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Geographical variation in carbon dioxide fluxes from soils in agro-ecosystems and its implications for life-cycle assessment

Georgia R. Koerber[1]*, Gareth Edwards-Jones[1], Paul W. Hill[1], Llorenç Milà i Canals[2], Philip Nyeko[3], Elizabeth H. York[1] and Davey L. Jones[1]

[1]*School of the Environment and Natural Resources, Bangor University, Gwynedd LL57 2UW, UK;* [2]*Centre for Environmental Strategy, University of Surrey, Guildford GU2 7XH , Surrey, UK; and* [3]*Department of Forest Biology and Ecosystems Management, Makerere University, PO Box 7062, Kampala, Uganda*

Summary

1. Exchange of carbon dioxide (CO_2) from soils can contribute significantly to the global warming potential (GWP) of agro-ecosystems. Due to variations in soil type, climatic conditions and land management practices, exchange of CO_2 can differ markedly in different geographical locations. The food industry is developing carbon footprints for their products necessitating integration of CO_2 exchange from soils with other CO_2 emissions along the food chain. It may be advantageous to grow certain crops in different geographical locations to minimize CO_2 emissions from the soil, and this may provide potential to offset other emissions in the food chain, such as transport.

2. Values are derived for the C balance of soils growing horticultural crops in the UK, Spain and Uganda. Net ecosystem production (*NEP*) is firstly calculated from the difference in net primary production (*NPP*) and heterotrophic soil respiration (R_h). Both *NPP* and R_h were estimated from intensive direct field measurements. Secondly, net biome production (*NBP*) is calculated by subtracting the crop biomass from *NEP* to give an indication of C balance. The importance of soil exchange is discussed in the light of recent discussions on carbon footprints and within the context of food life-cycle assessment (LCA).

3. The amount of crop relative to the biomass and the R_h prevailing in the different countries were the dominant factors influencing the magnitude of *NEP* and *NBP*. The majority of the biomass for lettuce *Lactuca sativa* and vining peas *Pisum sativum*, was removed from the field as crop; therefore, *NEP* and *NBP* were mainly negative. This was amplified for lettuces grown in Uganda (–16·5 and –17 t C ha^{-1} year^{-1} compared to UK and Spain –4·8 to 7·4 and –5·1 to 6·3 t C ha^{-1} year^{-1} for *NEP* and *NBP*, respectively) where the climate elevated R_h.

4. *Synthesis and applications.* This study demonstrates the importance of soil emissions in the overall life cycle of vegetables. Variability in such emissions suggests that assigning a single value to food carbon footprints may not be adequate, even within a country. Locations with high heterotrophic soil respiration, such as Spain and Uganda (21·9 and 21·6 t C ha^{-1} year^{-1}, respectively), could mitigate the negative effects of climate on the C costs of crop production by growth of crops with greater returns of residue to the soil. This would minimize net CO_2 emissions from these agricultural ecosystems.

Key-words: carbon balance, carbon dioxide exchange, heterotrophic soil respiration, net biome production, net ecosystem production, net primary production, soil respiration, vegetable

Introduction

Over the course of agricultural development, forests and grasslands have been extensively converted to arable land for farming. As a consequence, carbon (C) has been released to the atmosphere as carbon dioxide (CO_2) by processes such as burning, removing biomass, and disturbance of soil. Changes in land use have been estimated to release 156 Pg C to the atmosphere over the period 1850–1990, about half as much as those released from combustion of fossil fuels over the same

*Correspondence author. E-mail: g.koerber@internode.on.net

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period (Houghton 2003). Soils accounted for about a quarter of the long-term global release, although the fraction was higher in temperate-zone regions than in the tropics (Houghton 2003). Because soils can constitute a significant reservoir of terrestrial C, their effective management offers large potential for greenhouse gas mitigation. According to Land-use, Land-use Change, and Forestry (LULUCF) projects under the Kyoto Protocol (KP), soils deserve close examination for their sustainable management (Watson & Intergovernmental Panel on Climate Change 2000; Garcia-Oliva & Masera 2004). Improved terrestrial management over the next 50–100 years could sequester up to 150 Pg of carbon, the amount released to the atmosphere between 1850 and 1990 (Lal 1995).

UK imports of food have increased by 10% since 1961 and now represent 28 million tonnes annually. For some food types, the increase has been more dramatic. Imports of fruit have doubled and imports of vegetables have tripled. Half of all vegetables and 95% of all fruit consumed in the UK now come from overseas (Smith *et al.* 2005). Transportation of food by air has the highest CO_2 emissions per tonne, and is the fastest growing mode of food importation. Although air freight of food accounts for only 1% of food tonne kilometres and 0·1% of vehicle kilometres, it produces 11% of the food transport CO_2 equivalent emissions (Smith *et al.* 2005). The fuel used to import food and drink to the UK accounts for 2·5% of total annual UK CO_2 emissions or 0·001 Pg C year^{-1} (Pearce 2006).

Environmental concern about the emission of CO_2 from vegetables delivered to the UK by air and other means is offset by the convenience of supply beyond the UK growing season. There are also economic trade agreements and positive sociological benefits from trading with EU and Third World countries. An aspect which has been overlooked is that overseas countries supplying the UK typically have contrasting climates and dissimilar farming practices which may produce CO_2 emissions different to those of the UK. Consequently, it is vital to determine on-farm CO_2 emissions from within each of the different supply countries to produce an unbiased C balance comparison. There is increasing interest from retailers, industry and environmental regulators, plus initiatives in the UK, France and Germany to assess the life-cycle greenhouse gas emissions and express them per unit of product (PAS-2050 2008). The PAS-2050 excludes exchange of CO_2 from soil except for land-use change and thus is potentially fundamentally flawed.

The aim of this study was to determine C budgets for soils growing vegetables in three contrasting geographical locations (UK, Spain and Uganda), all of which supply the UK market. The difference between CO_2 emitted from and taken up into the soil over the course of a year is net ecosystem production (*NEP*) (Woodwell & Whittaker 1968). When *NEP* is positive, net sequestration of C into the ecosystem has occurred making it a 'C sink'. If *NEP* is negative, then there has been a net emission of CO_2 and the ecosystem is a 'C source'. A further calculation is of net biome production (*NBP*) (Schulze *et al.* 2000), which is *NEP* minus non-respiratory losses such as harvest. *NBP* is also termed as a rate of C sequestration (Hu *et al.* 2004). The null hypothesis of this study was that *NEP* and *NBP* do not differ significantly between the UK, Spain and Uganda.

Materials and methods

LOCATIONS

The sites were chosen as part of a large project investigating the issue of local versus overseas food production (see Edwards-Jones *et al.* 2008 for further details of the project). Soil properties and climate for locations in the UK, Uganda and Spain are shown in Table 1.

Within the UK, data were collected from commercial farms located across a production gradient and included large-scale farms in Lincolnshire, medium-scale farms in Worcestershire and small-scale farms in Anglesey.

Within Uganda, data were collected from farms located in the districts of: Wakiso, approximately 5 km west from Kampala; Mukono, approximately 20 km east from Kampala; and Luwero approximately 50 km north from Kampala. The rainfall regime allows two cropping seasons, February to July and August to December. All farms are mainly subsistence, supplying local markets and co-operatives supplying overseas markets.

Within Spain, data were collected from farms within the Murcia region of south-eastern Spain. All farms are established exporters to the UK. The growing season is from October to February, carrying on from the UK growing season. Most fields are bare from March until October with regular irrigation undertaken in the growing season.

FIELD SAMPLING

Crops studied were broccoli, purple sprouting broccoli, cabbages and Brussels sprouts *Brassica oleracea* L.; (collectively Brassicas), lettuces *Lactuca sativa* L., vining peas *Pisum sativum* L., French beans *Phaseolus vulgaris* L., wheat *Triticum aestivum* L., potatoes *Solanum tuberosum* L., sugar beet *Beta vulgaris* L. and rye grass *Lolium perenne* L. (temporary pasture). In Uganda, a local bean (Sim beans, *Phaseolus vulgaris* L.) was also studied (details in Table 1).

Approximately 20 fields in each location were sampled monthly from July 2005 until September 2006. The random stratified approach described by Webster & Oliver (1990) was adopted to reduce bias. The first level of stratification involved random selection of fields from the farmers' cropping allocation plans. The second level of stratification involved randomly selecting a 25 × 25 m plot within each field by gridding fields shown on 1 : 25 000 scale maps. To test within plot variation, nine measurements of soil respiration and soil temperature were recorded from July to November 2005. Soil respiration coefficients of variation (CV) ranged from 0·01–0·63. From December 2005 onwards, four measurements per plot produced similar CV values ranging from 0·004 to 0·66. The CV of extra plots measured within the same field were 0·21–0·59 in Lincolnshire during October 2005, 0·1–0·66 in February 2006 and 0·25–0·65 in March 2006, and in Worcestershire measurements were 0·11–0·5 in October 2005 and 0·01–0·63 in November 2005. As the CVs were similar, efforts were directed towards measuring more independent fields of each crop.

Soil respiration measurements were taken at various times during the day between 08·00 and 18·00 h, using an infrared gas analyzer

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Table 1. Summary of the crop types, soil properties and climate at each monitoring location. *n* indicates the number of fields sampled. Soil information is from FitzPatrick (1983). The climate data for each location were sourced from the UK MetOffice (2008), Sonko *et al.* (2005), Mubiru *et al.* (2007) and ISHS (2007)

Location	*n*	Crop type	Soil type	Soil texture	Mean daily temperature (°C)	Annual rainfall	Sunshine hours
UK							
Lincolnshire	5	Lettuces	Eutric Fluvisols	Silt loam and lilty clay loam	–2·1 to 8·8 during winter and 10·6 to 23·4 during summer	< 700 mm	1450
	5	Broccoli and cabbages					
	5	Vining peas					
	5	Wheat					
	5	Potatoes					
	5	Sugar beet					
Worcestershire	6	Lettuces	Eutric Cambisols and Eutric Gleysols	Loamy sand, loam and silty clay	–2·8 to 9·8 during winter and 13 to 26·1 during summer	< 600 mm	1550
	5	Purple sprouting broccoli					
	6	Vining peas					
	6	French beans					
	6	Wheat					
	6	Potatoes					
	6	Sugar beet					
Anglesey	5	Broccoli and Brussels sprouts	Eutric Cambisols	Loam	–0·6 to 10·7 during winter and 12·3 to 24·2 during summer	> 800 mm	1600
	5	Potatoes					
	5	Wheat					
	5	Temporary pasture					
Uganda	5	Lettuces	Rhodic Ferralsols	Sandy loam, sandy clay loam, loam and silt loam	Tropical, means ranging between 15 to 30 year round	750–2000 mm	> 1900
	10	Cabbages					
	4	French beans					
	4	Sim beans					
Spain	11	Lettuces	Haplic Calcisols	Silt loam, silty clay loam, clay loam, sandy loam and silty clay	Means of 11 in winter and 23 in summer	250–600 mm	> 2800
	10	Broccoli					

EGM-4 with a SRC-1 soil chamber attached (PP Systems Ltd, Hitchin, UK). To account for diurnal variation, a temperature correction algorithm (Parkin & Kaspar 2003) was used to calculate daily fluxes which were subsequently scaled to monthly fluxes (equation 1).

$$\text{Daily } CO_2 \text{ flux} = R \times Q^{(DMT-T)/10}, \qquad \text{eqn 1}$$

where *R* is the measured CO_2 flux at a specific hour, *DMT* is the daily mean temperature, *T* is the temperature at the time the flux was measured, and *Q* is the Q_{10} factor = 2. Annual soil respiration (SR) was estimated by calculating the areas under the curve of SR plotted monthly for every field.

PLANTS AND SOIL

From July to November 2005, five plant and soil samples were collected from each plot. As intra-field variability was negligible, sample numbers were reduced to three from December 2005 onwards. At least 20 fields in each location were sampled each month equating to 60 plant and soil samples per month in Anglesey, Lincolnshire and Worcestershire. Plants from each plot were separated into roots and shoots, and subsequently dried at 80 °C to calculate dry weight. Their C content was determined with a Leco CHN 2000 analyser (Leco Corp., St Joseph, MI, USA). On average, the biomass C content of the vegetables was 35%, similar to that reported by Hadley & Causton (1984).

Soils collected monthly at 0–10 cm depth from each plot were dried at 105 °C for 24 h to determine moisture content while loss on ignition at 450 °C was undertaken to determine soil organic matter (SOM) content. A correction factor of 1·724 was used to estimate soil organic C (SOC) from SOM (Nelson & Sommers 1996). In addition, soils collected at the start of the growing season from all locations were analysed for SOC with a Leco CHN 2000 analyser. Due to their calcareous nature, the Spanish soils were pre-treated with HCl fumes to remove inorganic C prior to SOC determination (Harris *et al.* 2001).

CARBON BALANCE

The difference between the sum of the C inputs and outputs (*NEP*) can be calculated by combining equations 2 and 3 to get equation 4 (Woodwell & Whittaker 1968; Melillo *et al.* 1995):

$$NEP = GPP - R_a - R_h \qquad \text{eqn 2}$$

$$\text{since } GPP = NPP + R_a \qquad \text{eqn 3}$$

$$NEP = NPP - R_h, \qquad \text{eqn 4}$$

where *GPP* is gross primary production or total C fixed by photosynthesis; R_a is autotrophic respiration (respiration dependent upon living plants); R_h is heterotrophic respiration (respiration not dependent upon living plants) and *NPP* is net primary production, which is the net C gain by vegetation over a particular time period.

NPP was calculated according to equations 5–8 (Raich & Nadelhoffer 1989; Nadelhoffer *et al.* 1998; Clark *et al.* 2001). The assumptions are that SOC, fine root biomass and coarse root biomass are close to steady state, such that if litter fall is the only significant above-ground source of C, then subtracting the litter fall

C from the C respired from the soil provides an estimate of below-ground C allocation by the plants (BGCA).

$$R_h \approx P_a + P_b, \quad \text{eqn 5}$$

where heterotrophic soil respiration is the sum of above-ground detritus production (P_a) and below-ground detritus production (P_b).

Soil respiration is the sum of heterotrophic respiration and root respiration (R_{roots}), equation 6:

$$SR = R_h + R_{roots}. \quad \text{eqn 6}$$

Combining equations 5 and 6 and rearranging:

$$SR - P_a \approx P_b + R_{roots}. \quad \text{eqn 7}$$

Therefore, BGCA ($P_b + R_{roots}$) can be estimated from the difference in annual soil respiration and above-ground detritus production, equation 7. Then adding ABCA gives *NPP*, equation 8:

$$NPP = \text{ABCA} + \text{BGCA}. \quad \text{eqn 8}$$

Heterotrophic soil respiration was estimated for locations in the UK, Spain and Uganda from the y-intercept of regressions of soil respiration against plant biomass (Kucera & Kirkham 1971; Kuzyakov 2006) and direct measurements of soil respiration from bare (non-vegetated) plots. The y-intercept approach was used for locations in Uganda and Spain when there was sufficient biomass; otherwise, soil respiration from bare plots was used as the estimate of R_h.

STATISTICAL ANALYSIS

Annual daily mean temperature (DMT), soil temperature (ST), moisture content (MC) and soil respiration (SR) were analysed with a univariate analysis of variance. The dependent variable was natural logarithm (SR – 1·5) in order for SR to fit a normal distribution. Location and crop were specified as fixed factors. Month, DMT, ST, and MC were specified as covariates.

Annual soil respiration (SR), net primary production (*NPP*), net ecosystem production (*NEP*), net biome production (*NBP*) and soil organic carbon (SOC) were analysed with nonparametric Mann–Whitney tests. All statistical analyses were performed in SPSS version 15 (SPSS Inc., Chicago, IL, USA).

Results

MONTHLY TEMPERATURES, MOISTURE CONTENT AND SOIL RESPIRATION

In the UK, the maximum DMT of 24·6 °C occurred at Worcestershire in July 2006 (see Supporting Information, Fig. S1a). Respective mean ST, MC and SR for vegetable fields were 21·3 °C, 11·7% and 2·61 t C ha^{-1} for Brassicas; 20·2 °C, 14·5% and 3·64 t C ha^{-1} for lettuces; 24·3 °C, 11·0% and 1·29 t C ha^{-1} for vining peas; and 23·9 °C, 10·9% and 2·21 t C ha^{-1} for French beans (see Supporting Information, Fig. S1a–c). UK minimum DMT of 1·4 °C occurred at Worcestershire in March 2006. Respective means were 2·3 °C, 11·4% and 0·33 t C ha^{-1} for Brassicas; 4·5 °C, 13·1% and 0·15 t C ha^{-1} for lettuces; 4.8 °C, 16·8% and 0·28 t C ha^{-1} for vining peas; and 3·3 °C, 10·8% and 0·21 t C ha^{-1} for French beans (see Supporting Information, Fig. S1a–c).

In Spain, maximum DMT of 27·8 °C occurred in August 2006 (see Supporting Information, Fig. S1a). Respective mean ST, MC and SR were 30·0 °C, 4·2% and 1·4 t C ha^{-1} for Brassicas and 32 °C, 3·9% and 0·75 t C ha^{-1} for lettuces. Minimum DMT of 7·8 °C occurred in January 2006 (see Supporting Information, Fig. S1a). Respective means were 6·6 °C, 20·6% and 1·87 t C ha^{-1} for Brassicas and 8·1 °C, 16·7% and 1·15 t C ha^{-1} for lettuces (see Supporting Information, Fig. S1a–c).

In Uganda, maximum and minimum DMT were similar, being 24 °C and 22 °C, respectively (see Supporting Information, Fig. S1a). Mean monthly ST, MC and SR were 24·3 °C, 25·4% and 2·81 t C ha^{-1} for Brassicas; 24·6 °C, 24·4% and 2·79 t C ha^{-1} for lettuces; 24·8 °C, 21·8% and 2·82 t C ha^{-1} for French beans; and 26·0 °C, 15·3% and 3·44 t C ha^{-1} for Sim beans, respectively.

PREDICTORS OF SOIL RESPIRATION

In a univariate analysis of SR, covariates, DMT, ST, MC and month were sufficient predictors over all of the locations and crops included in this study (model $r^2 = 0{\cdot}181$, $P < 0{\cdot}001$, Table 2). There were no significant differences in SR across all crops between locations. Across all locations, SR in Sim bean fields in Uganda (mean = 3·32 t C ha^{-1} $month^{-1}$) and temporary pasture in Anglesey (mean = 2·73 t C ha^{-1} $month^{-1}$), although not significantly different from each other, were both significantly higher compared to most other crop means (Brassicas = 1·58 $P = 0{\cdot}021$ and 0·001, lettuces = 1·41 $P = 0{\cdot}052$ and 0·008, vining peas = 1·22 $P = 0{\cdot}093$ and 0·029, French beans = 1·60 $P = 0{\cdot}072$ and 0·043, and wheat = 1·47 t C ha^{-1} $month^{-1}$ $P = 0{\cdot}085$ and 0·013 for Sim beans and temporary pasture, respectively).

HETEROTROPHIC SOIL RESPIRATION

Annual R_h for the UK was estimated to be 8·13 t C ha^{-1} $year^{-1}$, compared to 21·59 and 21·91 t C ha^{-1} $year^{-1}$ in Uganda and Spain (Table 3). For Uganda, data were collected for 10 months, and therefore were scaled by 12 : 10 to give an annual estimate. For Spain, the majority of fields are bare from April to July 2006; therefore, the average of soil respiration from bare fields was used as an estimate of R_h. The y-intercept approach was applied to give R_h of 5·47 t C ha^{-1} for January 2006.

SOIL CARBON EXCHANGE

BGCA and root biomass were significantly related for crops in the UK (Fig. 1). *NEP* was similar across all locations, both within and outside the UK for some crops, while for others, there were differences (Fig. 2). Wheat grown in Anglesey, Lincolnshire and Worcestershire behaved similarly with *NEP*s of 10·8, 7·2 and 6·7 t C ha^{-1} $year^{-1}$, respectively. *NEP*s for vining peas were also similar in Lincolnshire and in Worcestershire

Table 2. Univariate ANOVA. The dependent variable was natural logarithm (soil respiration – 1·5). (a) $r^2 = 0{\cdot}181$ (adjusted $r^2 = 0{\cdot}103$). Location and crop were specified as fixed factors. Month, daily mean temperature, soil temperature and moisture content were specified as covariates. Number of replicates in Anglesey, Lincolnshire, Spain, Uganda and Worcestershire were 83, 41, 37, 75 and 63, respectively. Number of replicates of Brassicas, French beans, lettuce, potatoes, Sim beans, sugar beet, temporary pasture, vining peas and wheat were 101, 16, 58, 26, 16, 5, 25, 19 and 33, respectively. Months were July 2005, August 2005, October 2005–October 2006, and December 2006

Variable	Type^{III} SS	d.f.	Mean square	*F* value	*P*
Corrected model	88·1 (a)	26	3·4	2·3	< 0·001
Intercept	13·7	1	13·7	9·3	0·002
Daily mean temperature	25·6	1	25·6	17·5	< 0·001
Soil temperature	10·1	1	10·1	6·9	0·009
Moisture content	4·2	1	4·2	2·8	0·093
Month	1·7	1	1·7	1·2	0·277
Location	8·2	4	2·0	1·4	0·235
Crop	20·0	8	2·5	1·7	0·097
Location × crop	21·3	10	2·1	1·5	0·157
Error	398·4	272	1·5		
Total	509·5	299			
Corrected total	486·5	298			

Table 3. Heterotrophic soil respiration (R_h) in the UK, Uganda and Spain. For the UK, annual rate is the sum of a 12-month period from October 2005 to September 2006. For Uganda, data were collected for 10 months, and therefore scaled by 12 : 10 to give an annual estimate. r^2 and *P* are the coefficient of determination and probability, respectively, from linear regressions. *n* is the number of values

	UK (t C ha^{-1})				Uganda (t C ha^{-1})				Spain (t C ha^{-1})			
Month	R_h	r^2	*P*	*n*	R_h	r^2	*P*	*n*	R_h	r^2	*P*	*n*
July 2005	1·13	0·41	0·05	10								
August 2005	0·83	0·25	< 0·01	35								
October 2005	1·35	0·34	0·01	19								
November 2005	0·02	0·41	0·12	7								
December 2005	0·16	0·02	0·78	7								
January 2006	0·13	0·40	0·37	4					5·47	< 0·0112	0·21	15
February 2006	0·17	0·39	0·03	12	6·29	0·00	0·98	5				
March 2006	0·55	0·80	< 0·01	8								
April 2006	0·21	0·66	0·03	7	2·38	0·34	0·05	12	3·68			21
May 2006	0·54	0·56	0·00	48								
June 2006	1·48	0·13	0·03	38	3·06	0·43	0·05	9	2·06			20
July 2006	0·97	0·14	0·01	47								
August 2006	1·42	0·00	0·88	46	1·76	0·43	0·02	12	0·78			20
September 2006	1·13	0·15	0·01	45								
October 2006					4·50	0·43	0·04	10	5·46			9
December 2006									4·46			5
Annual	8·13				21·59				21·91			

(–4·1 and –2·8 t C ha^{-1} year^{-1}, respectively). There was a range of *NEP* for Brassicas such that Anglesey was negative at –4·5 t C ha^{-1} year^{-1}, while Lincolnshire, Spain, Uganda and Worcestershire were positive at 1·7, 3·8, 7·6 and 9·0 t C ha^{-1} year^{-1}, respectively. Only for lettuces was there a clear difference between *NEP* values for production inside and outside the UK. Lincolnshire and Worcestershire were similarly negative at –4·8 and –7·3 t C ha^{-1} year^{-1}, respectively, Uganda was more negative at –16·5 t C ha^{-1} year^{-1}, while Spain was positive at 7·4 t C ha^{-1} year^{-1}.

NEP for lettuce fields tended to be more negative than for other crops grown in the same location, with the exception of Spain (Table 4). Other significant trends were that *NEP* of Brassicas, wheat and sugar beet from Lincolnshire (1·7, 7·2 and 8·7 t C ha^{-1} year^{-1}, respectively) and Worcestershire (9·0, 6·7 and 3·5 t C ha^{-1} year^{-1}, respectively) were positive while those for vining peas were negative (–4·1 and –2·8 t C ha^{-1} year^{-1}, respectively, Table 4).

Subtraction of C removed at harvest from *NEP* to give *NBP* somewhat reduced differences between crops (Fig. 2). *NBP* was lower than *NEP*, except for temporary pasture which was treated as if no crop had been harvested. The range of *NBP* for Brassicas was slightly reduced although it remained wide across locations, –5, 1·1, 2·5, 3·05 and 6·0 t C ha^{-1} year^{-1} for Anglesey, Lincolnshire, Worcestershire, Spain and Uganda, respectively. *NEP* and *NBP* for temporary pasture fields in Anglesey were most positive at 14·9 t C ha^{-1} yr^{-1}.

Differences in *NBP* between crops were qualitatively the same as those in *NEP*, but were larger. As for *NEP*, *NBP* for lettuces was again significantly more negative in comparison

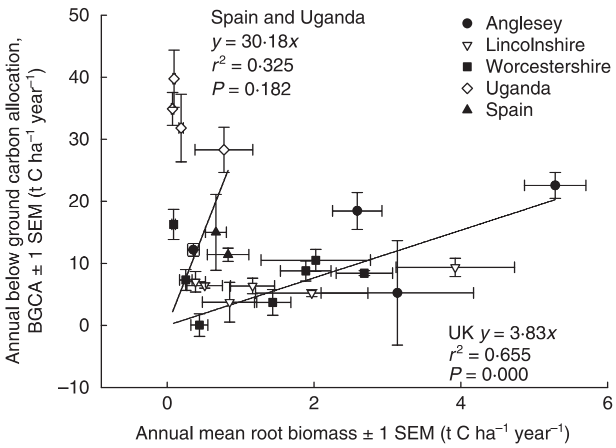

Fig. 1. Relationship between annual below-ground carbon allocation (BGCA) and annual mean root biomass. Each point is the mean of fields of each crop in each location. *n* for each point ranges from 4 to 10. Crops in the UK and Spain + Uganda were fitted with linear regressions through the origin.

to other crops at the same location, with the exception of Spain (Table 4). *NBP* for Brassicas, wheat and sugar beet from Lincolnshire and Worcestershire remained greater than those for vining peas. In addition, *NBP* for potatoes from Lincolnshire and Worcestershire were significantly greater than for vining peas.

SOIL ORGANIC CARBON

Soil organic C (SOC) was measured in order to ascertain if any fixed C had been partitioned to the soil, and in some attempt to ensure that *NPP* was not underestimated when calculating *NEP* and *NBP*. There was too much variation between fields of the same crop at each location; therefore, analysis was carried out with nonparametric tests (Table 4). SOC at the start of the season in temporary pasture fields (53 t C ha^{-1}) was significantly lower than in Brassica and wheat fields in Anglesey (87 t C ha^{-1} $P = 0{\cdot}032$ and 73 t C ha^{-1} $P = 0{\cdot}016$, respectively). At the end of the season, sugar beet

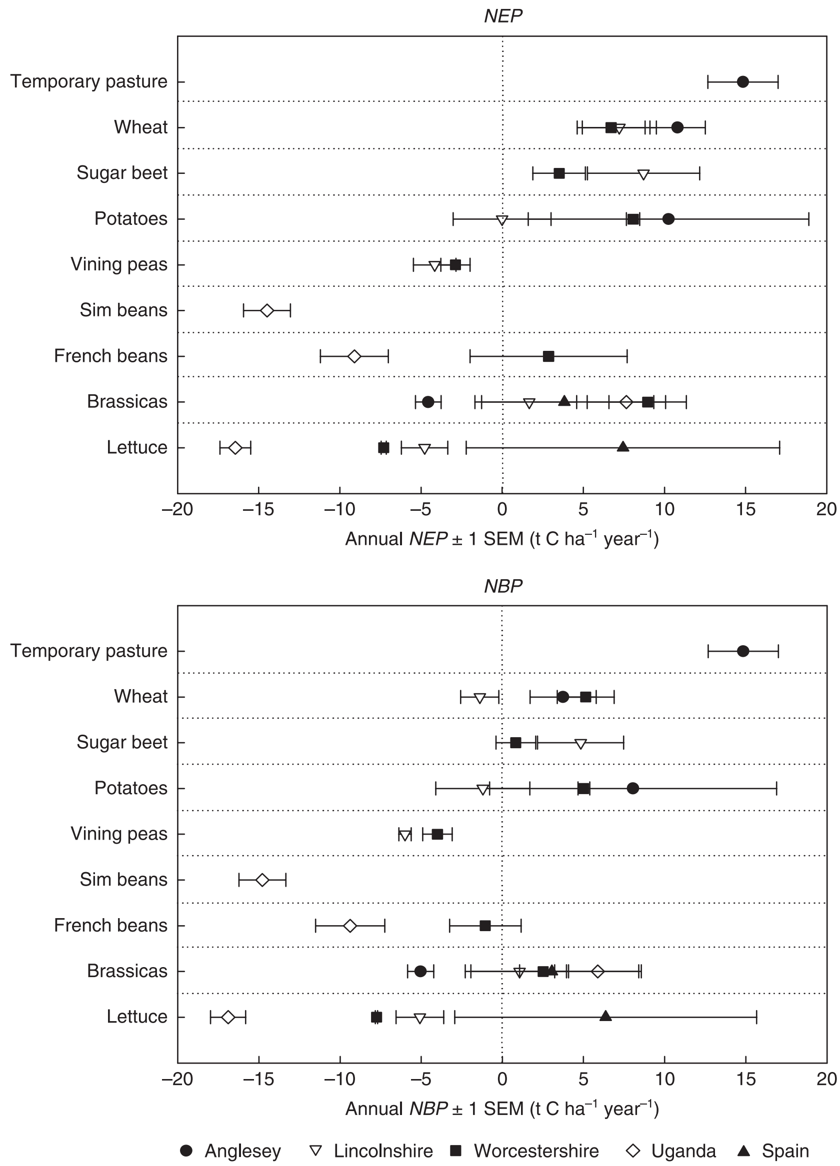

Fig. 2. Annual mean net ecosystem production (*NEP*) and annual mean net biome production (*NBP*). Each point is the mean of fields of each crop in each location. *n* ranges from 4 to 10.

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Table 4. Mean annual soil respiration, heterotrophic soil respiration (R_h), net primary production, crop biomass, net ecosystem production, net biome production, initial soil organic carbon, final soil organic carbon and the difference in soil organic carbon. *P* is the probability from nonparametric Mann Whitney tests. *n* is the number of fields of each crop. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, otherwise $P > 0.05$. Superscripts indicate crops compared

Crop	Location	*n*	Annual mean soil respiration (t C ha^{-1} yr^{-1})	*P*	Annual R_h (t C ha^{-1} yr^{-1})	Annual mean net primary production (t C ha^{-1} yr^{-1})	*P*	Annual mean crop (t C ha^{-1} yr^{-1})	*P*	Mean net ecosystem production (t C ha^{-1} yr^{-1})	*P*	Mean net biome production (t C ha^{-1} yr^{-1})	*P*	Mean initial soil organic C (t C ha^{-1})	*P*	Mean final soil organic C (t C ha^{-1})	*P*	Difference in soil organic C (t C ha^{-1})	*P*
Brassica[a]	Anglesey	5	13.9	**[a,i]	8.1	3.6	**[a,i]	0.5	**[a,i]	−4.5	**[a,i]	−5.0	**[a,i]	86.9	*[a,i]	83.6		3.3	
	Lincolnshire	5	9.7	*[a,f]	8.1	9.8	*[a,b]	0.6	**[a,g]	1.7	*[a,b]	1.1	*[a,c]	51.1		49.9	*[a,g]	1.2	
	Worcestershire		8.8		8.1	17.1	**[a,b]	6.5	**[a,b]	9.0	**[a,b]	2.5	**[a,b]	35.7		31.7		4.0	
	Spain	9	24.9		21.9	25.7		0.8		3.8		3.0		92.0		84.4		7.6	
	Uganda	10	30.3		21.6	29.2	**[a,b]	1.6	*[a,d]	7.6	**[a,b]	6.0	**[a,b]	53.1		56.3		−3.2	
Lettuce[b]	Lincolnshire	5	7.5	*[b,f]	8.1	3.3		0.3	**[b,f]	−4.8		−5.1		43.8		49.1	**[b,g]	−5.4	
	Worcestershire	6	16.3	*[b,f] **[b,g]	8.1	0.8	**[b,d] *[b,f]	0.5	*[b,d]	−7.3	**[b,d] *[b,f]	−7.8	**[b,d] *[b,f]	40.8		37.9		2.9	
	Spain	10	11.7		21.9	29.3		1.1		7.4		6.3		74.3		75.3		−1.0	
	Uganda	5	35.6		21.6	5.1	*[b,d]	0.5	*[a,b]	−16.5	*[b,d]	−17.0	*[b,d]	74.3		72.4		1.8	
Vining peas[c]	Lincolnshire	5	7.7		8.1	4.0		1.8	*[c,h] **[c,g]	−4.1		−5.9	*[c,f]	45.7		50.4		−4.7	
	Worcestershire	6	10.5	*[b,c]	8.1	5.3	**[a,c] **[b,c] *[c,f]	1.1	**[a,c] **[b,c] *[c,g]	−2.8	**[a,c] **[b,c] *[c,f]	−3.9	**[a,c] **[b,c] *[c,f]	74.2		71.6		2.6	
French beans[d]	Worcestershire	5	6.4	**[b,d]	8.1	11.0		3.9		2.9		−1.0		92.6		72.3		20.3	
	Uganda	4	33.6		21.6	12.5	*[a,d]	0.3		−9.1	*[a,d]	−9.4	*[a,d]	51.4		37.7		13.7	
Sim beans[e]	Uganda	4	38.5		21.6	7.1		0.3		−14.5		−14.8		61.0		57.3		3.8	
Potatoes[f]	Anglesey	5	10.2	*[f,h]	8.1	18.4		2.2		10.3		8.1		79.5		82.3		−2.8	
	Lincolnshire	5	4.6	*[f,h]	8.1	8.1		1.2	**[f,g] **[f,h]	0.0		−1.2		50.6		54.7		−4.1	
	Worcestershire	6	8.7	**[f,h]	8.1	16.2		3.1	*[b,f] *[c,f]	8.1		5.0		61.1		63.8		−2.7	
Sugar beet[g]	Lincolnshire	5	7.3		8.1	16.8	**[b,g] **[c,g]	3.9	**[b,g] *[g,h]	8.7	**[b,g] **[c,g]	4.8	*[b,g] **[c,g]	57.2		61.3		−4.1	
	Worcestershire	6	7.1	**[g,h]	8.1	11.6	**[b,g] *[c,g]	2.7	**[b,g] **[c,g] *[g,h]	3.5	**[b,g] *[c,g]	0.8	**[b,g] *[c,g]	57.5		56.8		0.8	
Wheat[h]	Anglesey	5	20.4		8.1	18.9	**[a,h]	7.1	**[a,h]	10.8	**[a,h]	3.7	**[a,h]	73.3	*[h,i]	66.9		6.3	
	Lincolnshire	5	8.6		8.1	15.3	*[b,h] *[c,h]	8.6	**[a,h] **[b,h]	7.2	*[b,h] *[c,h]	−1.4	*[c,h]	54.8		54.9		−0.1	
	Worcestershire	6	14.8	*[d,h] *[c,h]	8.1	14.8	**[b,h] **[c,h]	1.6	*[a,h] **[b,h]	6.7	**[b,h] **[c,h]	5.1	**[b,h] **[c,h]	92.4		66.8		25.6	
Temporary pasture[i]	Anglesey	5	25.3	**[f,i]	8.1	23.0		0.0	**[h,i]	14.9		14.9	*[h,i]	52.5		53.9		−1.4	

fields in Lincolnshire were higher in SOC (61 t C ha^{-1}) than in Brassicas and lettuce fields (50 t C ha^{-1} $P = 0{\cdot}021$ and 49 t C ha^{-1} $P = 0{\cdot}009$, respectively). The difference in SOC between measurement times did not vary significantly between locations or crops.

Discussion

In some C balance studies where *NPP* has been 'measured', there is concern that it has been underestimated by not accounting fully for below-ground C allocation (BGCA). Components are often ignored or are estimated as some theoretical proportion of ABCA or only root biomass is measured. Among 48 field *NPP* studies in tropical forests, only 13% assessed any aspect of BGCA (Clark *et al.* 2001). Studies have speculated that assimilated C partitioned into the rhizosphere was approximately 30% of *NPP* (Clark *et al.* 2001; Chapin & Eviner 2005). BGCA is not easy to fully account for because, besides roots, the two other main components of rhizosphere C, root exudates and root turnover are difficult to measure, especially in the field. Root exudates are rapidly taken up and respired by microbes adjacent to roots (Boddy *et al.* 2008; Hill *et al.* 2008) and are measured as a portion of root respiration, that is, a portion of C lost from plants, rather than a component of C gain (Chapin & Eviner 2005). In this study, the mass balance approach described by Raich & Nadelhoffer (1989) was applied in an attempt to fully account for BGCA when estimating *NPP*, although some uncertainty remains. This approach constrains *NPP* by providing an upper limit for BGCA to roots. This study's estimates of *NPP* are consistent with the assumptions set out by Raich & Nadelhoffer (1989). SOC was not significantly different between the start and end of season. The other assumptions of near-steady state for fine and coarse root biomass have not been verified in this study, except to indicate that crops were mature at the time of harvest, and crop residue was turned into the soil and thus, would have been the major addition of C to the soil at the end of season.

Few previous studies have focused on emissions from vegetable production, although the work of Baker & Griffis (2005) on maize *Zea mays* L. and soybean *Glycine max* L. did include a factor of 30% to account for BGCA. Their *NPP* was approximately 10 t C ha^{-1} $year^{-1}$ while in this study, comparable *NPP* for Brassicas ranged from 4 to 29 t C ha^{-1} $year^{-1}$, while French beans and potatoes ranged from 8 to 18 t C ha^{-1} $year^{-1}$. Wheat was included in this study as it is a typical component of vegetable crop rotations. Our estimates of *NPP* for wheat grown in Lincolnshire, Worcestershire and Anglesey (15 to 19 t C ha^{-1} $year^{-1}$) are greater than those suggested for wheat by Anthoni *et al.* (2004). Even if 30% is added to their *NPP* of 5·3 to give 6·9 t C ha^{-1} $year^{-1}$, it remains approximately half of our estimates. However, when R_h is subtracted, estimates of *NEP* are comparable to those of Verma *et al.* (2005) and Brye *et al.* (2005).

The other component estimated in this study for calculating *NEP* was R_h. The UK estimate of 8·1 t C ha^{-1} $year^{-1}$ determined from the y-intercept regression approach highly correlated with another approach involving measurement of bare plots (G.R. Koerber, unpublished data). Therefore, there is reasonable confidence with the UK estimate. For Uganda, there was sufficient biomass in most months to allow the use of the y-intercept regression approach and the majority of linear regressions were significant. Therefore, there is reasonable confidence in the Ugandan estimate. The estimate for Spain, although collected over 12 months, is probably an underestimate as it was mainly estimated from bare plots where respiration will be reduced due to microbes breaking down previous crops.

There are implications from *NEP* and *NBP* estimated for the crops and locations where they are grown. Lettuces grown in all UK locations and Uganda had negative values for both *NEP* and *NBP*. Where R_h is already high due to climate and *NEP* is calculated ($NEP = NPP - R_h$), it is necessary to return more crop residue to the soil to compensate. When *NPP* was the sum of BGCA and ABCA (above-ground carbon allocation), and given that the mass balance approach attempts to fully account for BGCA, then the magnitude of *NPP* relies on ABCA. We suggest that negative effects on *NEP* and *NBP* due to the response of R_h to climate could be mitigated by growth of crops with high returns of residue to the soil. There will inevitably be some variation in the decomposition rate of the various crop residues, due to their chemical composition. However, much of the residue is stem and leaf material with similar proportions of slowly decomposing compounds, such as lignin. Thus, it is likely that effects of residue chemical composition will be relatively small compared to the quantity incorporated into the soil.

Food system analysts should note that the contribution of soil C exchange to global warming can be estimated for inclusion in food life-cycle assessment (LCA) and carbon footprinting. For example, Muñoz *et al.* (2008) report the LCA of Spanish broccoli from the farms in this study, where the total life-cycle contribution to global warming lies around 2 kg CO_2eq kg^{-1} broccoli consumed. Taking an approximate value of 3·5 t C ha^{-1} $year^{-1}$ from Fig. 2 (C sink), and assuming an annual yield of 32 t broccoli ha^{-1} and a loss of 20% before it reaches the plate (processing waste), results in an uptake of approximately –0·5 kg CO_2eq kg^{-1} broccoli consumed (i.e. it has offset some of the emissions from the rest of the life-cycle stages altogether, including cooking). This result has clear implications for LCA studies of food, as well as for calculations of carbon footprinting, which currently do not include C uptake or emission by the soil. Furthermore, it appears from the variability in the soil emission values that assigning a single value to food carbon footprinting may not be adequate, even within a country.

The practical implications of this work are twofold. Firstly, initiatives should be directed at working with farmers to encourage greater returns of organic matter to the soil. This will maximize the potential to offset other CO_2 emissions along the food chain. Secondly, when considering policy responses to greenhouse gas emissions from agriculture, decision-makers need to be aware of the important geographical variation in emissions.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Fig. S1. Monthly daily mean temperature (DMT), soil temperature (ST), soil moisture content (MC) and soil respiration (SR) for each crop in each location.

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