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Impact of historical to current (1800-2010) intensive agriculture (arable and grassland) on carbon, nitrogen and phosphorus cycling in the UK

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Abstract

This paper describes a model that estimates carbon (C), nitrogen (N) and phosphorus (P) pools, pool changes, their balance and the nutrient fluxes exported from arable and grassland systems in the UK during 1800-2010 (at different periods: historical (1800-1950), transition (1950-70) and current (1970-2010)) using an agricultural model (Roth-CNP). The Roth-CNP model was developed as part of an Integrated Model (IM) to simulate C, N and P cycling for the whole of UK, comprising atmospheric, terrestrial, hydrological and hydro-chemical models. The model was calibrated and tested using long term experiment (LTE) data from Broadbalk (1843) and Park Grass (1856) at Rothamsted. We estimated C, N and P balance and their fluxes exported from arable and grassland systems in the UK on a 5 km x 5 km grid across the whole of UK taking into account arable and improved grass land management, crops (winter wheat, potato, oilseed rape, spring barley and fodder maize) and livestock numbers in each grid. Simulated crop and grass yields and estimated soil organic carbon (SOC) stocks and nutrient fluxes in the form of NH_4-N, NO_3-N and PO_4-P varied spatially across the whole UK. The simulated trends of crop yields were compared to that reported by national agricultural statistics for the historical to the current period. Overall, arable lands in the UK have lost SOC by −0.18, −0.25 and −0.08 Mg C ha y^{-1} whereas under improved grassland SOC stock has increased by 0.20, 0.47 and 0.24 Mg C ha y^{-1} during 1800−1950, 1950−1970 and 1970−2010 simulated in this study. Annual mineral N and P balance is dominated by different components at different time periods under both arable and grass lands. Simulated N loss (by leaching, run off, soil erosion and denitrification) increased both under arable (−15, −18 and −53 kg N ha y^{-1}) and grass (−18, −22 and −36 kg N ha y^{-1}) during different time periods. Simulated P surplus increased from 2.6, 10.8 and 18.1 kg P ha y^{-1} under arable and 2.8, 11.3 and 3.6 kg P ha y^{-1} under grass lands 1800−1950, 1950−1970 and 1970−2010.

Keywords: Roth-CNP, Integrated model, crops, nutrient flux, leaching

1. Introduction

Agriculture in the United Kingdom (UK) has a long history of human settlement and development which dates back to 6,000 years ago when humans began domesticating plants and animals in Neolithic times (Edwards and Hirons, 1984; Woodbridge *et al.*, 2014). By 900-700 BC, settled agriculture was established in the UK with crop rotations, pasture and coppiced woodlands. By 100-350 AD, natural forest was largely cleared with large estate-based farming systems with cattle, sheep and arable production. The UK's countryside has further changed dramatically since then with majority of the population living in small farmsteads under subsistence farming. By 1300 AD, increasing demand for food brought the subsistence farming system under huge pressure because of increasing population as the land area available for agriculture was already in use. However, between 1300 and 1800 average crop yields increased in the UK due to improvements in crop management such as mixed husbandry (by combining crop and livestock), grass and arable rotation, crop rotation by including fallow and legumes leading to a British agricultural revolution (Allen, 2008).

With the industrial revolution in 1850s, technological improvements also happened in agricultural sector, for example, switching from draught animals to machine. Much of the agricultural growth during this period came about as a result of increase in the area of crops and grass, which peaked in mid 1880s. After this, agricultural area underwent a steady decline as farms became more intensive and the availability of labour diminished. During the second half of the 20th century (Musel, 2009), agricultural intensification driven by new high yielding varieties, mineral fertilizer application, chemical pest control and improved methods of cultivation (Marks and Britton, 1989) led to increase in agricultural production many-fold. Per-hectare yields of wheat almost tripled whilst barley, potato yields and milk yields per cow more than doubled (Marks and Britton, 1989; DEFRA, 2014). The total cattle population increased sharply after the middle of 20th century although there has been a decline since 1974. About 170 million tonnes of animal excreta (slurry) are produced annually in the UK. In terms of farm inputs, mineral nitrogen (N) fertilizer used in the UK increased five times between 1950 and 1978 (Cooke, 1980). Greater use of N and P fertilizers during this period has led to an increased loss of these nutrients into our rivers and ground water through leaching, runoff (Hood, 1982; Hooda *et al.*, 2000), and increased atmospheric emissions of ammonia, nitrous oxide and other reactive N compounds . Agricultural land contributes 70% and 28% of the N and P load to UK waters (Hunt *et al.*, 2004; White and Hammond, 2007). Losses of these nutrients are associated with excessive or poorly timed applications of N or P or both (Dungait *et al.*, 2012). Pretty *et al.* (2000) calculated the annual external cost of agriculture for the UK in 1996 as £2343 M (£208/ha), with the major costs associated with contamination of drinking water by pesticides, nitrate and phosphate and increased greenhouse gas (GHG) emissions, soil erosion and organic carbon losses.

Numerous spatially-variable, interacting factors such as land-use, vegetation type, weather, catchment topography and total nutrient inputs over time determine the nutrient stocks and fluxes at a farm, landscape or catchment scale. For example, nutrient concentrations in groundwater under agricultural land have been found to be several times higher than that under semi-natural vegetation (Nolan and Stoner, 2000). Growing vegetables and crops such as potatoes and oilseed rape intensively has led to high rates of nitrate leaching (Stuart *et al.*, 2011). Nutrient concentrations in ground water have been found to be highly variable and related to changes in the weather

(Rozemeijer *et al.*, 2009) and increased as a result of land-use change (Whitmore *et al.*, 1992). There is a strong influence of catchment slope on water quality due to slope-dependent seasonal waterlogging, which determines the fate of dissolved substances produced within and moving through the catchment (D'Arcy and Carignan, 1997). Temporal dynamics of these nutrients depend on the relative occurrence of the nutrients in different pools at different points in time. Nutrients are retained during the dry summer months as a result of bioaccumulation and adsorption in case of P, and during the wetter autumn to spring periods, these nutrients are released and transported from the floodplain into the river channel (Bowes *et al.*, 2005).

Understanding the processes that are leading to the build-up of C, N, and P in soil, ground water and surface water from the past to the present is essential to understand how to manage the supply and utilisation of these nutrients into the future. This will contribute to the long-term goal of achieving a sustainable agricultural system by increasing or maintaining crop yields whilst minimising impacts on other ecosystem services (Powlson et al., 2011). It is also important to understand how these nutrient cycles (between atmosphere, terrestrial ecosystems including agriculture and hydrological systems) operate at large spatial scales across the whole UK in response to climate change and management options. A model that can summarise essential processes of soil and plant growth and their interactions and that can be applied over long timescales with readily-available driving data (climate, land-use, nutrient inputs) is essential to investigate the temporal and spatial responses in soil macronutrients at the national scale. This paper estimates C, N and P pools, pool changes, their balance and the nutrient fluxes exported from arable and grassland systems in the UK during the historical to current period (1800-2010) using an agricultural model that was developed as part of an integrated model to analyse and simulate long-term and large-scale (LTLS) interactions of C, N and P in the UK land, freshwater and atmosphere (http://www.ltls.org.uk/). This integrated model is referred here as LTLS-IM (Bell *et al.*, in prep), which comprises of atmospheric, terrestrial (semi-natural and agricultural), hydrological and hydro-chemical models (Figure 1).

2. Methodology

The agricultural model referred to as Roth-CNP model was developed by simplifying the Landscape Model (LM) (Coleman *et al.*, 2017) to an appropriate level of detail. The LM which works on a daily time step, simulates the biophysical processes of an agroecosystem at the field/farm scale taking into account the spatial interactions between the fields or farms across a landscape. The Roth-CNP model presented here aggregates the essential processes within the LM on a monthly time step without any spatial interactions between the spatial units. We briefly describe here the main features of Roth-CNP model together with any major changes from the LM. In Roth-CNP, we use the same parameters as the LM but adapting for a monthly timestep. We tested the Roth-CNP model using the data from Broadbalk and Park Grass long-term experiments (LTEs) at Rothamsted (*http://www.era.rothamsted.ac.uk/*), South-East England before undertaking the historical simulation for a continuous period from 1800 to 2010 for the whole of the UK. For these simulations, the whole land area in the country was divided into 5 km x 5 km square grids with improved grass present in in 91% and arable land in 76% of the grids cells (see SI, Figure S2.1).

2.1. Model description

The Roth-CNP model (Figure 1) has two major subunits: soil and landuse. In the soil module, the soil profile (can be of any depth, but in this study, it ranges from 30 cm to 150 cm) is divided into three layers. Depths of soil layers can be variable, but for this application the first and second layers were set to 15 cm each to enable a spatial comparison of CNP pools as most of the soil management activities affect the top 30 cm. Depth of third layer is variable depending on the actual soil profile, which varies spatially across the UK. The soil unit consists of organic C, N and P, mineral N and P modules. Variables such as actual evapotranspiration (AET), soil drainage, runoff and soil moisture are treated as inputs that are calculated by a hydrological model, which is a simplified version of the G2G model (Bell *et al.*, 2009). However, potential evapotranspiration (PET) for each landuse was estimated in a crop module (as it varies with crop type and developmental stage of the crop) based on the Penman's method (Penman, 1948). The PET estimated by the crop model was compared to the PET estimated by the hydrology model (using MORECS PET for grass assuming variable leaf area index (LAI) for summer and winter (Hough and Jones, 1997)) for a few selected sites and were found to be comparable (not reported here). The hydrology model within the LTLS-IM calculates components of the water balance (runoff, drainage, AET and soil moisture) for each 5x5 km grid-cell in the UK. Soil moisture for the entire profile (mm of water/ profile depth) was used to estimate moisture content in each soil layer within the Roth-CNP model. Soil organic carbon dynamics inherited from the RothC model has been described elsewhere (Coleman and Jenkinson, 1999; Smith, 2000; Jenkinson and Coleman, 2008). The model was extended for organic N and P with similar pool structures as that for carbon (Coleman *et al.*, 2017). Additional temporary pools of dissolved organic carbon (DOC), nitrogen (DON) and phosphorus (DOP) were created in the model in order to estimate the loss of dissolved organic C, N and P that enters soil solution. In agricultural soils, added organic amendments such as farm yard manure (FYM), slurry and other animal manures are the major sources that contribute to DOC (Bhogal *et al.*, 2010). Because of lack of information on the export of DOC from soils under agriculture, we assume that soil organic carbon (SOC) itself contributes only a negligibly small amount to DOC and therefore, its loss from agricultural lands was ignored in this study. In the model, we assume that when organic substrates are added, a fraction (FYM-4.6%; slurry-51%, and poultry manure- 6.6%) of these goes directly to the DOC, DON and DOP pools (Bhogal *et al.*, 2010) and is lost by leaching and/or runoff immediately before the reminder enters the SOC, SON and SOP pools.

Mineral N and P species exist in single (vertically integrated) stores without partitioning them between different soil layers to co-exist with the dynamics of soil water which estimates the water balance for the whole profile. All the N and P mineralised from SOM in the three soil layers is transferred to these mineral nutrient stores. Mineral N consists of NH_4N and NO_3N pools and mineral P includes *available* and *fixed* pools. Mineral N dynamics comprises N inputs (through atmospheric deposition, biological N fixation, fertilization), transformations (nitrification and denitrification) and losses (through plant uptake, denitrification, run off, leaching and erosion) (Coleman *et al.*, 2017). Similarly, P dynamics comprise of P inputs from fertilizers, chemical P fixation and release, crop uptake, run off, leaching and erosion. In the model we assume that biological N fixation (BNF) occurs only in grassland systems and on an average about 30% of grassland is a leguminous clover mix and can fix N biologically (Sanderson *et al.*, 2013; Lüscher *et al.*, 2014). In the model, BNF rate is calculated as a function of potential maximum N fixation rate and the rate modifying factors for temperature (f_T),soil moisture (f_m) and inorganic N (f_N) (Liu *et al.*, 2013).

$$Nfix_{rate} = Nfix_{max} \; f_T \; f_m \; f_N \qquad (1)$$

where $Nfix_{rate}$ and $Nfix_{max}$ are the actual and maximum rates of BNF (g N m^{-2} month^{-1}). Potential maximum BNF rate depends on the live shoot biomass (g DM m^{-2}), fixation rate per unit standing biomass (g N g^{-1} DM month^{-1}) and root growth rate (g DM month^{-1}). See Liu *et al.* (2013). Increases in mineral N (NH_4N and NO_3N) concentration reduces the BNF rate in the model and we assume N that is fixed is directly transferred to NH_4N pool.

Mineral N and P losses occur either through runoff (in water phase) or through soil erosion (particulate) and leaching. Loss of these nutrients through runoff depends on both the nutrient (NO_3N , available P) concentration (kg mm^{-1}) at the surface and the runoff (mm of water month^{-1}), whereas leaching depends on the nutrient concentration (kg mm^{-1}) in the soil solution and the drainage rate (mm of water month^{-1}). The rates of runoff and drainage were input from hydrology model (see section 2.2.5).

A generic plant growth model, which uses the light use efficiency (LUE, g dry matter MJ^{-1}) based approach (Monteith and Moss, 1977; Monteith, 1990) is used to simulate crop and grass growth within the landuse module. The rate of biomass production depends on the incoming solar radiation in terms of photosynthetically active radiation (PAR, *i.e*. 50% of the global radiation), crop/grass specific LUE and growth affecting factors such as moisture and nutrient stresses (Coleman *et al.*, 2017). The biomass formed is partitioned between roots, stem, leaves and storage organs based on the development stage (DVS) as described by Wolf (2012). In principle, crop phenology is expressed in terms of crop development stage (DVS), which is a function of temperature sum or growing degree days and includes the effect of vernalisation and/ or photosensitivity of the crop (deVries, 1989), which are variety specific and may vary across the country. As the model works on a monthly time step, and the flowering and maturity of the crop falls within a given month for a given crop across the whole country, we used a simple growth function to represent the DVS for each crop. We calculated DVS for each crop by applying the Landscape model for Rothamsted site for several years (1968-2012) and generated a general growth curve for each crop (Figure 2). For grass, we assume the plant remains in vegetative phase (DVS<1) throughout its growing period because it is continuously grazed or cut with sufficient frequency.

For older varieties of wheat (developed before 1970), a few parameters were changed by calibration (see the Supplementary information (SI 5) for more details). Insufficient water and nutrients (N & P) lead to stresses that affect crop growth and reduce the biomass production and yield as described by Coleman *et al*. (2017). The grass model differs from the crop only in the assumption that that grass is perennial in growth and is managed differently by allowing livestock grazing or frequent cutting.

A reasonably good agreement in the model results to the measurements from Broadbalk and Park Grass (see SI 5 for model calibration and testing) for plant yield, SOC, total N and NO_3N leaching over the last 160 years (RMSE: 4 − 71%, see SI, Tables S5.2 and S5.3) provides some degree of confidence in the Roth-CNP to estimate crop/grass yields, SOC and SON for the historical to current period of 1800-2010.

2.2. Model Inputs

2.2.1. Atmospheric deposition

Atmospheric N (NH_4-N and NO_3-N) input to arable and grassland systems were estimated for different time slices: 1800, 1900, 1950, 1970, 1990 and 2010 (see SI 1) at a 5 km x 5 km grid resolution across the UK, using land-cover dependent deposition velocities. Nitrogen deposition values for each land cover type in each grid square were interpolated for the whole period within these time slices.

2.2.2. Weather

For weather, data from several sources were combined to derive an observation-based dataset from 1800 to present. For rainfall (mm month^{-1}), daily observations, which are available back to the 19th century, were used, although network coverage ranges from only 2 rain gauges in 1853 to thousands in the late 20th century. National daily rainfall estimates for each a 5 km x5 km UK grid square were derived from any daily observations available for the period 1853 to 1910. From 1910 onwards, gridded 1 km resolution rainfall observations from CEH-GEAR (doi:10.5285/5dc179dc-f692-49ba-9326-a6893a503f6e) were used. No observed daily rainfall values were available prior to 1853, so daily rainfall for a median year (1904) was assumed to be representative for the period from 1800 to 1853.

For all other weather variables (temperature (°C), shortwave radiation (W m^{-2}), wind speed (m s^{-1}) surface pressure (Pa) and specific humidity (kg kg^{-1}), monthly mean values were used. These were obtained from the WATCH dataset (http://www.eu-watch.org/) for the period 1800 to 1970, and similar data from the UK Met Office (http://www.metoffice.gov.uk) were obtained for the later period 1970 to 2010. The Met Office dataset provided observation-based estimates of minimum and maximum temperature (°C), sunshine hours (h), wind speed (m s^{-1}) and vapour pressure (hPa). Prior to 1901, these data were not available for the whole country, and again, data from a nominal year (1904) is used.

Short wave radiation in W m^{-2} was converted to MJ m^{-2}. Surface pressure and specific humidity were used to calculate vapour pressure (KPa) (Nievinski, 2009).

2.2.3. Land cover and land use

A land cover history for the UK was constructed using contemporary land use datasets and the few historical maps available (see SI 2). Livestock populations and agricultural land use data were estimated for four time slices: 1900, 1950, 1970 and 1990. Five major crops (winter wheat, spring barley, oil seed rape, potato and fodder maize) were selected, which represented five major groups of crops (winter cereals, spring cereals, Oil seed crops, tuber crops and fodder crops) in the UK. The area under each of these crops represented the sum of the total area of all the crops within each of these groups. For example, the area under winter wheat represented the total area under winter wheat, winter barley and winter oats. Similarly, spring barley represented the area under both spring barley and spring wheat. Area under potato represented the area under potato and sugar beet and all the fodder crops under fodder maize. Estimates were based on historic agricultural census data and were distributed using the AENEID model (Dragosits *et al.*, 1998; Hellsten *et al.*, 2008) explained in SI3 with the land cover data summarised in SI2.

2.2.4. Soil

Soil texture and soil profile depth maps for 5 km × 5 km grid cells required by Roth-CNP were created from the Harmonised World Soil Database (HWSD). Soil organic C, N, P and mineral P pools were initialised with the outputs from semi natural model, N14CP (Tipping *et al.*, 2012; Davies *et al.*, 2016) at the point of their transition to agriculture on 1800 and 1950 (See SI, Figure S2.1). The N14CP model assumes three soil organic matter (SOM) pools (fast, slow and passive) to describe SOC, N and P dynamics compared to four active pools within the Roth-CNP.

Total SOC from N14CP was distributed between Roth-CNP's carbon pools for both surface and subsurface layers according to the RothC initialisation as follows:

$$TSOC_{N14CP} = SOC_{fast} + SOC_{slow} + SOC_{passive} \quad (2)$$

$$DPM_C = TSOC_{N14CP} \times 0.1$$

$$RPM_C = TSOC_{N14CP} \times 0.13$$

$$BIO_C = TSOC_{N14CP} \times 0.02$$

$$HUM_C = TSOC_{N14CP} \times 0.75$$

Here $TSOC_{N14CP}$, SOC_{fast}, SOC_{slow}, $SOC_{passive}$ refer to the total, fast, slow and passive N14CP SOC pools and DPM_C, RPM_C, BIO_C, HUM_C represent the carbon redistributed to DPM, RPM, BIO and HUM Roth-C pools.

Total organic N and P were redistributed to Roth-CNP pools based on the C/N or C/P ratios of fast, slow and passive pools of N14CP model as follows:

$$TSON_{N14CP} = SON_{fast} + SON_{slow} + SON_{passive} \quad (3)$$

$$DPM_N = DPM_C / CN_{fast}$$

$$RPM_N = RPM_C / CN_{slow}$$

$$BIO_N = BIO_C / CN_{BIO}$$

$$HUM_N = TSON_{N14CP} - (DPM_N + RPM_N + BIO_N)$$

The BIO pool of Roth-CNP is largely microbial in nature and is assumed to have a fixed C/N (8.5) and C/P (50) ratios. In a similar way, SOP was also allocated to different Roth-C pools. In this way, fast and slow pools C, N and P from N14CP were allocated to the corresponding pools within the Roth-CNP model, without creating or losing C, N and P.

2.2.5. Hydrology

Hydrological inputs such as AET (mm month^{-1}), soil moisture (mm), drainage (mm month^{-1}) and runoff (mm month^{-1}) on a 5x5 km square grid covering the UK were estimated by the hydrology component of the LTLS-IM (Bell *et al.*, in prep). The hydrology model is summarised in Supplementary information (SI 4).

2.2.6. Fertilizer

Manure and fertilizer application rates to arable and grass land were calculated based on the information available from various sources. During the period 1800 to 1840s, sewage in the form of “night soil” was applied to crops and grass (Naden *et al.*, 2016). After 1840, imported N fertilizers (seabird guano, Chilean nitrate) and superphosphate were applied in small amounts. Average N fertilizer input to agricultural land during this period was calculated based on the total fertilizer use (Archer, 1985) and the total area under agriculture (see Section 2.2.3). The average per hectare fertilizer use increased from 7.2 to 13.1 kg ha^{-1} for N and 4.4 to 16.2 kg ha^{-1} for P during 1840 to

1940 (Archer, 1985), with 75% of these nutrients were assumed to be applied to arable and 25% to the grass. Chemical fertilizers were applied from 1940s and their rates increased over the years (Archer, 1985; DEFRA, 2011b). For example, N fertilizer application in winter wheat increased from 19 to 195 kg N ha^{-1} and 4 to 100 kg N ha^{-1} for grass during 1943 to 2010 (Figure 3). Mineral fertilizer application N application before 1940 was negligibly small.

2.2.7. Manure

Manure contribution by deposition of grazing animals (beef, dairy and sheep), slurry, and poultry is calculated based on livestock population and their daily manure (dung and urine) excretion rate.

Carbon and nutrient contributions from deposition of grazing animals depend on the frequency of manure deposition, dry matter (DM) content, carbon, organic-N, NH4-N, and P content of the urine and dung for different livestock species (Table 1). Carbon and nutrient concentrations in dry matter are estimated by the equations

$$C_{dep,j,k} = F_{dep,j,k} \; eC_{dep,j,k} \qquad (4)$$

$$N_{dep,i,j,k} = F_{dep,j,k} \; eN_{dep,i,j,k} \qquad (5)$$

where $C_{dep,j,k}$ and $eC_{dep,j,k}$, are the carbon content (g) and carbon concentration in the dry matter (g event^{-1}). $F_{dep,j,k}$ is the frequency of occurrence of dung or urine event (month^{-1}) for different animal species. $N_{dep,i,j,k}$, is the nutrient, *i* (NH_4-N, NO_3-N, organic N, inorganic P and organic P) deposited (g animal^{-1} month^{-1}) in the form of dung or urine (*j)* of different livestock species (*k)* and $eN_{dep,i,j,k}$ is the nutrient deposited by urine or dung event (g event^{-1}).

Slurry is collected when cattle are housed during winter (for dairy and beef). Slurry production depends on the slurry volume, density, DM content, and the nutrient content (Table 1) of livestock species (beef, dairy and pig) as follows:

$$C_{sl,i,k} = V_{sl,k}\, fDM_{sl,i,k}\, D_{sl,i,k}\, cC_{sl,i,k} \quad (6)$$

$$N_{sl,i,k} = V_{sl,k}\, vN_{sl,i,k} \quad (7)$$

where $C_{sl,i,k}$ is the carbon (g C animal^{-1} month^{-1}) in the slurry of livestock species *k*. The variables $V_{sl,k}$, $fDM_{sl,i,k}$ and $D_{sl,k}$ represent the volume (m^3 month^{-1}), volume fraction of DM (m3 m^{-3}) and density (g m^{-3}) of the slurry collected from each animal for a given livestock species *k*, and $cN_{sl,i,k}$ is the nutrient concentration (g nutrient kg^{-1} of DM) of the slurry for a given livestock species *k*.

Poultry manure is collected during the whole year and of rate of C ($C_{man,k}$) and nutrients ($N_{man,i,k}$) produced (g animal^{-1} month^{-1}) is given by

$$C_{man,k} = DM_{man,k}\, cC_{man,,k} \quad (8)$$

$$N_{man,i,k} = DM_{man,i,k}\, cN_{man,i,k} \quad (9)$$

depends on the manure DM production ($DM_{man,k}$, g DM month^{-1}) and C ($cC_{man,i,k}$, g C g $^{-1}$ DM) and nutrient concentration ($cN_{man,i,k}$, g nutrient g^{-1} DM) (Table 1).

A part of NH_4-N is lost through volatilization (from manure management practice (housing, manure storage & application to land) and is found to be 0.09 and 0.60 for NH_4N in the urine and dung deposition by cattle and sheep, respectively (Whitehead, 1995; McGechan and Topp, 2004). For slurry, volatilization fractions for dairy, beef and sheep are 0.6, 0.31 and 0.6, respectively. For poultry manure the volatilization loss fraction is 0.3.

2.3. Historical to current simulation

Here we aim to estimate C, N and P pools, pool changes, their balance and the nutrient fluxes exported from arable and grassland systems in the UK on a 5x5 km grid across the whole of UK during the historical to current period (1800 to 2010). Crop and grass landuse models were run separately on the arable and grassland area within each 5 km grid cell. The arable area in each grid cell was assumed to grow up to a maximum of five major crops: winter wheat, spring barley, potato, oil seed rape, and fodder maize depending on their presence or absence in that grid cell. These five crops represent the major crop groups such as winter cereals (winter wheat, winter oats, winter barley and winter triticale), spring cereals (spring barley, spring wheat), tuber crop (potato, sugar beet), oil seed crop (oil seed rape) and a fodder crop (fodder maize, spring oil seed rape) in the UK. Based on these five crops, we identified a maximum of five crop rotations with the actual number of rotations dependent on the number of crops in each grid cell (Figure 4). The number of simulations in each grid cell depends on the number of these rotations. On finishing the simulation of one crop rotation, the model runs for the next rotation with the initial values (by reading the soil input file). In this way, all the crops that are present in each grid cell are simulated in each year. To calculate the mean yield of a crop we took the weighted average of the yield for each crop for each year by multiplying the area of the crop in each rotation at the end of all the simulations for all the rotations. Under improved grass, four types of grass land management: dairy, beef, sheep and silage (ungrazed) were simulated according to the livestock population at that location.

To estimate the area under each of these livestock management systems ($A_{lv,i}$), we used the livestock numbers in each grid ($N_{lv,i}$) and the standard stocking rate ($D_{lv,i}$, animals/ha) for different species of livestock

$$A_{lv,i} = \frac{N_{lv,i}}{D_{lv,i}} \qquad (10)$$

Where *i* represents livestock species such as dairy, beef and sheep.

Stocking rates may have been different in the past especially when the livestock population was much lower than today. Due to lack of any such information for the past, we use the current standard stocking rates which are 2 (dairy), 3.3 (beef) and 20 (sheep) (Nix, 2003) for the entire study period. Any grass areas left after allocating to different livestock management were assumed to be ungrazed (hay or silage). In locations where the grass area was smaller than that estimated based on the livestock population, the model stocking rate was increased to achieve the observed population.

Similarly to crop rotations, the model runs for different grazing management systems after re-initialising the model variables for soil and plant growth at each time and the nutrient fluxes are calculated as weighted averages of the area under each grazing management.

Under different livestock management systems, animals graze from April to September and the rate of manure (urine and dung) input and the grass removed depends on the stocking rate and animal species (Coleman *et al.*, 2017). During winter when animals are in housed, the manure is collected, stored and applied in March in the form of slurry. Nitrogen and P fertilizers are also applied and their rate increases over the years, which peak in the late 20th century before started declining in the recent years (Figure 3). All of the P fertilizer is applied in spring whereas N fertilizer is applied in splits (up to 6 in 1990 compared to one single application in 1950 (DEFRA, 2010).

After 1950, further expansion of agriculture occurred with more of the semi-natural land converted to improved grass and improved grass converted to arable whilst a modest area of arable land became improved grass. This created more than one landcover history for each landuse (Figure 5). For computational simplicity, Roth-CNP soil variables were reinitialised in 1950 with the outputs from the semi-natural model N14CP (Davies *et al.*, 2016) to incorporate new landcover histories applied from 1950 onwards.

Simulated model results were analysed in three different periods: *historical* (1800-1950), *transition* (1950-1970) and *current* (1970-2010), which are distinct in terms of landuse and agronomic practices. During the historical period, agriculture was more traditional with local varieties and manure and/or slurry based fertilizer inputs. During the transition (post war) period, widespread land cover changes occurred alongside increased use of chemical nitrogen fertilizers in agriculture. The current period is characterised by the so called ‘green revolution’ effect where improved crop varieties, mechanisation, increased livestock population with higher inputs of chemical fertilizers and pesticides were used, supplementing but also disturbing the natural cycle of C, N and P (Galloway *et al.*, 2004). To calculate the average of a nutrient variable (e.g.: C input, NO_3-N leached) in each grid cell, we calculated the weighted average for each variable for each year by multiplying with the area under arable or grass land in the cell. The overall C, N and P balance for the whole of UK was calculated by averaging the mean values for these different variables for different time periods across all the grid cells.

In summary, the changes of SOC (ΔSOC, kg N ha^{-1} y^{-1}), mineral N (ΔN, kg N ha^{-1} y^{-1}) and P (ΔP, kg P ha^{-1} y^{-1}) averaged for the whole of UK are then calculated as

$$\Delta SOC = C_{plant} + C_{animal} - DOC_{loss} - POC_{loss} \quad (11)$$

$$\Delta N = N_{dep} + N_{min} + N_{BNF} + N_{fert} - N_{loss} - N_{denit} - N_{uptk} \quad (12)$$

$$\Delta P = P_{min} + P_{fert} - P_{loss} - P_{uptk} \quad (13)$$

Where C_{plant} and C_{animal} are the overall mean average annual carbon input through plant and animal sources (Mg C ha^{-1} y^{-1}), DOC_{loss} is the loss of SOC (Mg C ha^{-1} y^{-1}) in the dissolved form through leaching and runoff, and POC_{loss} is the loss through soil erosion in the particulate form. N_{dep} , N_{min}, N_{BNF}, N_{fert} are the overall N inputs through atmospheric deposition, SOM mineralisation/immobilisation, biological N fixation and fertilizer N application (all in kg N ha^{-1} y^{-1}). N_{loss}, N_{denit} and N_{uptk} are loss of nitrogen through leaching, runoff and soil erosion and N removed from soil by plant uptake (all in kg N ha^{-1} y^{-1}). P_{min} and P_{fert} are the overall P inputs through SOM mineralisation and fertilizer P application and P_{loss} and P_{uptk} are loss the of P through leaching, runoff and soil erosion and P removed from soil by plant uptake (all in kg P ha^{-1} y^{-1}).

3. Results

3.1. Historical to current simulation

3.1.1. Historical period (1800-1950)

Simulated wheat yields ranged from 0.3 to 1.9 Mg DM ha^{-1} with an overall mean average yield of 1.0 Mg ha^{-1} (Figure 6; Table 2). Simulated potato yields were similar to those of wheat and ranged from 0.1 to 2.0 Mg DM ha^{-1} with an overall mean average yield of 0.9 Mg ha^{-1} and simulated fodder maize yield had an overall mean average yield of 4.9 Mg DM ha^{-1}. For both wheat and potato, simulated yields ranged between 0.08 to 2.0 Mg ha^{-1} (Figure 6) lower than that reported for this period in national statistics (Table 2). Simulated grass yields varied widely across the UK from 1.3 to 16 Mg ha^{-1} (Figure 6), with the lowest yields occurring mostly in Northern Scotland and Northern Ireland, where SOC was lower than elsewhere. A lower SOC indicates lower SON and SOP and lesser availability of N and P for plant uptake through their mineralisation.

For arable land, simulated average annual SOC change during the historical period is small (−0.08 to 0.12%) (Figure 7) across whole of the UK with an overall mean net carbon change of −0.18 Mg C ha^{-1} y^{-1} (Table 3). During the same period, there was a general build-up of simulated SOC with an overall mean net carbon change of 0.2 Mg C ha^{-1} y^{-1} under grass land with a change in carbon ranging from -0.2 to 0.17% annually (Figure 8). Simulated plant and animal C input to the grass land was greater (2.9 Mg C ha^{-1} y^{-1}) compared to that under arable (1.0 Mg C ha^{-1} y^{-1}). About 93% of simulated total (plant plus animal) carbon input under grass was decomposed, resulting in the build-up of C by 0.2 Mg C ha^{-1} y^{-1}.

For arable land, the major part of estimated N input during the historical period was from soil organic matter mineralisation (39 kg N ha^{-1} y^{-1}) (Table 3). Simulated N was removed from soil mainly by crop offtake (36 kg N ha^{-1} y^{-1}) followed by losses through leaching, surface runoff and soil erosion. Simulated N loss varies across the country with an overall mean average of 15 kg N ha^{-1} y^{-1} (Table 3; Figure 7). However, simulated N loss through denitrification was relatively smaller (0.3 kg N ha^{-1} y^{-1}). For grassland, overall simulated total N input was about 164 kg N ha^{-1} y^{-1} with the major contribution from N mineralisation (67 kg N ha^{-1} y^{-1}) and BNF (47 kg N ha^{-1} y^{-1}). Simulated N loss ranged across the country with an overall mean loss of 18 kg N ha^{-1} y^{-1} (Figure 8; Table 3). The net rate of change of N under grass was almost double of that under arable land.

Phosphorus balance takes account of similar components to the N balance except that for atmospheric deposition and BNF (Table 3). Simulated total annual P input includes P from weathering, SOM mineralisation and fertilizer application. Under both arable and grassland, simulated P offtake and P loss through leaching, runoff and soil erosion were less than the P input and resulted in a P build up in the soil at a rate of 2.6 and 2.8 kg P ha^{-1} y^{-1} (Figures 7 and 8; Table 3).

3.1.2. Transition period (1950-1970)

Simulated wheat (0.8 to 4.0 Mg ha^{-1}) and potato (1.2 to 5.2 Mg ha^{-1}) yields during the transition period were greater than that under historical period with an overall mean average yield of 2.1 Mg ha^{-1} and 3.4 Mg ha^{-1}, respectively (Figure 6, Table 3). Nevertheless, these yields were less than the reported average yield for the whole UK for 1950-1970 (Table 3). Simulated overall mean average fodder maize yield (7.4 Mg ha^{-1}) increased by half compared to that during the historical period. Simulated grass yield also increased during this period especially in the western parts of the country (Figure 6) with overall mean average annual yield increasing by 16% compared to the historical period (Table 3).

In arable land, there was a marginal increase in simulated SOC stock particularly in areas of England where grass was converted to arable land in 1950 and elsewhere, SOC changes were less apparent or even decreased (Figure 7). In grassland, there was a decrease in simulated SOC stock in large parts of England and a marginal increase in the rest of the UK (Figure 8). Plant derived C was the major source of C input under arable and grassland (Table 3). Under arable land, simulated SOC loss by decomposition exceeds the total C input resulting in decrease in SOC stock during this period. Simulated overall mean average annual changes during this period were −0.25 and 0.47 Mg C ha^{-1} y^{-1} under arable and grasslands, respectively.

For arable land, the major contribution of mineral N in the model is from fertilizer application followed by N input through mineralisation and atmospheric deposition (Table 3). A large part of this nitrogen is taken up by the crop (about 70%) and 25% is lost through leaching, runoff and erosion. Simulated N loss varies across the country with greatest losses occurring in the western England and Northern Ireland (Figure 7). For grassland, simulated overall average total N input was 206 kg N ha^{-1} y^{-1} with the major contribution of N from mineralisation and BNF followed by fertilizer application (Table 3).

Simulated N removal by grass offtake is about 85% of this total N and about 11% was lost through leaching, runoff and erosion. Similarly to the arable land, N loss was greater in the western parts of the country (Figure 8).

Simulated overall average P input (33–34 kg P ha^{-1} y^{-1}) and P offtake (22 kg P ha^{-1} y^{-1}) under both arable and grass were very similar resulting in an overall annual P build up at a rate of 11 kg ha^{-1} y^{-1} during this period (Table 3).

3.1.3. Current period (1970-2010)

Simulated crop yields increased substantially during the current period compared to the transition period (Table 2). Winter wheat yields ranged from 1.4 to 8.7 Mg ha^{-1} with maximum yields occurring in the South and South east England (Figure 6). Simulated overall mean average wheat yield more than doubled in the first half of the current period (1970-1990) and increased further during 1990-2010 by another 30% (Table 2). Potato yields increased in some parts of the country to about 8.8 Mg ha^{-1} with an overall mean average yield of 6.0 Mg ha^{-1} during this period. Similarly, overall mean average yields for spring barley and oilseed rape has also increased whereas fodder maize yields decreased slightly. However, simulated yields for winter wheat, potato and spring barley were lower by -6%, -25% and -12% than the reported average yields for these crops for whole of the UK during these periods. Simulated grass yields increased especially in the western parts of the UK (Figure 6; Table 2).

For arable land, simulated SOC decline during the current period was relatively small suggesting that SOC was approaching an equilibrium. The carbon inputs from plant and animal sources were marginally increased and SOC decomposition was slightly less than in the transition period (Figure 7, Table 3). Under grassland, SOC stock continued to build up during this period with increased carbon input through plant and animal sources with a reduced of loss C through SOC decomposition. (Figure 8; Table 3).

In both arable and grassland systems, the major contribution of simulated N was from fertilizer (Table 3) during this period with nitrogen offtake by grass more than double of that of crops. Simulated N loss by leaching, runoff and erosion increased and were greatest during this period both under arable and grass land especially in the western parts of the UK with overall mean average losses of 52 and 36 kg N ha^{-1} y^{-1} (Figures 7 and 8; Table 3).

The overall mean average annual P fertilizer application increased under arable land (35 kg P ha^{-1} y^{-1}) and decreased slightly under grassland (15 kg P ha^{-1} y^{-1}) during the current period compared to the transition period. As a result, simulated P continued to build up in the soil at a higher rate especially under arable land and there was an increase in overall mean average P loss by leaching, runoff and soil erosion under both arable and grass (Table 3).

4. Discussion

The Roth-CNP model developed from Landscape model by simplifying the processes for a monthly time-step reproduced the observed results with varying, but satisfactory degree of goodness of fit for different fertilizer treatments in Broadbalk and Park Grass LTE (See SI 5). In general, simulated wheat yields for Broadbalk and grass yields for Park Grass followed the measured trend although yields were slightly overestimated with an overall RMSE of 66% and 31%, respectively (Table S5.3).

For all the crops, simulated crop yields for the whole UK show a greater yield in the north west of England for different time slices (Figure 6). This trend is similar to the potential yield of cereals estimated by Sylvester-Bradley and Wiseman (2005) for whole UK, in which this region is characterised by greater summer rainfall and day length compared to the rest of the UK. The terrain and shallow soils may however, limit the actual production in this region. Simulated wheat and potato yields for the whole UK when compared to the national yield statistics reported by DEFRA every year since 1890s show that model underestimated these yields during the historical and transition periods, but agreed well during the current period (Figure 9; Table 2). Availability of N for crop uptake is the major yield limiting factor in the model particularly during the historical period. In grass, N is taken up sufficiently and a large fraction (1/3rd) of this is coming through BNF. Some BNF is undoubtedly occurring in arable land too, either through leguminous crops and/or free living bacteria. However, in the model we did not include either leguminous crops in the rotation or any other form of BNF, which could potentially increase the yields more. After 1950, although simulated yield increased with the increase in fertilizer application as reported by national yield statistics, these were still underestimated. Biological N fixation could be still a source of N, but would be proportionally smaller under fertilized systems. Powlson and Jenkinson (1990) reported that BNF could be contributing as much as 25 kg N ha^{-1} under fertilized treatments in Broadbalk.

An accurate comparison of the simulated and actual grass yield is not possible as the actual grass yield is removed by the livestock species and depends on grazing and grazing intensity in different parts of the country. In general, the simulated grass yields increased over the years since 1800 at an average annual growth rate of 0.6% (Figure 9). The average grass yields (grazed or cut) estimated by the model (9 Mg ha^{-1} y^{-1}) for the current period show that they are greater than the national average yield (6 Mg ha^{-1} y^{-1}) (Morris *et al.*, 2005). A greater overall mean N uptake, which is more than double of that under arable system leads to higher yields in the model.

Simulated SOC for whole of the UK changed in different parts of the country at different rates (Figures 7 and 8). Overall, arable lands in the UK have lost SOC during the historical to current period (Table 3). During the current period (1950-2010), average annual loss of SOC was at a rate of 0.22% for top soil (0-30 cm) (Figure 9). This is similar to the SOC loss (0.38% y^{-1}) reported by Reynolds *et al.* (2013) for England and Wales for 15 cm depth during 1978 to 2007 in their countryside survey. Under grassland, however, there was consistent build-up of SOC during this period at a rate of 0.49% y^{-1} (Figure 9), which was higher than that reported by Reynolds *et al.* (2013) for improved grasslands (0.03% y^{-1}). However, Bellamy et al (2005) reported a higher loss of SOC at a rate of 0.6% y^{-1} for 15 cm depth for most soils under most landuses in England and Wales. Hopkins et al. (2009) studied the SOC trends under two long-term grassland experiments (that included Park Grass LTE used in this study to test the model) and found that there were no significant trends in SOC as these plots were showing declines, no net changes or increases in SOC. Prior to

1800, a large fraction of the grassland area simulated was under semi natural systems with relatively smaller SOC contents (see SI, Figure S2.1) led to a build up with change in landuse from semi-natural to improved grass. Similarly, a large fraction of land area changed from semi natural and arable to improved grass in 1950 resulting in a dip initially and a build-up of SOC thereafter (Figure 9). It is quite possible that when a soil with little SOM is planted to permanent grass, SOM builds up and takes about 100 years to reach an equilibrium (Johnston *et al.*, 2009). Difference of in the structure of SOC pools of N14CP and Roth-CNP may also contribute to apparent carbon build up or depletion as a result of placing some fraction of carbon from N14CP model in slow or fast decomposing pools respectively in the Roth-CNP model at the point of landuse transitions in 1800 and 1950.

Under both arable and grass land, mineral N dynamics was dominated by different components at different time periods (Table 3). During the historical period, under arable land, the productivity was mainly determined by soil's natural fertility through N mineralisation and then fertilizers during the transition and current periods. Nitrogen mineralisation depends on SOM content and its rate of decomposition. As a result, a greater N input through mineralisation occurs under grass (65-81 kg N ha^{-1}) compared to arable (39-41 kg N ha^{-1}). Under grassland, BNF was always a major source of N input to soil during all periods. Legume-based N fixation can vary depending on the grass management and proportion of clover (assumed to be 30% all over in this study). The model estimated overall mean average annual N fixation to vary from 43-53 kg N ha^{-1} for different periods. The quantity of N fixed by high fertilizer, clover-rye grass mixture was 31-72 kg N ha^{-1} and was less than that of a low fertilizer system (120-160 kg N ha^{-1}) (Høgh-Jensen and Schjoerring, 1994). There is always some uncertainty in the rates of natural biological nitrogen fixation (Galloway et al 2004).

Simulated N loss by leaching, runoff and soil erosion increases through different time periods under both arable (15-52 kg N ha^{-1}) and grass (18-36 kg N ha^{-1}). These figures for the current period were comparable to those reported by Lord et al, (2002), who estimated N surpluses (i.e. the amount of N that could be potentially lost by leaching, runoff and denitrification) for arable and grassland were 51 kg N ha^{-1} and 23 kg N ha^{-1} (after discounting for N removal by grass) in 1995. Overall mean average N loss by denitrification in the model was negligibly small for both arable (0.3–1.5 kg N ha^{-1} y^{-1}) and grassland (0.3–0.6 kg N ha^{-1} y^{-}1) during different time periods. Annual denitrification is variable depending on the N-fertilizer application rate and grazing or slurry application (Whitehead, 1995). Global estimate of denitrification for different combinations soil drainage and N fertilizer application shows 10 and 14 kg N ha^{-1} y^{-1} for upland crops and grass for a fertilizer application in the range of 75-150 kg N ha^{-1} (Hofstra and Bouwman, 2005) . A lower denitrification rate in the model is because soil is rarely saturated as the soil water is uniformly distributed in the profile as a result of averaging across the whole soil depth. This is a weakness of our approach where soil water is not integrated within the soil model and the total soil moisture storage (mm) estimated by the hydrology model is averaged for the profile depth in the soil model. Although total moisture is same, its distribution within a profile (in different soil layers) may vary depending the season: relatively more water stored at the surface layer during the autumn (rainy season) and at the lower layers during the summer (dry season). Nitrogen offtake estimated by our model for arable (128 kg N ha^{-}1) and grass (284 kg N ha^{-1}) were higher than that estimated for arable (100 kg N ha^{-1}) and grass (116 kg N ha^{-1}) land for the whole UK Lord et al, (2002). When an intensively managed grassland, which is harvested by cutting or grazing may yield between 8 to 15 Mg ha^{-1} y^{-1} of DM and contain 200-550 kg N ha^{-1} (Whitehead, 1995). In that case, with an average yield of simulated yield of 9 Mg ha^{-1} y^{-1} (Table 2), the grass may well take up more than 250 kg N ha^{-1} y^{-1}. A negligibly small loss through denitrification may also contribute to an excess N uptake of N especially under grass.

Phosphorus loss varies across the UK with maximum losses found in the North-west England where soils are shallow (Figures 7 and 8). Similarly to N, overall mean annual P loss through leaching, runoff and soil erosion followed the trend of P fertilizer application, which increased over the years (Figure 9). Simulated P builds-up in soil during different time periods under both arable and grassland. Withers et al. 2001 estimated the P balance for the whole of UK both under arable and grassland systems for 1993 showing that there is a surplus of 19 and 12 kg P ha^{-1}. Simulated overall mean average P build up was comparable to that reported by Withers *et al*., (2001) for arable (18.0 kg P $ha^{-1}y^{-1}$) but was underestimated for the grassland (3.61 kg P $ha^{-1}y^{-1}$) (Table 3). Other studies also found greater P surplus for grasslands in the UK ranging from 14 to 26 kg P ha^{-1} y^{-1} from farm to region (CAS, 1978; Brouwer et al.1995; Smith et al., 1995). The difference in P balance between the simulated and that reported by Withers *et al.*, (2001) is mainly due to high simulated P uptake by grass. However, simulated annual P uptake (30 kg ha^{-1}) is similar to that reported elsewhere for grassland systems (Haygarth et al., 1998).

5. Conclusions

This paper describes an agricultural model (Roth-CNP) that was developed as part of an Integrated Model (LTLS-IM) to simulate the cycles of C, N and P for the whole of UK, comprising atmospheric, terrestrial, hydrological and hydro-chemical model over the long-term period from 1800 to the present. The Roth-CNP model summarises the CNP cycling in an agricultural ecosystem by aggregating soil and crop processes using a daily to monthly timestep. The model simulated crop and grass yields and estimated SOC stocks, DOC and POC losses, and nutrient fluxes (NH_4-N, NO_3-N and PO_4-P) spatially across the whole UK taking into account the biophysical characteristics at each location. The simulated trends of crop yield are comparable to those reported by national agricultural statistics for the same period. Overall, arable land in the UK lost SOC between 1800 and the present day whereas under grassland, SOC stock increased over the same period. It is quite possible that SOC builds up when a soil with little SOC is planted to permanent grass and it may decrease under arable crops Simulated N losses were comparable to losses/surpluses reported in the literature. Similarly, P dynamics including P loss and P surpluses were comparable to the literature reports although the P surplus was underestimated for the grass. In summary, a relatively simple agriculture model described in this paper was able to capture variability in the dynamics of CNP at the national scale coupled to other large scale models of atmospheric deposition, hydrology and soil erosion. The model could be potentially applied at subnational or catchment scale to optimise multiple stakeholder interests and for projecting the plausible outcomes under different scenarios of climate and management.

6. References

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Table 1. Parameters used to calculate the carbon and nutrient contribution from manures

Parameters	Dairy	Beef	Sheep	Pig	Poultry	Reference
Manure (dung and urine) deposition						
Frequency of deposition of dung, (month^{-1})	360	300	660	–	–	(Lantinga *et al.*, 1987; Williams and Haynes, 1995; McGechan and Topp, 2004; Orr *et al.*, 2014)
Frequency of deposition of urine, (month^{-1})	360	258	510	–	–	(Wheeler, 1959; Lantinga *et al.*, 1987; McGechan and Topp, 2004; Rosen *et al.*, 2004)
Carbon deposited, (g C event^{-1})	90	106	14	–	–	(Whitehead, 1995; Williams and Haynes, 1995; Orr *et al.*, 2014)
Organic-N deposited, (g C event^{-1})	0.32	0.83	0.19	–	–	Whitehead (1995)
Organic-N deposited, (g N event^{-1})	1.07	3.88	0.55	–	–	(Lantinga *et al.*, 1987; Sakadevan *et al.*, 1993)
NH_4-N deposited, (g N event^{-1})	0.01	0.03	0.003	–	–	(Sakadevan *et al.*, 1993; Whitehead, 1995)
NH_4-N deposited, (g N event^{-1})	6.07	11.07	0.05	–	–	(Lantinga *et al.*, 1987; Sakadevan *et al.*, 1993; Whitehead, 1995)
Total-P deposited, (g P event^{-1})	1.40	0.01	0.21	–	–	(Haynes and Williams, 1993; Williams and Haynes, 1995; Orr *et al.*, 2014)

Total-P deposited, (g P event^{-1})	0.00	1.20	0.00	–	–	(Shand *et al.*, 2002; Manston and Vagg, 2009; Orr *et al.*, 2014)
Slurry						
Volume, (m^3 month^{-1})	1.5	0.90	–	0.15	–	DEFRA (2011a)
Volume fraction of dry matter, (m^3 m^{-3})	0.06	0.06	–	0.04	–	DEFRA (2010)
Density, (g m^{-3})	1040000	1040000	–	800000	–	
Carbon concentration, (g C g^{-1} DM)	0.20	0.20	–	0.2	–	MAFF (1998)
Organic-N concentration, (g N m^{-3})	1900	2300	–	1300	–	ADAS (2007)
NH4N concentration, (g N m^{-3})	1300	2000	–	2300	–	ADAS (2007)
Total-P concentration, (g P m^{-3})	622	933	–	0.025	–	ADAS (2007)
Poultry manure						
Dry matter, (g DM month^{-1})	–	–	–	–	2.5	DEFRA (2011a)
Carbon concentration, (g C g^{-1} DM)	–	–	–	–	0.24	MAFF (1998)
Total-N, (g N month^{-1})	–	–	–	–	0.048	Nicholson *et al.* (1996)
Total-P, (g P g^{-1} DM)	–	–	–	–	0.015	Nicholson *et al.* (1996)

Table 2. Overall mean average simulated crop/grass yields (Mg dry matter ha^{-1}) compared to that reported by national statistics[†] for different time periods in the UK.

Crop/ grass	1800-1950		1951-1970		1971-1990		1991-2010	
	Simulated	Reported	Simulated	Reported	Simulated	Reported	Simulated	Reported
Winter wheat	1.0	1.9[‡]	2.4	3.1	4.8	4.8	6.1	6.5
Potato	0.9	3.2[‡]	3.4	4.4	5.9	6.5	6.1	8.2
Spring barley	−	−	−	−	3.9	4.1	4.2	4.8
Oilseed rape	−	−	1.6	NA	1.9	2.5	3.0	2.8
Fodder maize	4.9	NA	7.4	NA	7.6	NA	6.9	NA
Grass	6.8	NA	7.9	NA	8.8	NA	9.2	NA

[†]MAFF (1988); Marks and Britton (1989)

[†]1884-1950;

NA: Not available

Table 3. Overall mean average annual carbon, nitrogen and phosphorus balance[1] (for the whole profile) for arable and grass lands estimated based on simulation results for different time periods for whole of the UK.

Components	1800-1950		1950-1970		1970-2010	
	Arable	Grass	Arable	Grass	Arable	Grass
Soil organic carbon (Mg ha^{-1} y^{-1})						
Plant C input	1.01	2.88	0.99	3.40	1.05	3.86
Animal C input	0.01	0.70	0.02	0.65	0.03	0.75
Dissolved organic carbon loss	0.00	−0.04	0.00	−0.04	0.00	−0.04
Particulate organic carbon loss	0.00	−0.01	0.00	−0.01	0.00	−0.02
Carbon loss (by decomposition as CO_2)	−1.2	−3.33	-1.25	-3.53	-1.16	-4.30
Net carbon change	−0.18	0.20	-0.25	0.47	-0.08	0.25
Mineral nitrogen (kg ha^{-1} y^{-1})						
Atmospheric N deposition	3.9	4.03	8.8	9.09	11.5	11.91
Fertilizer N input	8.1	2.03	64.0	35.0	127.9	134.8
N input by mineralisation	38.7	67.3	41.0	65.92	41.4	81.73
Animal N input	0.9	43.2	2.1	41.44	2.9	48.53
N input by biological N fixation	0.0	47.4	0.0	54.30	0	43.4
N loss by leaching, runoff and soil erosion	−14.9	−17.7	-29.0	-21.47	-52.3	-36.02
N loss by denitrification	−0.3	−0.28	-0.78	-0.38	-1.49	-0.61
Plant N uptake	−35.9	−144.9	-79.3	-173.9	-128.9	-283.6
Net N change	0.50	0.98	6.8	10.0	1.0	0.14
Mineral Phosphorus (kg ha^{-1} y^{-1})						
Fertilizer P input	8.7	2.34	26.4	16.67	34.6	14.54
P input by mineralisation	5.6	10.2	6.6	9.19	5.41	11.62
Animal P input	0.10	8.0	0.2	7.75	0.32	7.93
P loss by leaching, runoff and soil erosion	−0.03	−0.03	-0.14	-0.05	-0.28	-0.14
Plant P uptake	−11.8	−17.8	-22.3	-22.25	-22.0	-30.34
Net P change	2.57	2.8	10.8	11.3	18.05	3.61

[1]A Positive sign indicates input or gain and negative sign indicates loss from the soil system.

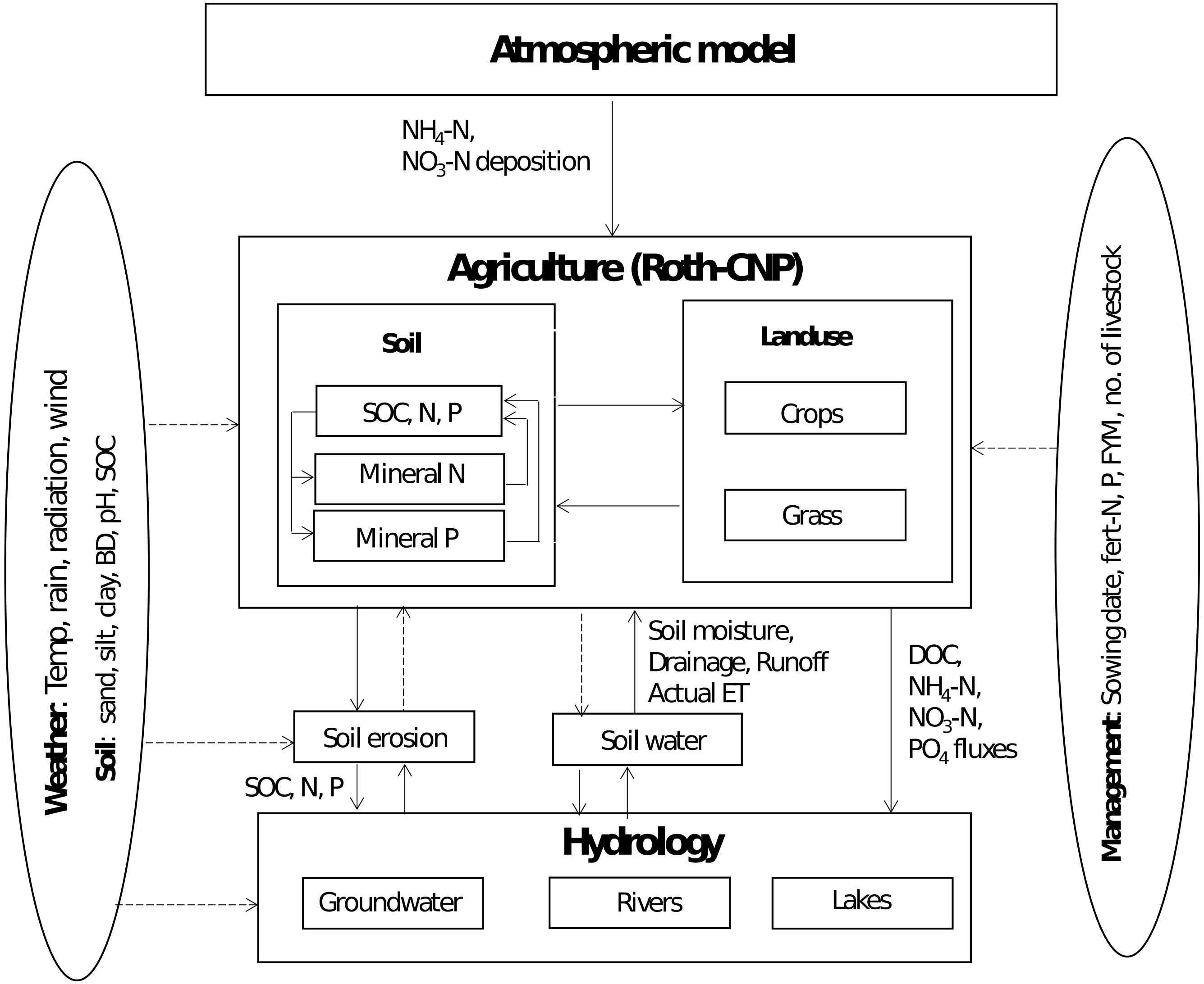


Figure 1. Schematic diagram showing the structure of Roth-CNP model interacting with components (atmospheric, hydrology, soil water and soil erosion models) of the Long-term Large Scale Integrated model (LTLS-IM) (Arrows indicate material and information flow; dotted arrow indicate information flow only).

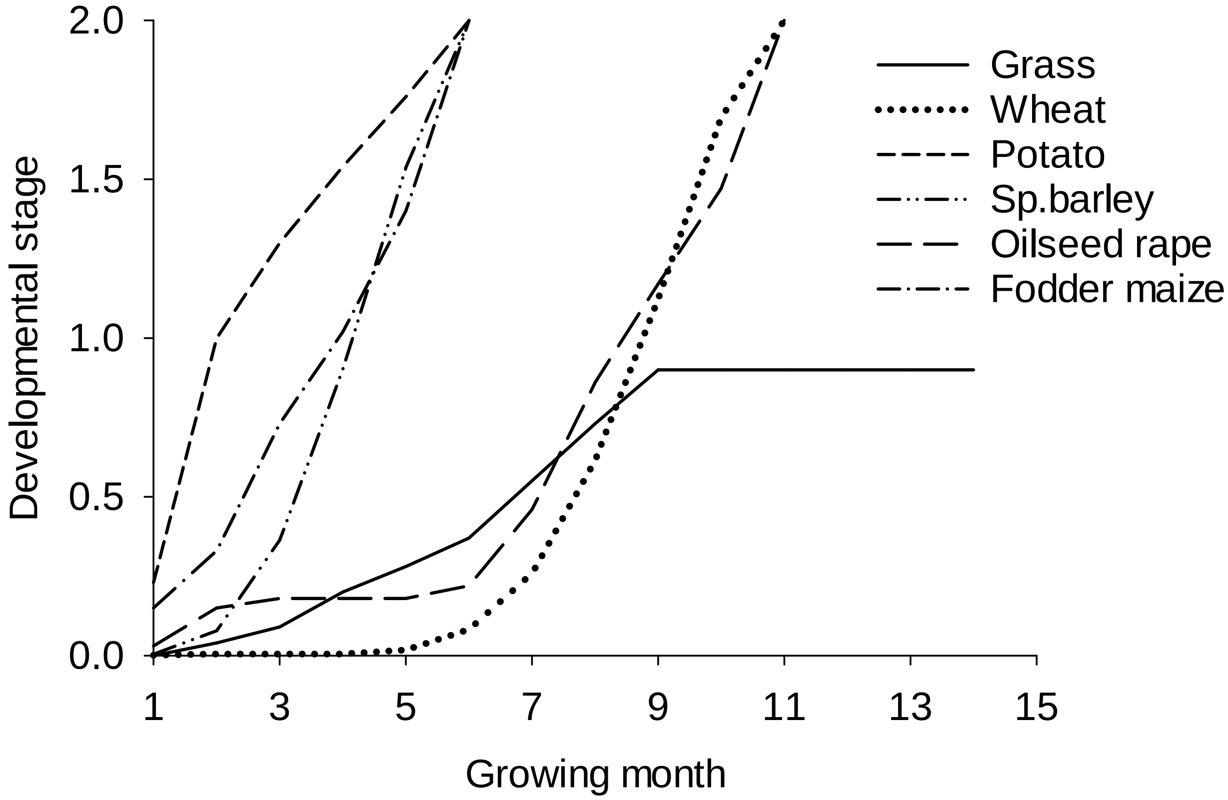


Figure 2. Developmental stage (DVS) estimated for different crops and grass as a function of their growing months (for wheat, 1–11 growing months = October–August; for potato, 1–5 growing months= April–August; for barley, 1–6 growing months= March–August; for Oilseed rape, 1–11 growing months= September–July; for fodder maize, 1–4 growing months= May–August, for grass, growing months are indefinite. Growing months are based on MAFF (1998)).

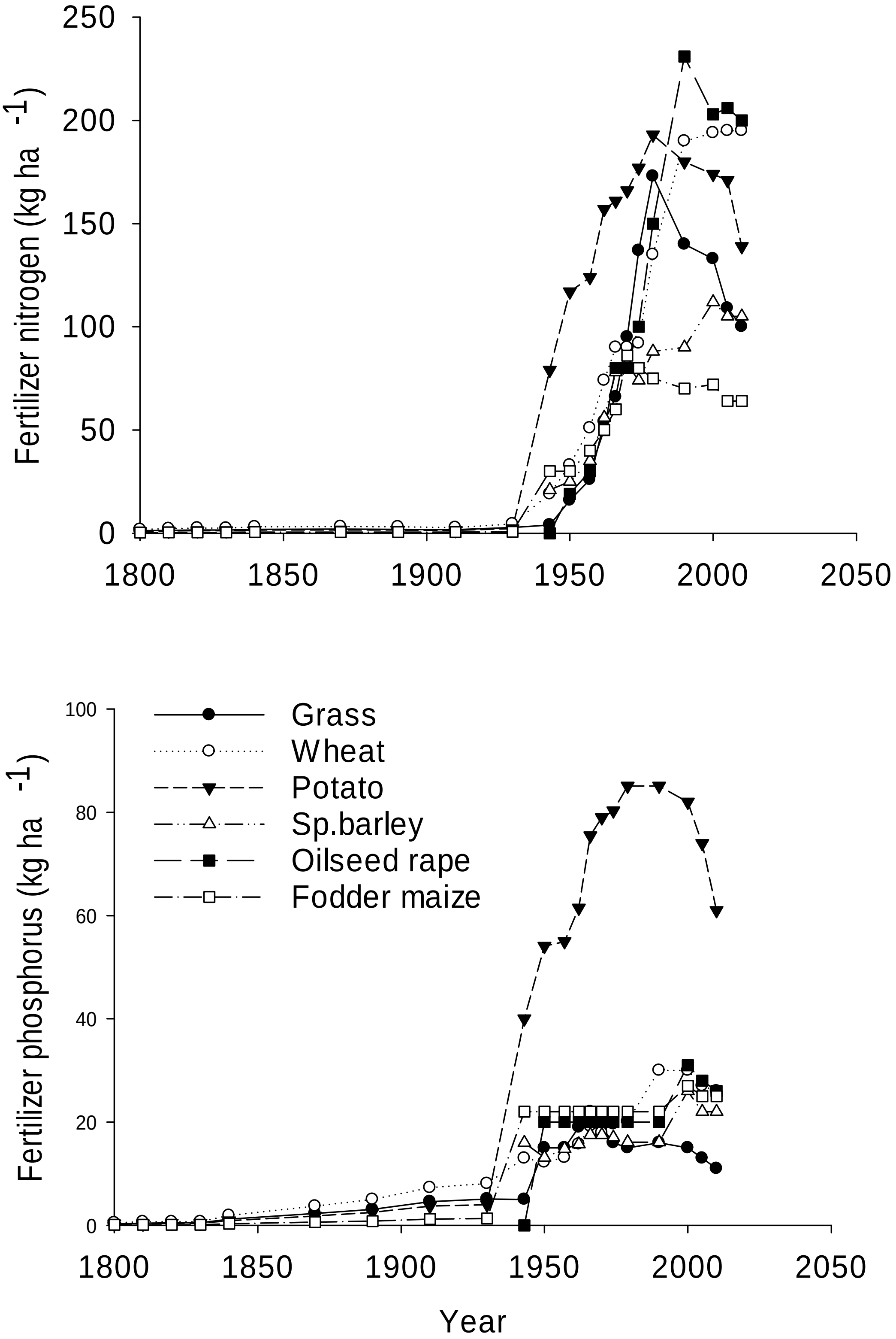
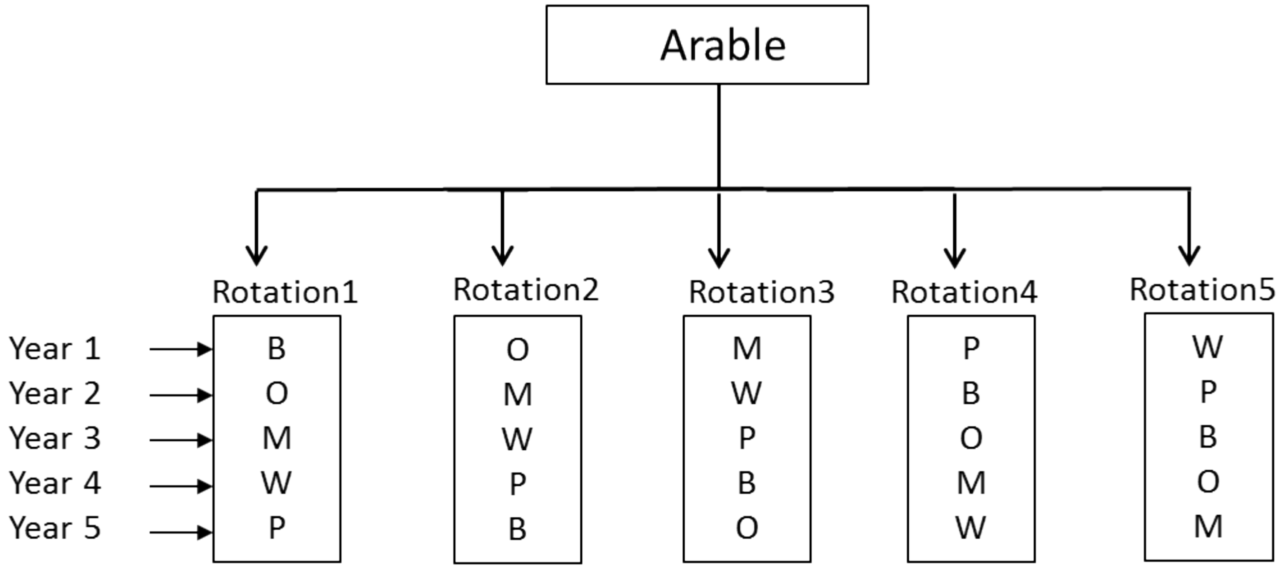


Figure 3. Historical to current rates of nitrogen and phosphorus fertilizer application rates under grass and crops (Archer, 1985; DEFRA, 2011b; Naden *et al.*, 2016).



B: Spring barley, M: fodder maize, O: OSR, P: potato, W: winter wheat

Figure 4. An example scheme of crop rotation in a grid cell with five crops. (This results in five crop rotations with five crops in each individual rotation on a five-year cycle. This scheme will be adapted when the number of crops in a grid cell is less than five by reducing the number of crop rotations, number of crops in each rotation and the duration of the crop rotation cycle).

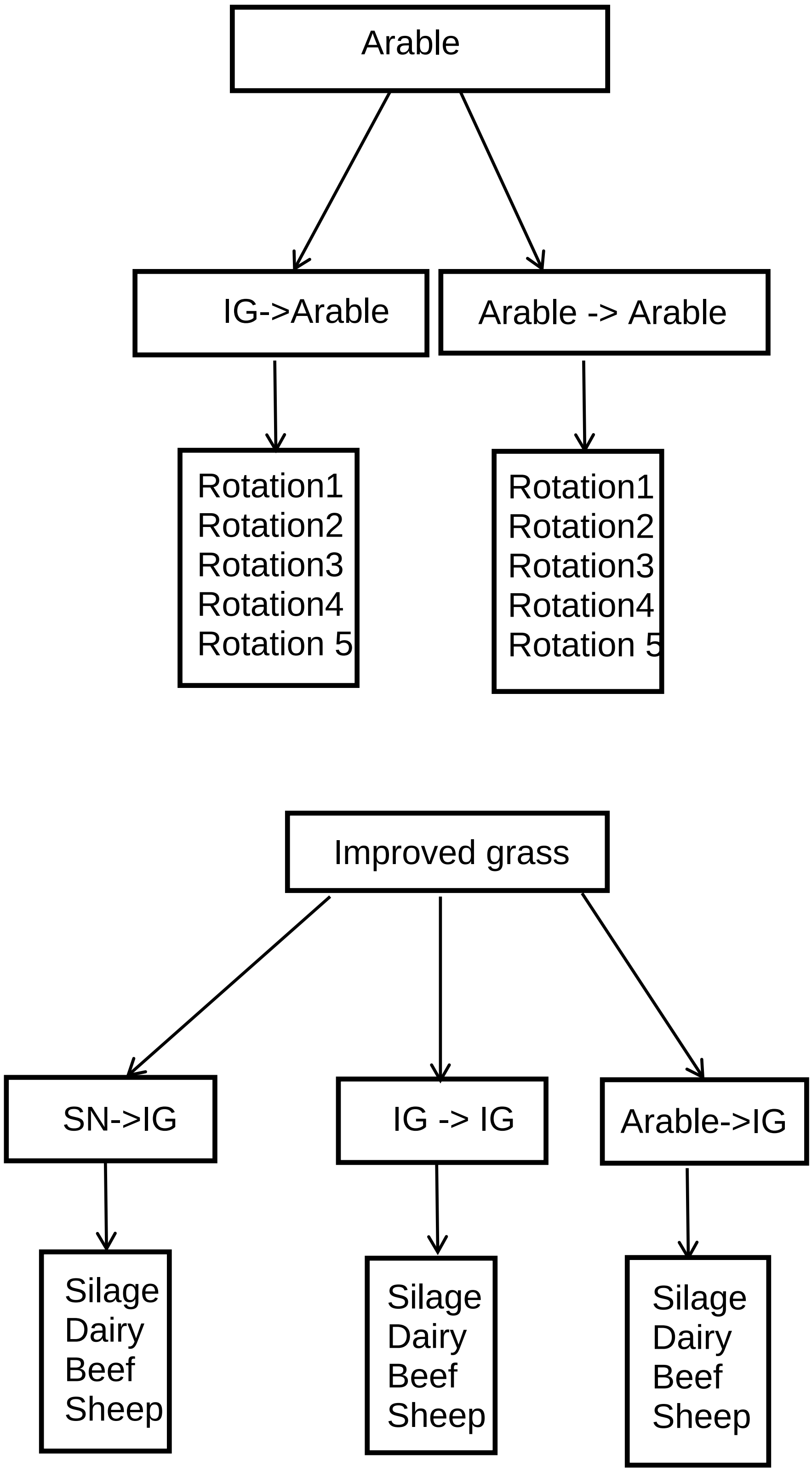


Figure 5. Land cover changes at 1950 leading to different simulation schemes for arable and improved grassland (SN: semi-natural; IG: improved grass).

1800-1950 **1950-1970** **1970-2010**

Winter wheat

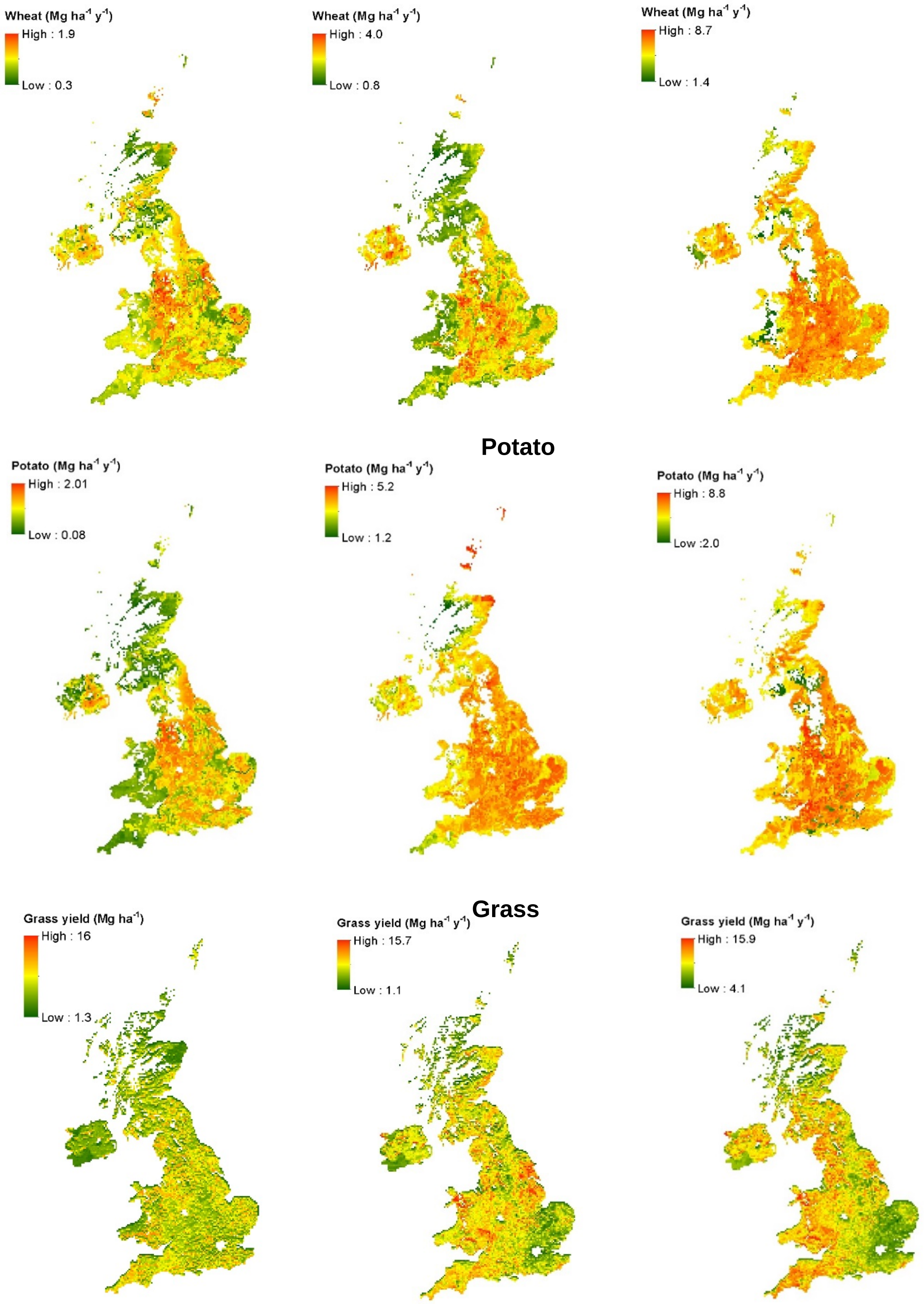


Figure 6. Simulated average wheat, potato and Grass (grazed and/or cut) yields (Mg DM ha^{-1}) at different time periods (1800-1950, 1950-1970 and 1970-2010) across the whole UK (*please note the change in scales*).

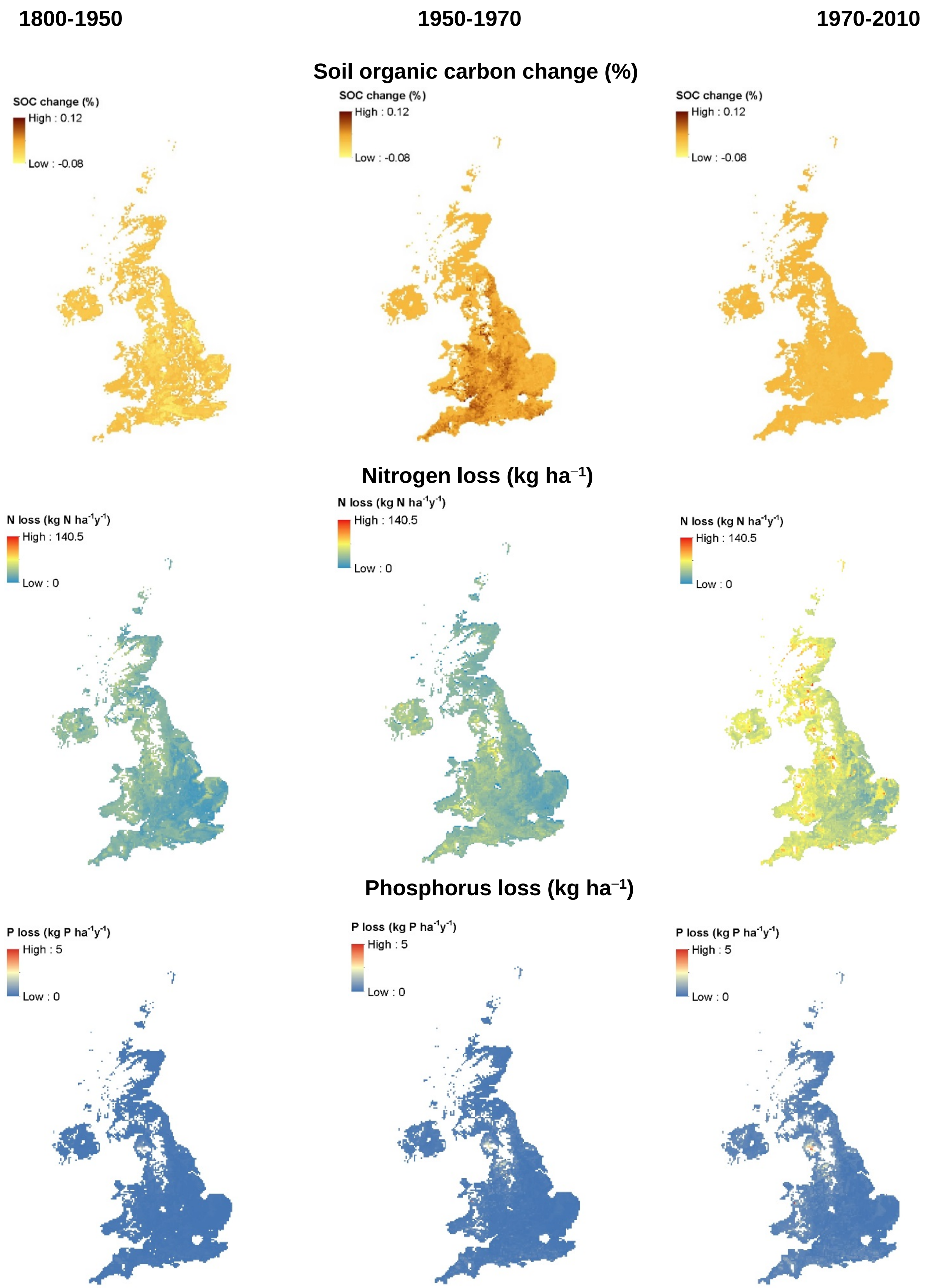


Figure 7. Simulated soil organic carbon change, average annual N and P losses (leaching + runoff) at different time periods (1800-1950, 1950-1970, and 1990-2010) under arable land for the whole UK.

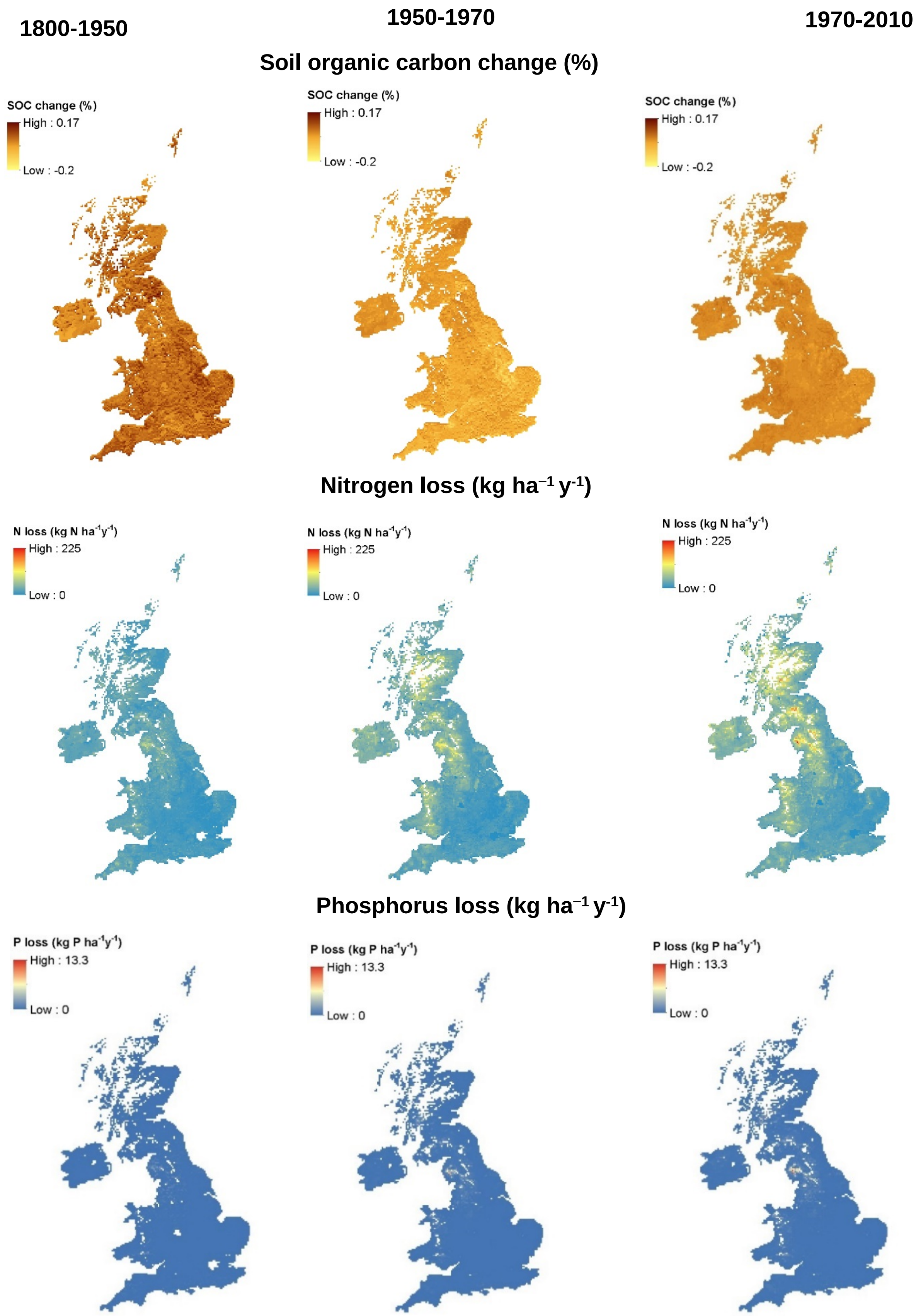


Figure 8. Simulated soil organic carbon change (%), average annual N and P losses at different time periods (1800-1950, 1950-1970 and 1970-2010) under grass land for the whole UK.

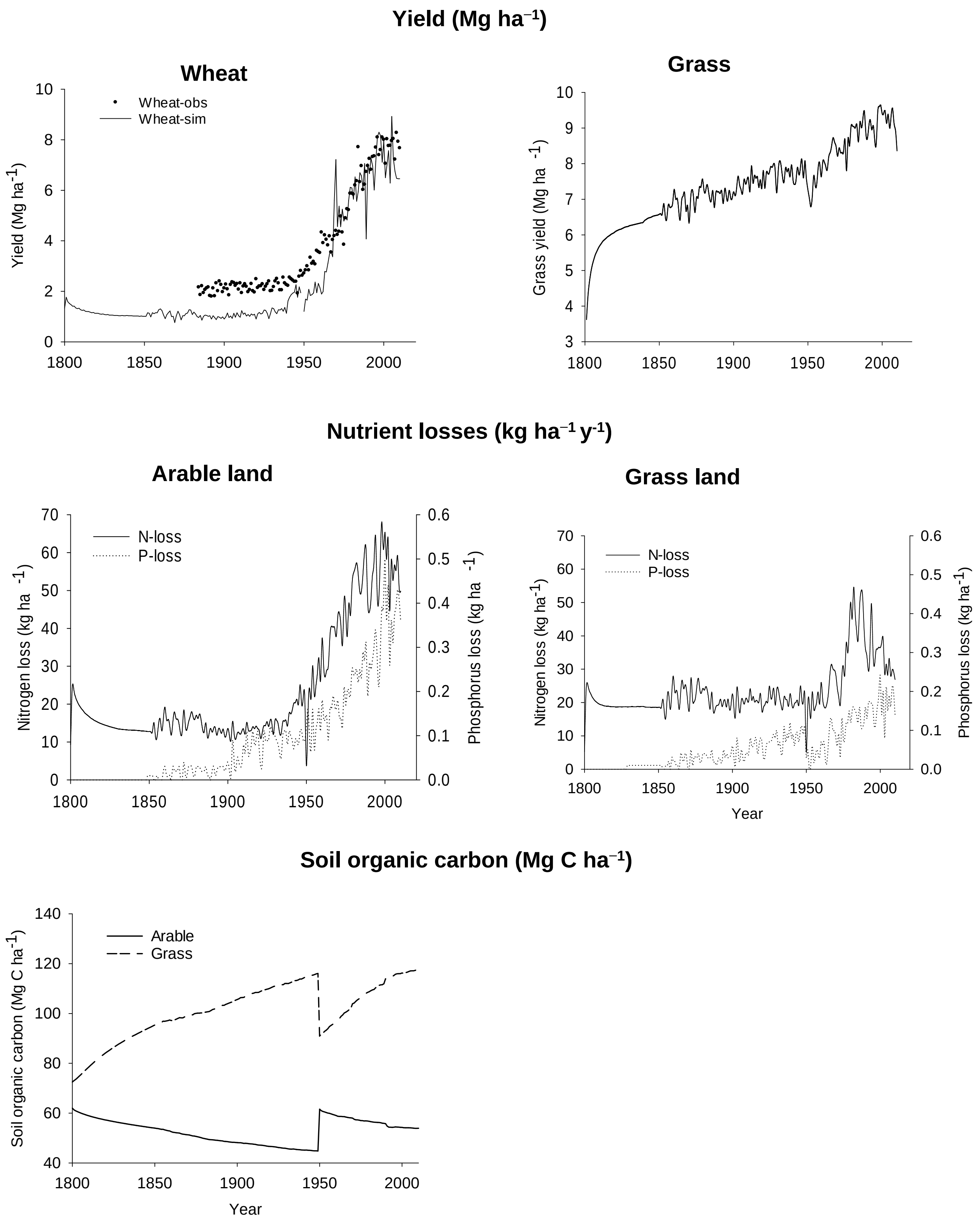


Figure 9. Simulated wheat yield (85% DM) compared to DEFRA reported yield statistics, simulated grass yield, nutrient losses and soil organic carbon (0-30 cm) under arable and grasslands during 1800-2010 averaged across the whole UK.