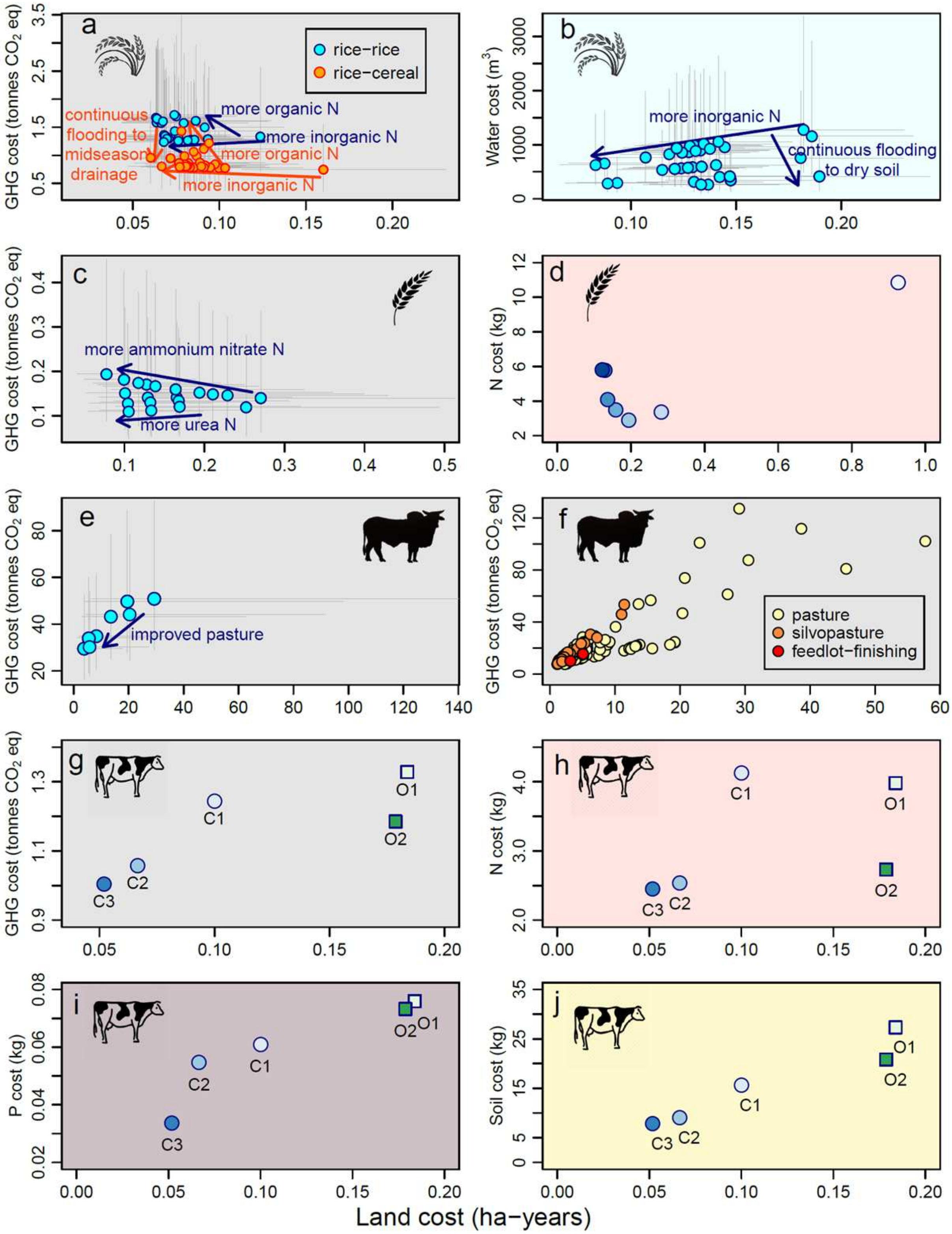
Supplementary information for

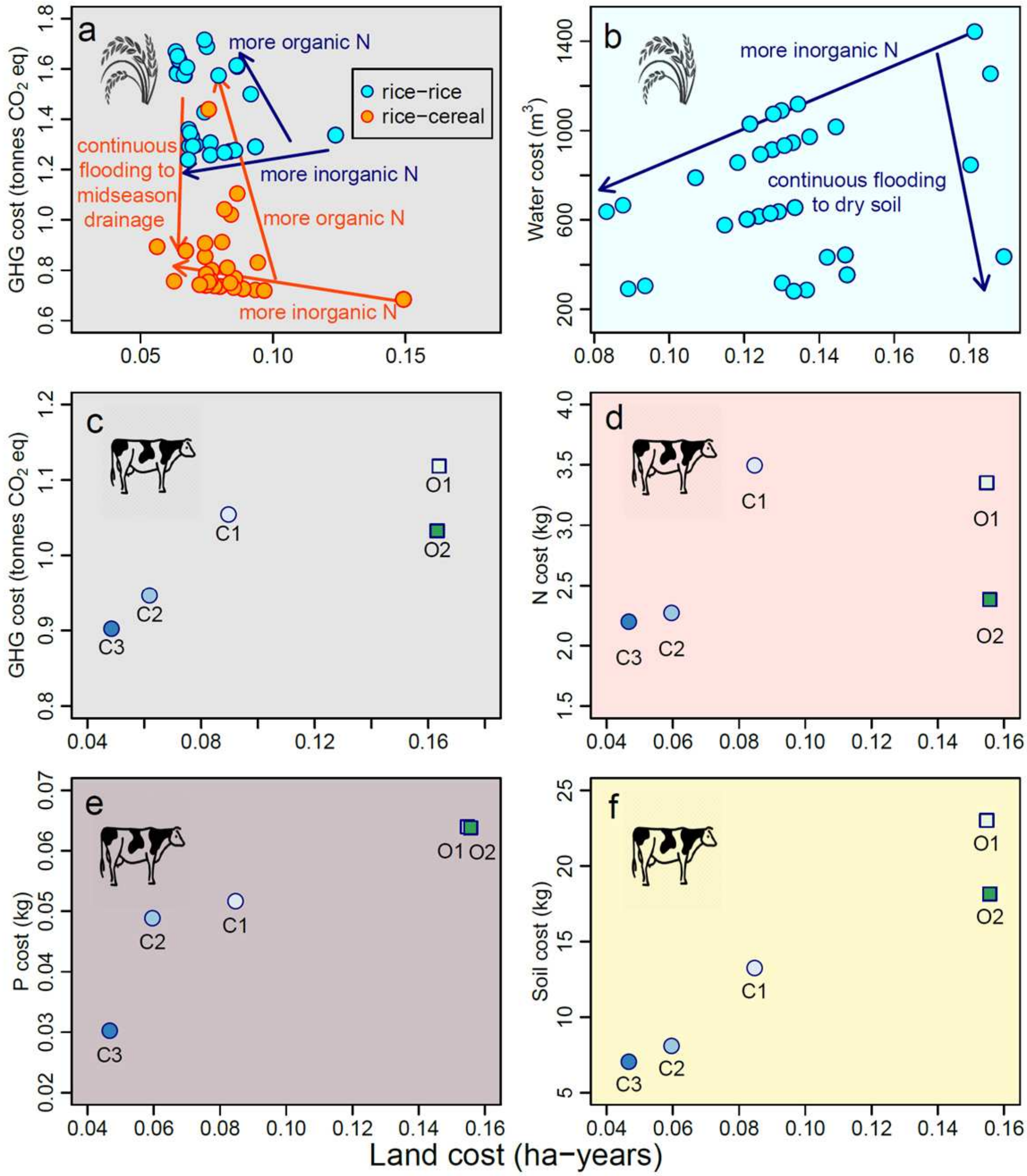
The environmental costs and benefits of high-yield farming

Balmford, A., T. Amano, H. Bartlett, D. Chadwick, A. Collins, D. Edwards, R. Field, P. Garnsworthy, R. Green, P. Smith, H. Waters, A. Whitmore, D.M. Broom, J. Chara, T. Finch, E. Garnett, A. Gathorne-Hardy, J. Hernandez-Medrano, M. Herrero, F. Hua , A. Latawiec, T. Misselbrook, B. Phalan, B. Simmons, T. Takahashi, J. Vause, E. zu Ermgassen & R. Eisner.

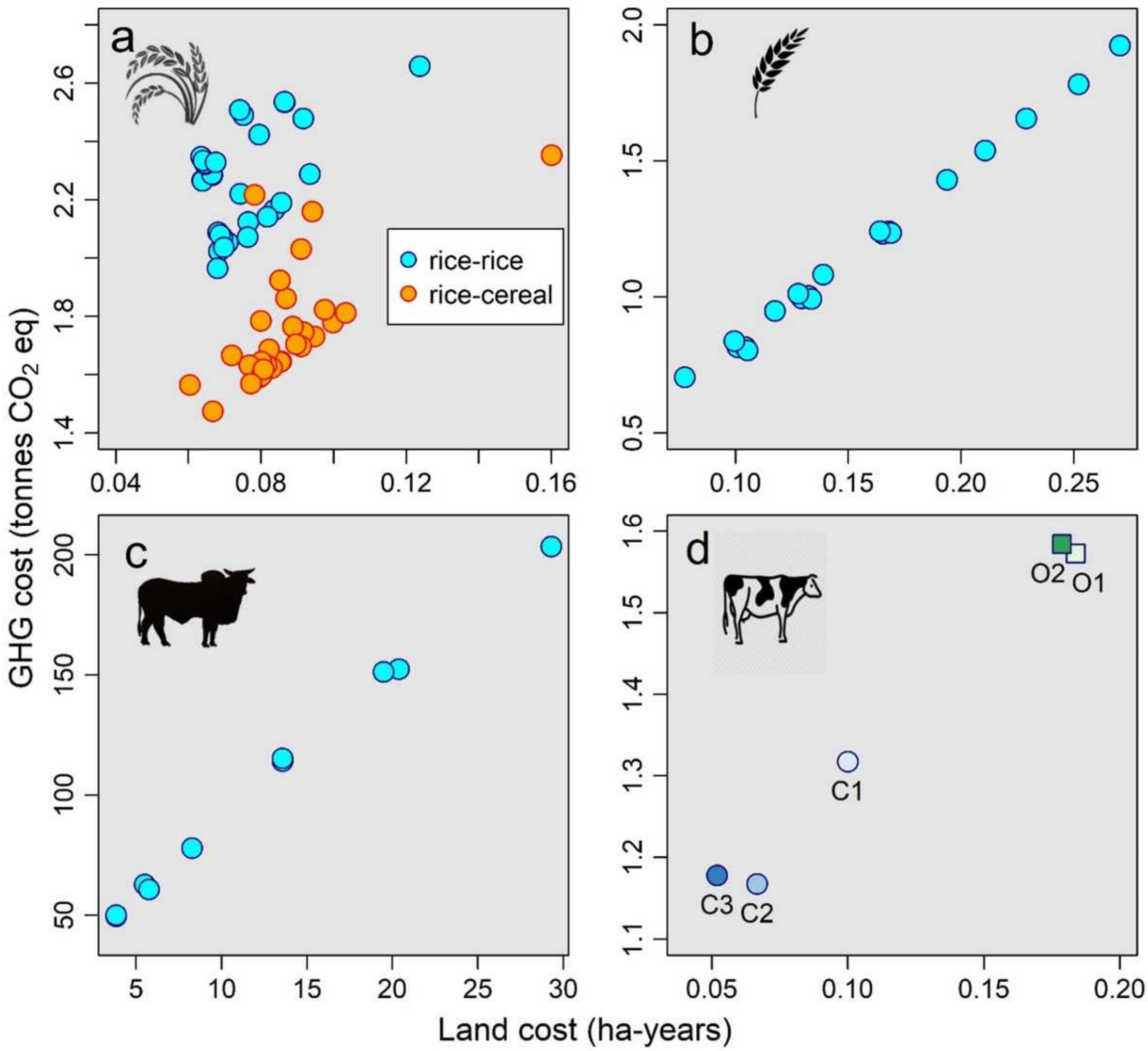
Supplementary Figures



Supplementary Figure 1. Externality costs of alternative production systems against land cost for five externalities in four agricultural sectors, showing uncertainty for statistically derived estimates. Plots are modified versions of those in Fig. 2, with pale grey lines in **a**, **b**, **c** and **e** representing 95% confidence intervals around our GLMM-derived predictions. All other notation as in Fig. 2.



Supplementary Figure 2. Sensitivity tests of associations between externality costs and land costs. Plots are modified versions of those in Fig. 2. **a,** The effect in rotational paddy systems of allocating land and GHG costs between rice and co-products based on their relative contribution to production of energy (rather than of gross monetary value; Methods). **b,** The effect on the association between water cost and land cost of paddy rice of excluding early-season data from the only study reporting data for two seasons per year. **c-f**, The effects in European dairy systems of allocating land and externality costs between milk and its beef co-product in proportion to their relative contribution to production of protein per unit area of farmland (rather than of gross monetary value; Methods). Notation as in Fig. 2. Spearman's rank correlation coefficients (p-values) are **a.** rice-rice: -0.51 (0.002), rice-cereal: -0.32 (0.10), **b.** 0.17 (0.34), **c.** 0.90 (0.08), **d.** 0.60 (0.35), **e.** 0.90 (0.08) and **f.** 0.90 (0.08).



Supplementary Figure 3. Sensitivity tests of associations between overall GHG costs (including GHG opportunity costs of land use) and land costs. Plots are modified versions of those in Fig. 3, but show the effects of assuming either that carbon sequestration rates of recovering habitat are half those given in IPCC guidelines or that half of the area potentially freed from farming because of higher yield is retained under agriculture (Methods); these assumptions have identical effects. Notation as in Fig. 3. Spearman's rank correlation coefficients (p values) are **a.** rice-rice: 0.07 (0.69), rice-cereal: 0.66 (< 0.001), **b.** 0.97 (< 0.001), **c.** 0.98 (< 0.001) and **d.** 0.80 (0.13).

Supplementary Tables

Supplementary Table 1. Types of data used for investigating each sector-externality combination, and (*in italics*) combinations which were not considered important or which we were unable to assess. Cell entries also show where each sector-externality combination is plotted.

sector / externality	Asian paddy rice (China)	European wheat (UK)	Latin American beef (Brazil)	European dairy (UK)
greenhouse gas emissions	multi-site experiments providing 147 estimates from 17 studies (Fig. 2a)	multi-site experiments providing 96 estimates from 3 studies (Fig. 2c)	8 LCA* studies providing 33 estimates + process-based model providing 144 estimates (Fig. 2e, f)	process-based model providing 5 estimates (Fig. 2g)
water use	multi-site experiments providing 123 estimates from 15 studies (Fig. 2b)	*irrigation not widespread in UK wheat production*	*irrigation not widespread in Brazilian beef production*	*insufficient data available*
nitrogen loss	*insufficient data available*	single-site experiment providing 7 estimates (Fig. 2d)	*insufficient data available*	process-based model providing 5 estimates (Fig. 2h)
phosphorus loss	*insufficient data available*	*insufficient data available*	*insufficient data available*	process-based model providing 5 estimates (Fig. 2i)
soil loss	*insufficient data available*	*insufficient data available*	*insufficient data available*	process-based model providing 5 estimates (Fig. 2j)

*LCA = Life Cycle Assessment

Supplementary Table 2. Details of Generalised Linear Mixed Models for the effect of management variables and covariates on land and externality costs. Estimated coefficients are shown; those whose 95% confidence intervals (in parentheses) did not overlap zero are in bold. Tillage in Rice-GHG models represents the effect of a tillage regime (compared to a no-tillage regime). Irrigation in Rice-GHG models is for the effect of episodic midseason drainage compared to continuous flooding. The effect of irrigation in Rice-Water models is based on five levels compared to continuous flooding: continuous flooding with a drainage (CF-drain), alternative wetting and drying (AWD), controlled irrigation (CI), mulches or plastic films (F-M) and long periods of dry soil (Dry). In Beef-GHG models, improved breed represents the effect of using an improved breed relative to an unimproved breed. Cell entries also show where the results of each GLMM are plotted.

Model		Coefficients						
Rice - GHG		Inorganic N	Organic N	Tillage	PC1	PC2		
monoculture n = 60 # studies = 5	Land cost	**-1.53×10^{-3} (-2.13×10^{-3}, -0.94×10^{-3})**	**-1.43×10^{-3} (-2.35×10^{-3}, -0.50×10^{-3})**	-0.061 (-0.23, 0.11)	**-0.052 (-0.071, -0.033)**	**0.038 (0.0026, 0.074)**		
(Fig. 2a)	Externality cost	-0.20×10^{-3} (-1.08×10^{-3}, 0.69×10^{-3})	**1.76×10^{-3} (0.39×10^{-3}, 3.12×10^{-3})**	0.19 (-0.062, 0.45)	**-0.12 (-0.15, -0.092)**	-0.029 (-0.082, 0.023)		
		Inorganic N	Organic N	Tillage	Irrigation	Soil pH	PC1	PC2
rotational n = 80 # studies = 12	Land cost	**-1.46×10^{-3} (-1.70×10^{-3}, -1.22×10^{-3})**	**-0.89×10^{-3} (-1.54×10^{-3}, -0.25×10^{-3})**	0.023 (-0.27, 0.31)	-0.018 (-0.21, 0.18)	0.081 (-0.016, 0.18)	-0.015 (-0.062, 0.032)	-0.022 (-0.068, 0.023)
(Fig. 2a)	Externality cost	1.28×10^{-4} (-3.34×10^{-4}, 5.95×10^{-4})	**1.56×10^{-3} (0.32×10^{-3}, 2.74×10^{-3})**	-0.083 (-0.65, 0.45)	**-0.51 (-0.89, -0.13)**	0.086 (-0.038, 0.21)	**-0.094 (-0.17, -0.011)**	0.016 (-0.047, 0.081)
rotational with energy allocation	Land cost	**-1.45×10^{-3} (-1.69×10^{-3}, -1.20×10^{-3})**	**-0.95×10^{-3} (-1.60×10^{-3}, -0.30×10^{-3})**	-0.0084 (-0.30, 0.28)	-0.020 (-0.22, 0.17)	**0.11 (0.012, 0.22)**	-0.037 (-0.086, 0.011)	-0.013 (-0.063, 0.034)
(Supplementary Fig. 2a)	Externality cost	1.62×10^{-4} (-2.62×10^{-4}, 6.13×10^{-4})	**1.50×10^{-3} (0.29×10^{-3}, 2.58×10^{-3})**	-0.14 (-0.71, 0.43)	**-0.52 (-0.90, -0.17)**	0.11 (-0.032, 0.26)	**-0.11 (-0.20, -0.028)**	0.032 (-0.044, 0.10)
Rice – Water		Inorganic N	Irrigation CF-drain	Irrigation AWD	Irrigation CI	Irrigation F-M	Irrigation Dry	Rainfall
n = 123 # studies = 15	Land cost	**-1.68×10^{-3} (-2.02×10^{-3}, -1.33×10^{-3})**	0.021 (-0.056, 0.098)	-0.0076 (-0.066, 0.051)	0.088 (-0.010, 0.19)	0.041 (-0.071, 0.15)	0.066 (-0.039, 0.17)	-0.70×10^{-4} (-2.66×10^{-4}, 1.21×10^{-4})
(Fig. 2b)	Externality cost	-1.26×10^{-3} (-2.64×10^{-3}, 0.13×10^{-3})	-0.095 (-0.41, 0.22)	**-0.53 (-0.76, -0.28)**	**-0.88 (-1.28, -0.48)**	**-1.12 (-1.58, -0.65)**	**-1.29 (-1.72, -0.87)**	**-1.12×10^{-3} (-1.90×10^{-3}, -0.35×10^{-3})**
excluding three records in ref. 68	Land cost	**-1.67×10^{-3} (-2.02×10^{-3}, -1.32×10^{-3})**	0.023 (-0.057, 0.10)	-0.0066 (-0.068, 0.055)	0.089 (-0.011, 0.19)	0.042 (-0.072, 0.16)	0.067 (-0.040, 0.17)	-1.02×10^{-4} (-3.94×10^{-4}, 1.87×10^{-4})
n = 120 # studies = 15 (Supplementary Fig. 2b)	Externality cost	**-1.41×10^{-3} (-2.73×10^{-3}, -0.068×10^{-3})**	-0.14 (-0.44, 0.17)	**-0.53 (-0.77, -0.30)**	**-0.92 (-1.31, -0.54)**	**-1.19 (-1.64, -0.74)**	**-1.32 (-1.72, -0.91)**	0.28×10^{-3} (-0.82×10^{-3}, 1.38×10^{-3})
Wheat - GHG		Ammonium N rate	Urea N rate	dicyandiamide rate				
n = 96 # regions = 3	Land cost	**-4.17×10^{-3} (-4.87×10^{-3}, -3.47×10^{-3})**	**-3.97×10^{-3} (-4.92×10^{-3}, -3.02×10^{-3})**	-0.0035 (-0.011, 0.0039)				
(Fig. 2c)	Externality cost	**1.10×10^{-3} (0.25×10^{-3}, 1.94×10^{-3})**	-0.37×10^{-3} (-1.51×10^{-3}, 0.77×10^{-3})	-0.0080 (-0.017, 0.00086)				

Beef – GHG (empirical)		Improved breed	Supplementary feed	Improved pasture
n = 33 # studies = 8	Land cost	-0.41 (-1.01, 0.19)	-0.36 (-0.92, 0.20)	**-1.26** **(-1.81, -0.68)**
(Fig. 2e)	Externality cost	-0.022 (-0.26, 0.23)	-0.14 (-0.34, 0.071)	**-0.38** **(-0.57, -0.17)**

Supplementary Table 3. Summary of input settings used to characterise contrasting Brazilian beef production systems in RUMINANT and DYNMOD.

	pasture systems	silvopasture systems	feedlot-finishing systems
forage quality	very low (i.e. unimproved), low, moderate or high		high or very high
feed type	none, moderate quality grain or high quality grain (boosted in silvopasture systems to simulate access to *Leucaena*)		mixed ration while in feedlot, high quality grain while on pasture
feed quantity (kg/animal/day)	0, 0.5, 1 or 2		1.1-2.5 (over life, and adjusted in feedlot to meet target weight)
cattle breed	unimproved or improved	unimproved or improved	unimproved or improved
replacement rate (%/year)	7.5, 10 or 20	20	10 or 20
age at first calving (years)	3, 4 or 4.5	3	3 or 4
parturition rate (%/year/reproductive female)	55, 65 or 80	80	65 or 80
adult mortality (%/year)	2, 4 or 5	2	2 or 4
juvenile mortality (%/year)	5, 8 or 10	5	5 or 8

Supplementary Table 4. Profile of the key features of our contrasting model systems of UK dairy production.

	conventional			organic	
	C1	**C2**	**C3**	**O1**	**O2**
grazing access (days/year)	270	180	0	270	200
milk yield (Energy-Corrected Milk kg/animal-year)	5500	7800	9200	4700	6300
proportion of forage when grazing					
grazed grass	1	0.5	n/a	1	1
grass silage	0	0.5	n/a	0	0
proportion of forage when housed					
grass silage	1	1	0.5	1	1
maize silage	0	0	0.5	0	0
replacement rate (%)	31	28	33	28	30
age at first calving (months)	26	30	26	34	34
mean live weight of replacements (kg)	340	372	340	404	404
area used (ha/animal*)					
grazing	0.367	0.122	0.039	0.472	0.326
grass silage	0.130	0.268	0.182	0.201	0.381
maize silage	0	0	0.096	0	0
concentrates	0.053	0.129	0.161	0.191	0.419
total	0.550	0.519	0.478	0.864	1.126
N excreted (kg/animal*-year)	110	105	116	106	109
P excreted (kg/animal*-year)	15.0	17.5	18.1	14.8	17.2
manure management – housing					
dairy adults	slurry	slurry	slurry	straw	slurry
young stock	straw	straw	straw	straw	straw
beef	straw	straw	straw	straw	straw
manure management – hardstanding (h/day)	4	4	0	4	4
manure management – storage					
dairy slurry	above-ground tank, no separator			farmyard manure heap	as C1-C3
beef and youngstock	farmyard manure heap				as C1-C3
manure management – land spreading					
dairy slurry	trailing shoe	trailing shoe	50% grass trailing shoe, 50% on maize incorporated within 6h	surface	trailing shoe
beef and youngstock	surface	surface		surface	surface

*an animal is an adult cow plus her replacements

Supplementary Table 5. Sources of values used to estimate the rate of accumulation of above- and below-ground carbon when farmland recovers to natural habitat.

variable	value(s) used	source
rate of recovery of above-ground biomass (tonnes dry matter/ha-year)	domain-, ecosystem- and continent-specific values	Table 4.9 in ref. 32
carbon content of biomass (tonnes C/tonne dry matter)	0.47	Table 4.3 in ref. 32
soil carbon content of natural habitat (tonnes C/ha)	climate- and soil-specific values	Table 2.3 in ref. 32
proportional change in soil carbon upon land-use transition	transition-specific values	Ref. 113