a risk that may be mitigated if it is incorporated rapidly into the soil immediately after application (Chambers *et al*. 1999; Moorby *et al*. 2007).

Container crops do not fumigate the soil (although the substrate is fumigated) and tillage operations are less intensive or non-existent compared with soil-grown systems. A further advantage is they can be grown anywhere irrespective of soil quality and presence of pathogens. Container crops typically lasted 1 cropping year and for one crop. Covered coir and peat systems were among the most energy efficient/t class 1 fruit. This was not the case for two crops or for GHG emissions. Container crops do not experience such a large decrease in GWP_{100} and PE with additional cropping years. Further, the extraction of peat causes loss of sequestered C (Choudrie *et al*. 2008) and its use as a substrate is not conducive with minimizing GHG emissions when growing strawberries. Soil-grown strawberry crops need relatively small quantities of N or K (MAFF 2000) in contrast to container crops, particularly those with coir growing media. Coir fibre has a high C to N ratio, between 75:1 and 97:1 (Abad *et al*. 2002) while immobilization that renders N unavailable for uptake by the plant occurs when the C:N ratio is above 25 (Wallace *et al*. 2004). Additional N fertilizer, a product with relatively high embodied GHG emissions (Jenssen & Kongshaug 2003; Brentrup & Pallière 2008), is needed to replace the N that is immobilized.

In summary, compared to arable crops such as cereals and sugar beet, strawberries have a greater GWP_{100} and are more energy intensive due primarily to mulch, tunnels, irrigation and soil fumigants. The most efficient methods of production, taking into account crop yield, were soil-grown and cropped for at least 2 years with efficiency improved further in those systems that cropped for a third year. It is possible to grow strawberries in a low input system if cropped in season (without covers), if there is sufficient land to permit a long rotation and if suitable soil conditions are present. Covering crops allows their early and sequential production but in many cases at a cost of increased GWP_{100} and PE. Class 2 fruit is typically not sold by growers although to do so would reduce the environmental burdens per unit of output of UK grown short-day strawberry crops.

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Table 1. *Description of strawberry production systems: SPNP 2nd: summer planted, non-covered 2nd year; NP 2nd: non-covered 2nd year; NC 1st: no crop 1st year; SP: summer planted; RB/T: raised bed / table), cultivar type (JB = Junebearer, EB = Everbearer), soil type (SCL = sandy clay loam, C = clay, S = sand, PB = peat bag, CB = coir bag), F = fumigation, Cov = covered with a polytunnel, Org = organic. The mean yield of class 1 fruit (t/ha) gives yield range (number of examples) [mean yield ± 1 standard error of the mean] of class 1 fruit. A mean of 2300 and 1550 m^3/ha/year of water was applied to covered and non-covered soil grown crops respectively, 1640 and 1480 m^3/ha/year to covered and non-covered container grown crops with peat respectively and 2200 m^3/ha/year to covered container crops that used coir*

System & soil type	Type	Medium	F	Cov	Org	Mean yield class 1 fruit (t/ha)		
						1st crop	2nd crop	3rd crop
1	JB	SCL	yes	yes	–	8.0–21 (5)[13 ± 2.2]	20–24 (4)[22 ± 0.8]	16–22 (2)[19 ± 3.2]
1	JB	C	yes	yes	–	14–23 (4)[19 ± 2.0]	19–30 (3)[24 ± 3.1]	–
1 (SPNP 2nd)	JB	SCL	yes	1st year only	–	20.0 (2)	12–13 (2)[13 ± 0.5]	–
1 (SPNP 2nd)	JB	C	yes	1st year only	–	27.6	–	–
1 (NP 2nd)	JB	SCL	yes	1st year only	–	8–21 (5)[13 ± 2.2]	17.1	–

2	JB	SCL	yes	–	–	7–10 (4)[8 ± 0.6]	12–20 (4)[16 ± 1.7]	10–11 (2)[10 ± 0.3]
2 (SP)	JB	SCL	yes	–	–	27.0	23.0	–
3	JB	SCL	–	yes	–	18.0	19.0	–
4	JB	SCL	–	–	–	6.4	13.5	13.5
4 (NC 1st)	JB	S	–	–	–	23.8	11.0	–
5 (SP)	JB	SCL	–	yes	yes	11.3	11.3	–
5 (SP) 40 t/ha FYM	JB	C	–	yes	yes	17.0	20.0	–
6 (SP)	JB	SCL	–	–	yes	5.0*	5.0*	–
7 (RB/T)	JB	PB†	–	yes	–	17–21 (4)[19 ± 0.9]	10–8 (2)[19 ± 9.1]	–
8 (RB/T)	JB	PB †	–	–	–	6–8 (2)[7 ± 1.5]	6–16 (2)[11 ± 4.9]	–
9 (T)	JB	CB †	–	yes	–	13–21 (4)[18 ± 1.8]	24.5	–

*Hypothetical yield assumed based on lower yield than System 4

†Bags or tables placed on clay or sandy clay loam soil

Table 2. *Pest and disease programme (product and rate of application per ha) with assumed application dates for each strawberry production system 1st year. Second year covered and non-covered Junebearer crops receive identical programmes to summer planted (SP) Systems 1 and 2 respectively (except Chloropicrin). Alliette is not applied to second year container crops*

System Product	1	1 SP	1 NP 2nd	2	2 SP	3	4	4a NC1st *	5 SP	6 SP	7	8	9
Chloropicrin 200-400 l	Feb	July	Feb	Feb	July	–	–	–	–	–	–	–	–
Aliette 80 WG 3.75 kg	–	02/03	–	–	02/04	–	–	–	–	–	–	–	–
Amistar 0.75 l	14/05	14/04	14/05	06/07	16/06	14/05	06/07	20/06	–	–	14/05	06/07	14/05
Aphox 560 g	14/04	01/04	14/04	14/05	02/05	14/04	14/05	20/06	–	–	14/04	14/05	14/04
	15/05	01/05	15/05	15/06	25/05	15/05	15/06	–	–	–	15/05	15/06	15/05
Apollo 50 SC 400 ml	–	04/04	–	–	04/04	–	–	–	–	–	–	–	–
Calypso 250 ml	14/04	–	14/04	14/04	–	14/04	14/04	–	–	–	14/04	14/04	14/04
Corbel 1 l	–	20/07	–	–	25/07	–	–	–	–	–	–	–	–
	–	04/08	–	–	08/08	–	–	–	–	–	–	–	–
DiPel DF 750 g	14/04	16/04	14/04	14/05	04/05	14/04	14/05	–	–	–	14/04	14/05	14/04
Frupica 0.6 kg	11/05	12/04	11/05	05/07	15/06	11/05	05/07	–	–	–	11/05	05/07	11/05
0.8 kg	20/05	05/05	20/05	–	–	20/05	–	–	–	–	20/05	–	20/05
Majestik 25 l	–	–	–	–	–	–	–	–	14/04	21/05	–	–	–
	–	–	–	–	–	–	–	–	15/05	22/06	–	–	–
Nimrod 1.4 l	28/05	28/05	28/05	15/07	28/06	28/05	15/07	–	–	–	28/05	15/07	28/05

PBI Slug Pellets 15 kg	15/05	15/04	15/05	15/06	25/05	15/05	15/06	–	–	–	15/05	15/06	15/05
Phytoseiulus 5-25K	16/04	16/04	16/04	02/06	02/06	16/04	02/06	–	16/04	16/05	16/04	02/06	16/04
Plenum WG 0.4 kg	–	15/03	–	–	15/03	–	–	–	–	–	–	–	–
Signum 1.8 kg	–	–	–	12/06	22/05	–	12/06	–	–	–	–	12/06	–
	–	–	–	26/06	05/06	–	26/06	–	–	–	–	26/06	–
Stroby WG 0.3 kg	04/05	05/04	04/05	–	–	04/05	–	–	–	–	04/05	–	04/05
Systhane 20EW	28/04	28/03	28/04	05/06	15/05	28/04	05/06	–	–	–	28/04	05/06	28/04
230 ml	18/05	19/04	18/05	19/06	29/05	18/05	19/06	–	–	–	18/05	19/06	18/05
Teldor 1.5 kg	28/04	28/03	28/04	15/06	28/06	28/04	15/06	–	–	–	28/04	15/06	28/04
	18/05	19/04	18/05	–	–	18/05	–	–	–	–	18/05	–	18/05
	28/05	28/04	28/05	–	–	28/05	–	–	–	–	28/05	–	28/05
Thianosan 2 kg	–	15/03	–	–	15/03	–	–	–	–	–	–	–	–

*4aNC1st (2nd year) (No Crop 1st year): Draza (5 kg) 14/05; Dursban (1 l) 24/04; Unicrop Thianosan 1.5 kg 02/05 & 13/05; Frupica (0.6 kg) 21/05; Plenum WG (0.4 kg) 02/10; Scala (2 l) 11/06; Teldor (1.5 kg) 30/05

Formulations: Chloropicrin (995 g/kg); Aliette 80 WG (fosetyl-aluminium 800 g/kg); Amistar (azoxystrobin 250 g/l); Aphox (pirimicarb 500 g/kg); Apollo 50 SC (clofentezine 500 g/l); Calypso (thiacloprid 480 g/l); Corbel (fenpropimorph 750 g/l); DiPel DF (*B. thuringiensis* 64 g/kg); Frupica (mepanipyrim 500 g/kg); Majestik (plant extract 100 g/kg); Nimrod (bupirimate 250 g/l); PBI Slug Pellets (metaldehyde 30 g/kg); Plenum WG (pymetrozine 500 g/kg); Scala (pyrimethanil 400 g/l); Signum (boscalid 267 g/kg and pyraclostrobin 67 g/kg); Stroby WG (kresoxim methyl 500 g/kg); Systhane 20EW (myclobutanil 200 g/l); Teldor (fenhexamid 500 g/kg); Thianosan (thiram 800 g/kg).

Table 3. *Herbicide programme with assumed application dates for each strawberry production system 1st year. Second year Junebearer crops receive identical programmes to summer planted Systems 1 and 2*

System	1	1	1	2	2	3	4	4a	5	6	7	8	9
Product		SP	NP 2nd		SP			NC 1st *	SP	SP			
Alpha propachlor 5 l	–	–	–	–	–	–	–	03/04	–	–	–	–	–
	–	–	–	–	–	–	–	19/05	–	–	–	–	–
Beetup 2.5 l	–	–	–	–	–	–	–	01/05	–	–	–	–	–
	–	–	–	–	–	–	–	12/05	–	–	–	–	–
	–	–	–	–	–	–	–	19/05	–	–	–	–	–
	–	–	–	–	–	–	–	30/05	–	–	–	–	–
Dacthal 5 kg	–	15/10	–	–	15/10	–	–	03/04	–	–	–	–	–
	–	–	–	–	–	–	–	19/05	–	–	–	–	–
Dacthal 4.6 l	–	15/12	–	–	15/12	–	–	–	–	–	–	–	–
Flexidor 125 1 l	15/03	–	15/03	15/03	–	15/03	15/03	–	–	–	15/03	15/03	15/03
Laser 1 l	–	–	–	–	–	–	–	03/06	–	–	–	–	–
Partna 1.25 l	–	–	–	–	–	–	–	03/06	–	–	–	–	–
Ramrod Flowable 5 l	–	15/10	–	–	15/10	–	–	–	–	–	–	–	–
Stomp 400 SC 3.5 l	15/03	–	15/03	15/03	–	15/03	15/03	–	–	–	15/03	15/03	15/03

*4aNC1st (year 2): Devrinol (4.6 l) 03/03; Flexidor 125 (1 l) 13/12; Laser (2.25 l) 11/04 & 14/06; PDQ (5.5 l) 17/07; Stomp 400 SC (3.5 l) 13/12.

Formulations: Alpha propachlor (propachlor 500 g/l); Beetup (phenmedipham 114 g/l); Dacthal (chlorthal-dimethyl 750 g/kg); Devrinol (napropamide 450 g/l); Flexidor 125 (isoxaben 125 g/l); Laser (cycloxydim 200 g/l); Partna (alkylphenol ethoxylate 100 g/kg): PDQ (paraquat + diquat 80:120 g/l): Ramrod Flowable (propachlor 480 g/l): Stomp 400 SC (pendimethalin 400 g/l).

Table 4. *Energy consumption (MJ/ha) for field operations derived from method described in Hunt (1995) with additional data for proportion field efficiency (FE) to account for refuelling or filling (Donaldson* et al. *1994)*

Operation	Implement	Width (m)	Force (kN/m)	Power (kW)	Speed (km/h)	Time (h/ha)	FE	Energy (MJ/ha)
shallow cultivations (light soils)	spike toothed harrow	3	0.60	60	8	0.4	0.85	164
shallow cultivations (heavy soils)	field cultivator	3	2.65	75	7	0.5	0.85	253*
rotary hoe	row cultivator (shallow)	6	0.90	65	7	0.2	0.85	102
mow	mower (cutter bar)	1	1.10	65	8	0.8	0.85	333†
bed formation	field cultivator	1	2.65	75	6	1.0	0.85	513†
lay mulch and T-tape	field cultivator equivalent	1	2.65	75	4	1.6	0.85	769†
grub	spring toothed harrow	1	2.70	75	4	2.5	0.85	601‡
fumigation	shank	1	0.60	60	3	2.1	0.80	872†

*two passes of a field cultivator (506 MJ/ha) required to create a seedbed on heavy (clay) soil, one pass on sandy clay loam soil.

†beds only (62.5 beds/ha).

‡beds only (62.5 beds/ha), includes mulch removal. System 4 (no crop 1st year) with no mulch forward speed 7 km/h (344 MJ/ha).

Table 5. *Nutrition regime (kg/ha)*

Scenario	N	P	K	MgO
1	40*	17.4	66.4	50
1 (SP)	40*	17.4	66.4	50
1 (NC 2nd)	40*	17.4	66.4	50
2	40*	17.4	66.4	50
2 (SP)	40*	17.4	66.4	50
3	40*	17.4	66.4	50
4	40*	17.4	66.4	50
4a (NC 1st)	63†	17.4	66.4	50
5 (SP)	60 (240) ‡ / 0	61 (102) / 0	347 (386) / 0	0
6 (SP)	0	0	0	0
7	102*	36.6	93	50
8	102*	36.6	93	50
9	177*	40.1	272	65

*0.25 ammonium nitrate: 0.75 potassium nitrate applied via fertigation and 0 kg N/ha as a base dressing pre-planting.

†ammonium nitrate

‡40 t/ha FYM. N available to crop (total N input) Scenario 5 and 6 applied 27 July.

Table 6. *Chemical composition of fertilizer products and media, and energy and GWP for their manufacture (Brentrup & Pallière 2008; Jenssen & Kongshaug 2003) excluding 1.3 MJ/kg packaging and transport (Kaltschmidt & Reinhardt 1997) unless stated otherwise*

Product	**Composition**	**Energy (MJ)**	**GWP_{100} (t CO_2 equiv)**
ammonium nitrate	0.345 N	13.5 MJ/kg product	0.00217/kg product
ammonium sulphate	0.21 N; 0.6 SO_3	6.0 MJ/kg product	0.00034/kg product
potassium nitrate	0.13 N; 0.45 K_2O (K_2O: 0.83 K)	11.3 MJ/kg product	0.00197/kg product
seaweed meal	0.13 N; 0.25 K_2O	2.0* MJ/l product	
triple superphosphate	0.48 P_2O_5 (P_2O_5: 0.436 P)	6.4 MJ/kg product	0.00035/kg product
sulphate of potash	0.5 K_2O; 0.45 SO_3	1.4 MJ/kg product	0.0001/kg product
magnesium sulphate	0.16 MgO (MgO: 0.6 Mg); 0.33 SO_3	2.5† MJ/kg product	
coir		3.05‡ MJ/kg dry	
peat		0.02§ MJ/kg dry	

*0.5 MJ/kg washing & shredding, 1.25 MJ/kg dried by 0.25 (50 MJ/t/0.1 mc, Daalgard *et al.*, 2001), 1.3 MJ/kg packaging and transport (Kaltschmidt & Reinhardt 1997), bulk density 0.7 kg/l (Richards 2001).

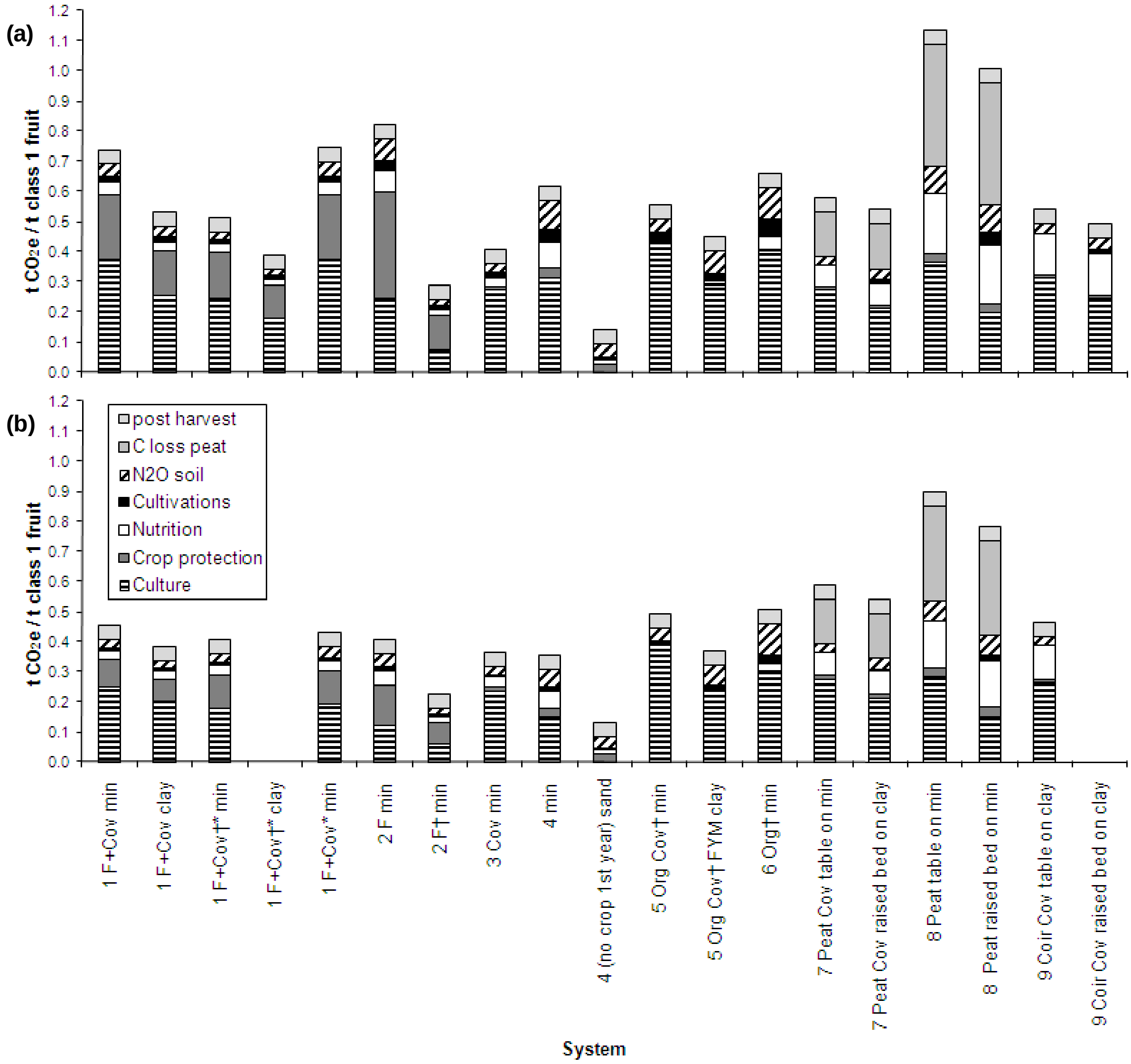
†mineral extraction 0.8 MJ/kg (Jenssen & Kongshaug 2003), packaging and transport 1.3 MJ/kg (Kaltschmidt & Reinhardt 1997) plus estimate for processing.

‡1.56 kg/m growbag when dry, sterilization with chloropicrin (full rate) 0.13 MJ/kg dry, transport 2 km to storage and packaging area 0.2 l t/km (Daalgard *et al*. 2001), shipped 8711 km from Sri-Lanka 0.006 kg CO_2e/t/km (DEFRA 2009b; two journeys within UK port to supplier to grower, of 114 km each (average haulage distance by road for 'crude materials ', National Statistics 2009) by 38 t gross weight truck 0.086 kg CO_2e/t/km (DEFRA 2009b).

§ extraction needed 0.001 MJ/kg, and transport when dry and weighing 0.4 t/m (Lindström 1980) required 0.2 l/t/km (Daalgard *et al.* 2001) for an average distance of 2 km to the storage and packaging area; 0.5 imported from Ireland, 0.5 extracted North and West of England; transport within and from Ireland assumed 124 km by road and 150 km by ship, transport within the UK as two journeys 124 km each by 38 t gross weight truck 0.086 kg CO_2e/t/km (DEFRA 2009b).

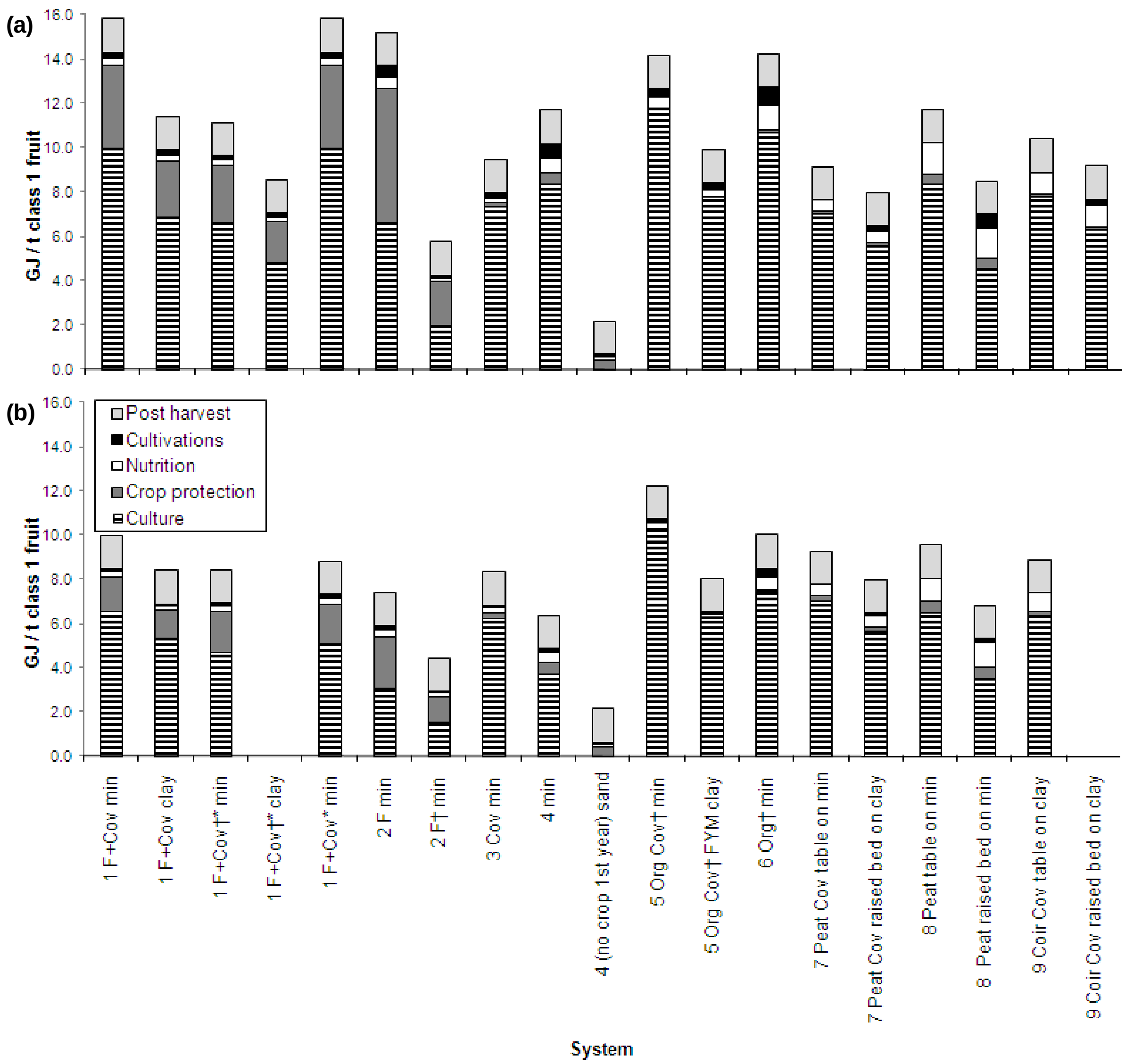
Fig. 1. Greenhouse gas emissions (t CO_2 equiv) per tonne of class 1 fruit for each production system (inclusive of post harvest operations) after (*a*) 1 and (*b*) 2 years of cropping. F = fumigated, Cov = covered with a polytunnel, †summer planted, *no cover year two. Total emissions (t CO_2 equiv) per tonne of class 1 fruit after 3 years of cropping (in brackets): system 1 F+Cov min (0.41), system 2 F min (0.37) and system 4 min (0.30).

Fig. 2. Input of energy (GJ) per tonne of class 1 fruit for each production system (inclusive of post harvest operations) after (*a*) 1 and (*b*) 2) years of cropping. F = fumigated, Cov = covered with a polytunnel, †summer planted, *no cover year two. Total energy (GJ) per tonne of class 1 fruit after 3 years of cropping 1 F+Cov min (7.49), 2 F min (5.05) and 4 min (3.85).



(a)
(b)
t CO2e / t class 1 fruit
post harvest
C loss peat
N2O soil
Cultivations
Nutrition
Crop protection
Culture
1 F+Cov min
1 F+Cov clay
1 F+Cov†* min
1 F+Cov†* clay
1 F+Cov* min
2 F min
2 F† min
3 Cov min
4 min
4 (no crop 1st year) sand
5 Org Cov† min
5 Org Cov† FYM clay
6 Org† min
7 Peat Cov table on min
7 Peat Cov raised bed on clay
8 Peat table on min
8 Peat raised bed on min
9 Coir Cov table on clay
9 Coir Cov raised bed on clay
System

Fig. 1.



(a)
(b)
GJ / t class 1 fruit
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Post harvest
Cultivations
Nutrition
Crop protection
Culture
1 F+Cov min
1 F+Cov clay
1 F+Cov† min
1 F+Cov†* clay
1 F+Cov* min
2 F min
2 F† min
3 Cov min
4 min
4 (no crop 1st year) sand
5 Org Cov† min
5 Org Cov† FYM clay
6 Org† min
7 Peat Cov table on min
7 Peat Cov raised bed on clay
8 Peat table on min
8 Peat raised bed on min
9 Coir Cov table on clay
9 Coir Cov raised bed on clay
System

Fig. 2.