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Exploring the effects of land management change on productivity, carbon and nutrient balance: application of an Ensemble Approach to the upper River Taw observatory, UK

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Supplementary 1: Tables detailing information on the upper River Taw observatory catchment

Table S1: Dominant soil series, slope, elevation and climate allocation for each grid cell. The series were derived from NATMAP and topography from the CEH Integrated Hydrological Digital Terrain Model.

Cell ID	Soil Series	Mean slope / degrees	Elevation / m above sea level	Land use zone
1	Crowdy	4.3	525	High rainfall moorland
2	Crowdy	5.2	547	High rainfall moorland
3	Crowdy	5.3	513	High rainfall moorland
4	Crowdy	5.1	483	High rainfall moorland
5	Moor Gate	8.2	433	High rainfall moorland
6	Princetown	6.2	437	High rainfall moorland
7	Princetown	8.5	418	High rainfall moorland
8	Princetown	7.0	382	High rainfall moorland
9	Moor Gate	6.1	393	Low rainfall moorland
10	Moor Gate	8.2	371	Low rainfall moorland
11	Moor Gate	7.9	378	Low rainfall moorland
12	Moor Gate	6.7	369	Low rainfall moorland
13	Moor Gate	7.9	404	Low rainfall moorland
14	Moor Gate	8.5	452	Low rainfall moorland
15	Moor Gate	8.6	367	Low rainfall moorland
16	Moor Gate	8.2	312	Low rainfall moorland
17	Moor Gate	8.6	322	Low rainfall moorland
18	Moor Gate	12.4	353	Low rainfall moorland
19	Laployd	5.0	268	Rural land register area
20	Parc	8.7	290	Low rainfall moorland
21	Parc	12.5	282	Rural land register area
22	Denbigh	8.1	252	Rural land register area
23	Denbigh	6.8	209	Rural land register area
24	Denbigh	6.6	192	Rural land register area
25	Denbigh	6.3	217	Rural land register area
26	Denbigh	4.3	219	Rural land register area
27	Denbigh	5.9	226	Rural land register area
28	Hallsworth	5.1	207	Rural land register area
29	Denbigh	5.3	179	Rural land register area
30	Denbigh	5.5	181	Rural land register area
31	Neath	5.4	223	Rural land register area
32	Hallsworth	2.9	206	Rural land register area
33	Denbigh	5.9	195	Rural land register area
34	Hallsworth	4.1	211	Rural land register area
35	Hallsworth	5.4	210	Rural land register area
36	Hallsworth	5.2	190	Rural land register area
37	Hallsworth	4.7	188	Rural land register area
38	Hallsworth	4.6	173	Rural land register area
39	Hallsworth	4.6	160	Rural land register area
40	Hallsworth	2.9	169	Rural land register area
41	Hallsworth	2.9	158	Rural land register area
42	Hallsworth	3.2	167	Rural land register area
43	Hallsworth	3.6	145	Rural land register area
44	Hallsworth	2.5	146	Rural land register area

Table S2: Summary of weather variables for the upper River Taw observatory catchment

	Zone	Minimum	Maximum	SD
Max daily temperature	RLR area	12.5	13.7	0.3
	Low rainfall	10.9	12.9	0.5
	High rainfall	10.7	11.7	0.4
Ground frost days	RLR area	87.1	90.5	0.8
	Low rainfall	87.5	97.1	2.6
	High rainfall	92.5	96.3	1.4
Average daily temperature	RLR area	9	10.3	0.3
	Low rainfall	7.7	9.4	0.4
	High rainfall	7.6	8.2	0.3
Minimum daily temperature	RLR area	5.7	6.9	0.3
	Low rainfall	4.6	5.8	0.3
	High rainfall	4.6	4.9	0.1

Table S3: The baseline landcover classes derived from the CEH landcover map.

Cell ID	Land Cover Type				
	Arable / %	Improved grass / %	Rough grazing / %	Woodland / %	Non-ag / %
1	0	0	0	0	100
2	0	0	0	0	100
3	0	0	0	0	100
4	0	0	0	0	100
5	0	0	47	0	53
6	0	0	40	0	60
7	0	0	100	0	0
8	0	0	94	0	6
9	0	0	100	0	0
10	0	0	100	0	0
11	0	0	100	0	0
12	0	0	100	0	0
13	0	0	100	0	0
14	0	0	100	0	0
15	0	31	55	13	1
16	0	0	99	1	0
17	0	0	100	0	0
18	0	13	71	15	1
19	2	72	6	17	3
20	0	31	40	26	3
21	0	12	63	25	0
22	1	62	1	25	11
23	4	74	0	4	18
24	5	87	1	7	0
25	52	38	0	8	2
26	2	89	0	6	3
27	2	84	2	9	3
28	3	69	0	19	9
29	1	73	0	21	5
30	33	61	0	4	2
31	19	74	0	7	0
32	72	14	0	13	1
33	63	9	0	27	1
34	7	82	0	10	1
35	41	35	0	23	1
36	34	47	0	13	6
37	4	91	0	5	0
38	35	52	0	12	1
39	17	72	0	11	0
40	3	67	10	20	0
41	37	44	0	16	3
42	19	68	0	12	1
43	26	69	0	2	3
44	14	82	0	3	1

Table S4: Crop percentages derived from the UKCEH Land Cover® plus: Crops 2016, 2017, 2018, 2019 and 2020, detected in the whole River Taw catchment.

Crop name	**2016**	**2017**	**2018**	**2019**	**2020**
Field beans	0.25	0.23	0.06	0.08	0.23
Grass	86.37	84.45	85.49	83.64	82.91
Maize	2.11	2.52	3.01	3.72	4.00
Oilseed rape	0.55	0.48	0.12	0.32	0.29
Other crops	2.73	3.33	1.02	1.22	2.15
Potatoes	0.05	0.22	0.31	0.06	0.12
Spring barley	2.41	2.52	1.56	2.25	4.33
Spring wheat	0.41	0.40	1.98	0.38	0.52
Winter barley	3.06	2.47	2.80	2.59	1.74
Winter wheat (includes winter oats)	2.07	3.37	3.65	0.00	0.00
Winter oats	0.00	0.00	0.00	1.43	0.59
Winter wheat	0.00	0.00	0.00	4.31	2.34
Spring oats	0.00	0.00	0.00	0.00	0.64
Peas	0.00	0.00	0.00	0.00	0.01
Solar panels	0.00	0.00	0.00	0.00	0.12

Table S5: Crop percentages used in each model formulation. Percentages for the RLM were derived according to the calibrated stochastic crop generator which uses crop areas derived for the NUTS region that contains the upper River Taw catchment (Sharp et al., 2021). Percentages for CSM were derived from agriculture census returns completed by farms in the study catchment. Percentages for SPACSYS and AGREMOSA were derived from the CEH landcover plus crop proportions (Table S4) by subsetting down to the crops each model simulated and taking the relative proportions averaged over the 5 years of available data. It was assumed that the 2016–2018 winter wheat category was a 70:30 split between winter wheat and winter oats (as seen in 2019 and 2020 crop maps) and that there is a 50:50 split between winter and spring oats (as seen in 2020 crop maps). Grass ley proportions for AGREMOSA were obtained from CEH landcover plus crop proportions (Table S4).

Crop	RLM	SPACSYS	CSM	AGREMOSA
Barley - Spring	6.8	20.9	3.9	27.8
Barley - Winter	13.0	21.1	11.8	27.7
Fieldbeans	3.6	1.4	11.2	
Maize	13.4	24.5	5.6	
OSR - Winter	11.65	2.9	6.1	
Potato	0.3			
Wheat - Winter	25.8	20.6	44.0	27.3
Wheat - Spring	5.5			
Oats - Spring		4.7		
Oats - Winter		4.7		
Other			5.9	
Grass ley	17.2		11.5	17.2

Table S6a: Sowing dates and harvest dates associated with each crop simulated in AGREMOSA.

Crop	Sowing date	Harvest date(3)
Grassland - Intensive	1st Jan	30th May, 20th Jul, 30th Sep
Grassland - Extensive	1st Jan	21st Jun, 30th Oct
Grassland - Rough Grazing	1st Jan	21st Jun, 30th Oct
Miscanthus	1st Jan	29th Feb/ 1st Mar (Leap/Regular year)
Willow	1st Jan	14th Feb every 3 years
Wheat -Winter	15th/16th Oct (Leap/ Regular year)	28th Aug
Barley - Spring	26th/27th Mar (Leap/ Regular year)	30th Aug
Barley - Winter	29th/30th Sep (Leap/ Regular year)	25th June

Table S6b: Fertilizer rates, sowing dates and harvest dates associated with each crop simulated in the RLM.

Crop	Fertilizer N rate(1) kg N ha^{-1}	Fertilizer P rate(2) kg P ha^{-1}	Sowing date	Harvest date(3)
Barley - Spring	106 (32.5, 49.4, 24.1)	20.5	1st Mar	
Barley - Winter	146 (44.8, 68, 33.2)	26.7	15th Sep	
Beet	82 (25.2, 38.2, 18.6)	18.4	15th Mar	
Field beans	0	26.2	1st Mar	
Maize	66.1 (20.3, 30.8, 15)	25.3	10th May	24th Oct
Oats - Spring	106 (32.5, 49.4, 24.1)	22.3	1st Mar	
Oats - Winter	106 (32.5, 49.4, 24.1)	22.3	1st Oct	
Oilseed - Winter	191 (80.5, 80.5, 30)	24.9	1st Sep	
Potato	133 (55.5, 48.7, 28.8)	46.8	1st Apr	1st Oct
Wheat - Spring	149 (45.7, 69.4, 33.9)	26.2	15th Feb	
Wheat - Winter	191 (58.6, 89, 43.4)	25.8	22nd Oct	

(1): application dates are 2nd March, 2nd April and 2nd May.

(2): application date is 2nd April.

(3): Maize and potato have a forced harvest, other crops mature based on the accumulated photo-vernal-thermal time.

Table S6c: Fertiliser rates and dates, sowing dates and harvest dates used in SPACSYS.

	Chemical N fertiliser (kg N ha^{-1})			Sowing date	Harvest date
Winter oats	Early March (40)	Mid-April (70)		20th Aug	14th Sep
Winter wheat	Early March (40)	Mid-April (160)		14th Sep	20th Aug
Winter oilseed rape	Seedbed (97.4)	Early April (97.4)		20th Aug	20th Jul
Winter field beans	Seedbed (71)			30th Aug	20th Jul
Winter barley	Early March (40)	Mid-April (110)		14th Sep	20th Jul
Spring barley	Seedbed (40)	Mid-April (73)		20th Feb	20th Aug
Maize	End April (78)			30th Apr	20th Sep
Spring oats	Seedbed (40)	Early April (73)		20th Feb	20th Aug
Ryegrass	Mid-Apr (32.3)	Mid-Jun (32.3)	Mid-Aug (32.3)		
Miscanthus					1st Feb

Table S7: The numbers of livestock units recorded for the upper River Taw catchment according to zone and extracted from input files for CSM based on the June Agriculture Survey.

Livestock type	**Rural land register area**		**Moorland**	
	Lowland grazing	Mixed farming	Low rainfall	High rainfall
Cattle				
Male Cattle under a year	375	74	0	0
Beef Female Cattle under a year	271	56	0	0
Dairy Female Cattle under a year	53	0	0	0
Male Cattle 1 - 2 years	235	53	0	0
Beef Female Cattle 1 - 2 years	223	57	0	0
Dairy Female Cattle 1 - 2 years	4	0	0	0
Male Cattle 2 years and over	56	26	0	0
Beef Females without offspring	133	19	0	0
Dairy Females without offspring	9	0	0	0

Beef Cows, Heifers that have calved and culled cows	571	119	0	0
Dairy Cows, Heifers that have calved and culled cows	38	0	0	0
Sheep and lamb				
Breeding ewes intended for further breeding	3727	872	983	303
Breeding ewes intended for slaughter	238	57	66	11
Ewes intended for first time breeding	1280	83	172	53
Rams	113	23	30	10
Other sheep, 1 year and over not for breeding	57	40	8	5
Lambs	4711	714	1344	344

Table S8: Livestock configuration for SPACSYS simulations.

	Number per km^2 (RLR, LOW, HIGH)	Turnout	Return	Age (d)	Live weight (kg)
Beef Cows and Heifers	43	12-Apr	18-Oct	365	345
Beef Heifers in Calf Over 2yrs	10	12-Apr	18-Oct	900	520
Beef Heifers in Calf Under 2yrs	36	12-Apr	18-Oct	400	480
Calves	48	25-Apr	12-Oct	100	200
Dairy Cows and Heifers	2	15-Apr	17-Oct	365	345
Dairy Heifers in Calf Over 2yrs	5	15-Apr	17-Oct	900	520
Other Cattle under 1yr	3	12-Apr	18-Oct	400	450
Sheep ewe breeding	287, 94, 108	01-Jan	31-Dec	700	60
Sheep ewe breeding slaughter	18, 6, 4	01-Jan	31-Dec	1000	60
Sheep ewe intend breeding	85, 16, 19	01-Jan	31-Dec	1000	60
Ram	8, 3, 4	01-Jan	31-Dec	1000	70

other sheep	6, 1, 2	01-Jan	31-Dec	300	60
Lamb	339, 128, 122				

Table S9: Calorie calculations for different cropping and livestock systems. The calories, c (kcal ha^{-1}) of a given crop were calculated by: $c = 1000\ y\ p\ k$ where y, is the yield (t ha^{-1}), k, is the number of calories obtained from consuming a kg of this crop (USDA, 2021) and p is the proportion of the yield that reaches the plate once losses have been accounted for. This proportion is calculated from $p = (1 - w)(1 - s)e(1 - f)$ where w, is the proportion that is lost between harvest and processing; s, is the estimated proportion of the yield that is taken for seed; e is the percentage that remains after processing (e.g. after milling); and, f, is the proportion lost during food preparation (Table S10).

Land use	**Crop / Livestock**	**Calories (per kg)**	**Carbohydrate (%)**	**Protein (%)**	**Fat (%)**
Arable	Winter Wheat	3640	76	10.9	1.1
Arable	Spring Wheat	3640	76	10.9	1.1
Arable	Spring Barley	3320	73	11	1.8
Arable	Winter Barley	3320	73	11	1.8
Arable	Oats	3850	66.3	13	7.5
Arable	Maize (Forage)	3560	70	9.5	4.3
Arable	Seed Potato	670	17	1.6	0.1
Arable	Sugar beet	700	100	1.3	0.1
Arable	OSR	8840	0	0	100
Arable	Fieldbeans	500	22	3	0.4
Livestock	Lambs (Lowland)	2940	0	25	21
Livestock	Lambs (Upland)	2940	0	25	21
Livestock	Beef	1068	0	13	6
Livestock	Dairy (Milk)	420	0	3.4	1
Bioenergy	Miscanthus	4681380	-	-	-
Bioenergy	Willow	4585841	-	-	-

Table S10. Estimates used to calculate losses from field to fork. The data information is based on (FAO, 2001) and (Shepon et al., 2016) apart from where stated.

Crop	Wasted at farm gate / proportion	Used for seed / Proportion	Extraction rate (e.g. flour milling)/ proportion	Wasted in preparation/ proportion
Winter Wheat – milling	0.05	0.068	0.75	0.03
Spring Wheat – milling	0.05	0.068	0.75	0.03
Spring Barley	0.03	0.02	0.55	0.03
Winter Barley	0.03	0.02	0.55	0.03
Oats	0.05*	0.09	0.75*	0.03*
Maize	0.05*	0.02**	0.625[3]	0.03
Potatoes	0.13	0	1	0.02***
Sugar beet	0.25[1]	0.01[1]	0.13[1]	0
OSR	0.1[2]	0.02**	0.3[4]	0
Peas human fresh	0.18[5]	0.02**	1	0.05***
Peas dry human/animal consumption	0.18[5]	0.02**	1	0.05***
Beans/ human consumption	0.18[5]	0.02**	1	0.05***
Rye	0.05*	0.02**	0.75*	0.03*

* based on wheat, ** based on barley *** expert opinion

(1): FAO (2009)

(2): JIC (2019)

(3): Food Pricing Monitoring Committee (2003)

(4): AGICO Group (2021)

(5): Hartikainen et al. (2017)

Table S11: Regional statistics (South West) from the Defra June Survey based on 2004 – 2020 (t dry matter ha^{-1}).

	Mean	Sdev	Min	Max
Winter Wheat	7.5	0.65	5.6	8.3
Spring Barley	5.3	0.34	4.6	6.0
Winter Barley	6.4	0.53	5.6	7.9
Maize*	18	0.23	16.3	20.6
Field Beans**	4.3		3.75	5.0
Winter OSR	3.4	0.41	2.6	4.4

* BSPB (2020), ** average values listed in (Nix, 2021)

Brief description of SPACSYS

The main processes concerning plant growth in the model are plant development, assimilation, respiration, and partitioning of photosynthate and nutrients from uptake estimated with various mechanisms implemented in the model, plus N fixation for legume plants, and root growth and development that is described in 3D root system by the following processes: branching, extension, architecture, mortality, water uptake and nutrient uptake.

Nitrogen cycling coupled with carbon cycling in the SPACSYS model covers the transformation processes for organic matter (OM) and inorganic N. The organic matter pool is further divided into fresh OM, dissolved OM, a litter pool as well as a humus pool, and inorganic N includes a nitrate pool and an ammonium pool. The main processes and transformations causing size changes to soluble N pools are mineralization, nitrification, denitrification and plant N uptake. Most of these are dependent on soil water content and temperature. Nitrate is transported through the soil profile and into field drains or deep groundwater with water movement. A biological-based component for the denitrification process has been implemented that can estimate nitrogen gaseous emissions.

The process-based phosphorus (P) cycling component is linked to other components, e.g. plant component, heat transformation and water cycle. The P pool for organic forms was subdivided into certain subpools with different forms and similar to soluble P. There are some connections among those sub-pools with chemical, physical and biological processes.

The Richards equation for water potential and Fourier's equation for temperature are used to simulate water and heat fluxes, which are inherited from the SOIL model. Water in the soil profile is held mainly in the micro and meso pores of the soil matrix, but if the water content in a layer rises above a specified value a proportion is held in macropores from where rapid downward water (and solute) movement takes place due to gravitational forces alone. Water flow from the soil profile to a drainage pipe occurs when the ground water table is above the bottom level of the pipe and the soil below the ground water table is saturated. The Hooghoudt (1940) drainage flow equation with modification is adopted for the subsurface drainage flow.

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