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Predicting the effect of rotation design on N, P, K balances on organic farms using the NDICEA model

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Abstract

The dynamic model Nitrogen Dynamics in Crop rotations in Ecological Agriculture (NDICEA) was used to assess the nitrogen (N), phosphorus (P) and potassium (K) balance of long-term organic cropping trials and typical organic crop rotations on a range of soil types and rainfall zones in the UK. The measurements of soil N taken at each of the organic trial sites were also used to assess the performance of NDICEA. The modeled outputs compared well to recorded soil N levels, with relatively small error margins. NDICEA therefore seems to be a useful tool for UK organic farmers. The modeling of typical organic rotations has shown that positive N balances can be achieved, although negative N balances can occur under high rainfall conditions and on lighter soil types as a result of leaching. The analysis and modeling also showed that some organic cropping systems rely on imported sources of P and K to maintain an adequate balance and large deficits of both nutrients are apparent in stockless systems. Although the K deficits could be addressed through the buffering capacity of minerals, the amount available for crop uptake will depend on the type and amount of minerals present, current cropping and fertilization practices and the climatic environment. A P deficit represents a more fundamental problem for the maintenance of crop yields and the organic sector currently relies on mined sources of P which represents a fundamental conflict with the International Federation of Organic Agriculture Movements organic principles.

Key words: organic farming, nutrients, sustainability, crop rotation

Introduction

Organic cropping systems focus on feeding the soil, rather than the plant, to build long-term system health and resilience (Lampkin, 2002). This approach results in a reliance on fertility building ley periods and the application of composts and manures, which supply a source of nutrition for the growing crops while potentially improving the soil microbial life and organic matter contents (Lampkin, 2002; Watson et al., 2002). The length of the ley period can vary from short-term (12–18 months) to long-term (around 5 yr), but typically the ley is kept for about 18 months to 3 yr. In Europe, organic farmers most frequently use grass–clover mixes for their leys, with white clover (*Trifolium repens*) and red clover (*Trifolium pratense*) being popular legume species and perennial ryegrass (*Lolium perenne*) and Italian ryegrass (*Lolium multiflorum*) as commonly chosen grass species (Döring et al., 2013). The crops following the ley period make use of the built-up fertility, although the ley period can also remove fertility, in particular potassium (K) in conserved grass (silage). Cropping following the ley phase often includes rotational use of over-winter green manures and cover crops such as cereal rye (*Secale cereale*) and vetch (*Vicia satvia*) to reduce losses and to supply additional nitrogen (N) through biological fixation (Lampkin, 2002). The use of these approaches on organic farms creates systems in which the N supplied is in a less available form, compared with conventional systems using mineral fertilizer (Torstensson et al., 2006). The supply of available N in organic systems can therefore be a limiting factor for the maintenance of crop yields (Berry et al., 2002; Dawson et al., 2008; de Ponti et al., 2012). In addition, poor synchronicity between the supply and demand for N can lead to leaching and gaseous losses, particularly following ley cultivation. Nevertheless, this is also an issue for conventional farmers, particularly following periods of high rainfall (Dawson et al., 2008; Patil et al., 2010; Liang et al., 2011). Under organic management, the surplus of N following ley cultivation can be followed by an N deficit later in the crop rotation (Berry et al., 2002). Although this shortage can be resolved through the application of organic composts, manures and/or through the use of short-term green manures, it can be difficult to match the N supplied from such sources with crop demand. A reliance on such methods can therefore contribute to lower N use efficiencies compared with non-organic systems applying targeted mineral N (Torstensson et al., 2006; Dawson et al., 2008). Despite the challenges of N availability and synchronicity of N supply/demand on organic farms, Berry et al. (2003) found positive N balances in a comparison of nine organic farms, and reported that the farms were probably sustainable in terms of N supply and offtake. However, the same study found that P and K levels were in deficit within the stockless systems assessed, and that only farms with large manure returns from stock fed with bought-in feed had a positive or neutral K budget. Korsaeth (2012) and Torstensson et al. (2006) also found P and K deficits within organic arable cropping and mixed dairy farming systems in Norway and Sweden, respectively.

The research presented here aimed to assess the effect of rotation design on the supply and offtake of N, P and K (NPK) on organic farms using the dynamic model Nitrogen Dynamics in Crop rotations in Ecological Agriculture (NDICEA). Five hypotheses were posed at the outset of this study. First, NDICEA can effectively calculate the course of mineral-N over a range of organic crop rotations. Second, the N supplied through biological fixation in stockless organic rotations is sufficient to support crop offtake. Third, organic cropping systems incorporating livestock manure applications are able to maintain a positive or neutral NPK balance. Fourth, organic rotations will typically rely on imported P to maintain a balance of this nutrient. Fifth, a deficit of K is a common feature in the overall nutrient balance of typical organic crop rotations.

Methods

The NDICEA model (Van der Burgt et al., 2006) was applied to assess the supply and demand of NPK within a range of stocked (i.e., with manure) and stockless rotations applied at experimental organic farms in the UK. In addition, typical organic rotations were drawn from the literature.

Model description

NDICEA is a dynamic, target-oriented model with crop yield and crop quality parameters, e.g., dry matter, NPK contents, used as a basis for crop uptake calculations. Mineralization of N from soil organic matter and organic inputs such as manure and compost is also calculated, factoring in the effects of weather, irrigation and soil type, although the model does not account for volatilization losses during composting/storage of manure. The model uses a daily time step, utilizing site-specific weather data (rainfall, temperature and evapotranspiration) and user-defined soil and crop parameters. Although the model contains default values for a range of soil types these values can be automatically adjusted through the addition of data on measured soil mineral nitrogen (SMN) and soil organic matter within the user interface. Following the entry of these values calibration of the model takes place through the implementation of an algorithm that selects an optimum parameter value from a range of plausible values for such variables as N leaching, denitrification and water-holding capacity (Van der Burgt et al., 2006). Within this study, measured values of SMN and soil organic matter were used to calibrate the model runs and improve the accuracy of the assessments (see Table 1). A repeat calculations function within the model also allows the user to assess the longer term impacts of rotations both in terms of the nutrient supply and the effect on organic matter stocks. The focus of the model is on N dynamics. For P and K, a simpler farm-gate balance approach is taken (i.e., only crop offtake and atmospheric deposition is calculated, based on the user-defined input parameters and/or default values). The calculations for P and K are also unaffected by changing the soil type or daily rainfall and evapotranspiration values within the model. The wide range of cover crops and green manure-options within the NDICEA interface makes the tool particularly applicable for organic farmers; however, the tool can also be used to improve understanding of N dynamics under non-organic management (Van der Burgt et al., 2006). Under both organic and non-organic management model performance will be improved by calibration, with a higher number of measurements improving the accuracy of the estimates of N supply and losses (van der Burgt and Rietberg, 2012).

Description of sites and cropping systems

The model was run using crop, soil and weather data from the UK Government-funded organic conversion trials held at Advanced Driver Assistance Systems (ADAS) Terrington (Cormack, 2006), Warwick University's Hunts Mill site (Lennartsson, 2000) as well as other long-term trials at Elm Farm Research Centre (EFRC) (Welsh et al., 2002), Scotland's Rural College (SRUC Tulloch and Woodside; Taylor et al., 2006) and a grazing only trial at the Institute of Biological, Environmental and Rural Sciences (IBERS) at the University of Aberystwyth (Ty Gwyn) (Haggar and Padel, 1996). Please see Table 2 and Fig. 1 for more information on the trials.

Table 1. Comparison of the error found in calculating soil N (kg N ha^{-1}) produced by uncalibrated and calibrated runs of NDICEA using data collected for the rotations applied at each experimental site.

Site/experiment	*n*	RMSE uncalibrated model	RMSE calibrated model
EFRC A	7	48.8	16.6
EFRC B	7	57.6	48.7
EFRC C	7	30.4	21.5
ADAS Terrington	10	10.9	6.3
Warwick, Hunts Mill Area 1 with FYM	12	47.7	44.1
Warwick, Hunts Mill Area 6 with FYM	12	22.3	19.3
Warwick, Hunts Mill Area 1 no FYM	12	41.0	38.8
Warwick, Hunts Mill Area 6 no FYM	12	23.7	18.6
SRUC Woodside W37	30	12.8	11.6
SRUC Woodside W50	30	14.1	11.8
SRUC Tulloch T50	5	22.0	18.9
SRUC Tulloch T67	5	13.4	6.0
Ty Gwyn	2	8.3	7.5

Note: RMSE = Root-rmean-square error across all measurements, *n* = number of soil mineral N samples used for calibration of the model.

Table 2. Crop rotations used at each of the experimental sites.

Rotation	Course											
	1	2	3	4	5	6	7	8	9	10	11	12
EFRC A	RC	WW	WW	SO								
EFRC B	RC	P	WW	WO								
EFRC C	RC	WW	WB	WW								
ADAS Terrington	RC	RC	P	WW	SB	SW	RC	P	WW	SB		
Warwick, Hunts Mill—Area 1	SB	G/C	G/C	P	C	SBA	G/C					
Warwick, Hunts Mill—Area 6	P	C	SB	P	C	SBA	G/C					
SRUC—Tulloch T50	G/C	G/C	G/C	SO	S	SO						
SRUC—Tulloch T67	G/C	G/C	G/C	G/C	SO	SO						
SRUC—Woodside W37	G/C	G/C	SO	P	SO	G/RC	S	SO				
SRUC—Woodside W50	G/C	G/C	G/C	SO	P	SO						
IBERS—Ty Gwyn*	G/C	G/C	G/C									

Note: C, Carrots; G/C, Grass White Clover; P, Potatoes; RC, Red clover; SBA, Spring barley; SB, Spring beans; SO, Spring oats; S, Swede; SW, Spring wheat; WB, Winter beans; WO, Winter oats; WW, Winter wheat.
*3 year organic conversion period assessed within this study.

Soils data from each site were collected from project reports, site records and published literature (Haggar and Padel, 1996; Lennartsson, 2000; Welsh et al., 2002; Cormack, 2006; Taylor et al., 2006). The bulked soil samples at each site were taken along a W transect twice each year in the case of Elm Farm (Welsh et al., 2002), Warwick University (Lennartsson, 2000) and ADAS Terrington (Cormack, 2006) (after sowing and harvest) and once per year at the SRUC sites (Watson et al., 2011) and at Ty Gwyn (Haggar and Padel, 1996) (January and April, respectively). Samples were analyzed for available P (Modified Morgan's solution at SRUC sites and Olsen's method at other sites), available K (Modified Morgan's solution at SRUC sites and ammonium nitrate extraction at ADAS and Elm Farm), mineral N (potassium chloride solution) and organic matter (loss on ignition). Soil samples were taken at a range of depths. At Elm Farm, separate topsoil (0–15 cm) and subsoil (15–30 cm) samples were assessed for the above parameters. At Warwick University, assessments were carried on samples from 0 to 30 cm and 30 to 60 cms. At Ty Gwyn, mineral N was sampled to 80 cm in 15 and 20 cm increments, respectively, although only the first sample layer was assessed for P, K and organic matter. At ADAS Terrington, all samples were taken to 90 cm in 15 cm increments. At Woodside, the mineral N was sampled to 45 cm in increments of 15 cm, and at Tulloch, the mineral N was sampled to 30 cm in increments of 15 cm.

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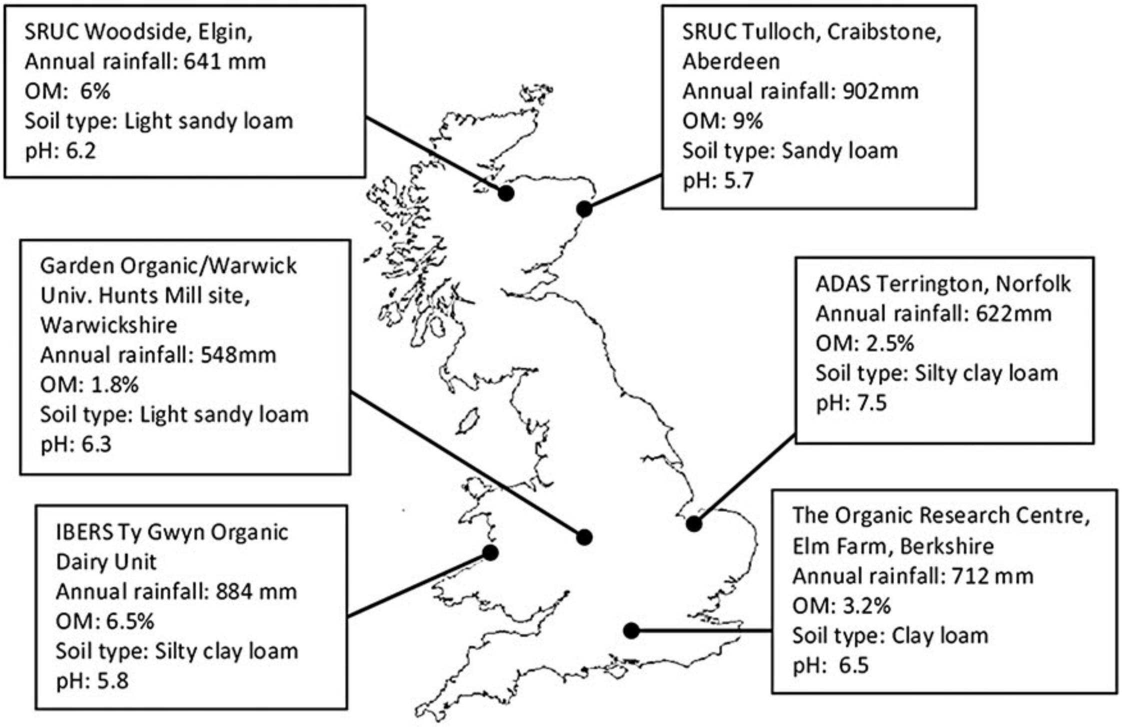

Figure 1. Approximate location and site parameters for each of the long-term organic trial sites. OM, organic matter content of the soil (% loss on ignition). Rainfall amounts are mean values over the course of the trial(s).

Table 3. Typical organic rotations assessed within this study.

Rotation	Course 1	2	3	4	5	6	7	8	9	10
Stocked ‘complex’	G/WC	G/WC	G/WC	WW	WO	RC/G	RC/G	P	SB	SW
Stocked ‘simple’	RC/G	RC/G	WW	P	WW	WR				
Stockless ‘complex’	RC/G	RC/G	P	WO	SB	SW				
Stockless ‘simple’	RC/G	WW	PE	SO						

Note: G/WC, Grass/white clover; RC/G, Red clover/grass; SO, Spring oats; SW, Spring wheat; SB, Spring beans; WO, Winter oats; WW, Winter wheat; WR, Winter rye; P, Potatoes; PE, Peas.

The rotations applied at EFRC and ADAS Terrington were managed as stockless systems, although phosphate fertilizers permitted under organic standards were applied. The EFRC trial received lime up to a maximum rate of 2 t ha^{-1} yr^{-1}. Lime was similarly applied at the ADAS site in order to keep the pH between 6 and 6.5. All of the red clover leys at each site were managed through cutting and mulching. The Hunts Mill plot trials included both ‘with manure’ and ‘without manure’ treatments. Both sites at Hunts Mill, received a single application of green waste compost at a rate of 20 t ha^{-1}. At the Ty Gwyn organic dairy unit, manure was deposited at a rate consistent with 2 Livestock Units (LSU) ha^{-1} and lime was applied at a mean rate of 0.7 t ha^{-1} over 3 yr. At both the SRUC sites (i.e., Tulloch and Woodside) total annual manure applications were based on 2.8 LSU ha^{-1} for the period 1991–1998. In addition, ground limestone and potassium sulfate (K_2SO_4) were applied to all Woodside plots in 1991, at a rate of 3.75 t ha^{-1} and 150 kg ha^{-1}, respectively. All grass–clover leys at SRUC sites were managed through a combination of grazing with sheep and cutting for silage as described in Taylor et al. (2006).

In addition to data from the organic trials, information on typical organic rotations was gathered based on examples within the Organic Farm Management Handbook (Lampkin et al., 2011) and following guidelines given to organic farmers with respect to the proportion of fertility building leys to exploitative phase (Lampkin, 2002; Lampkin et al., 2011) (see Table 3 for description of the rotations used). Manure application rates for the typical stocked cropping systems were derived using typical livestock numbers for cropping farms (i.e., 0.3 Grazing LSU per utilizable agricultural hectare) reported within a sample of approximately 30 organic farms included within the Farm Business Survey (FBS) for England

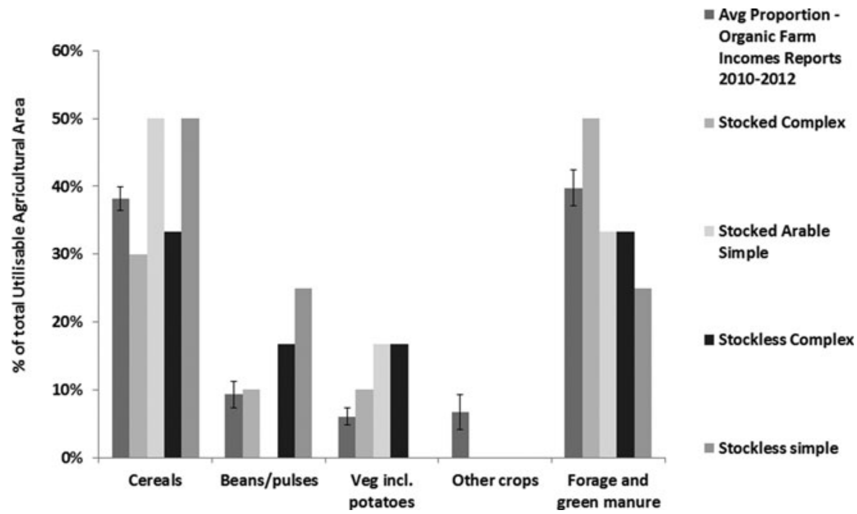

Figure 2. Comparison of the land use by crop type for the typical rotations used within this study to data for 30 'Cropping Farms' collected with the FBS-based Organic Farm Incomes Reports (2010–2012). Error bars = standard error.

and Wales (Moakes and Lampkin, 2010, 2011; Moakes et al., 2012). Rock phosphate application rates were derived with expert input from the Institute of Organic Training and Advice registered advisers.

The rotations were chosen to represent a range of stocked and stockless organic cropping systems. To assess the representativeness of the rotations crop areas were compared with those reported for a stratified sample of 30 organic farms included within the Organic Farm Income Reports published by Aberystwyth University and The Organic Research Centre (Moakes and Lampkin, 2010, 2011; Moakes et al., 2012).

As shown in Fig. 2, the typical rotations are broadly representative of the crop areas reported on actual organic farms within the Farm Income Reports' matched sample. Although there are some differences by crop type (e.g., both stocked simple and stockless simple containing a high percentage of cereal crops), the differences are generally in the region of 15–20%. In view of the wide variation between the rotations on individual farms, this is an acceptable margin of error and the rotations applied here can be considered to be broadly representative of organic cropping farms.

Model application

The model was applied to assess the effect of rotation design on the supply and offtake of NPK on the above experimental sites and within typical organic rotations. The measured changes in soil organic matter over time were small for most of the sites assessed (data not shown). It was therefore necessary to run the model a number of times to ensure a minimal gain or loss of soil organic matter and to avoid erroneous conclusions. Based on measured data and results from long-term experiments (Melillo et al., 1989; Johnston et al., 2009) a uniform, near steady state was assumed to have been reached once the annual change in soil organic matter was less than 2% of the total organic matter pool (expressed in kg ha^{-1}) over the rotation. Two runs of the model were implemented for each site, an uncalibrated run, using only the basic, user-adjusted soil and crop parameters, and a calibrated run following the input of measured amounts of SMN and soil organic matter to make the model automatically adjust to advanced soil parameters such as N leaching and denitrification factors. The root-mean-square errors (RMSE) were calculated based on the size of the deviation between the measured soil N and modeled soil N values and the number of samples at each site. The observed N values were therefore used in the calibrated runs as both inputs to the model and as comparator for assessing model performance. Following the calculation of NPK balances for the trial sites, a further application of the model was implemented for the typical organic rotations described above, using the same soil and weather conditions as the trial sites.

Results and Discussion

The modeled estimates for SMN were compared with the sampled soil N values from each of the sites to test the ability of the model to simulate the measured rotations. An NPK balance for each of the rotations was then calculated.

Comparison of the NDICEA model's estimates for soil N with measured mineral N values at each of the trial sites

A RMSE of 20 kg N ha^{-1} or less was proposed by Van der Burgt et al. (2006) to represent acceptable model performance for practical purposes. This could be achieved for most of the sites, although in some cases

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(e.g., EFRC and Hunts Mill) the modeled results are above this value (see calibrated model output in Table 1). The higher errors at EFRC could be a result of the small number of measurements (i.e., 7). The high errors for the stocked rotations at Hunts Mill could be explained by the fact that soil N measurements were taken soon after application of manures (the modeled values for this phase of the rotation were more than 100 kg N ha^{-1} lower than the recorded values). It may also be possible that the model is underestimating the N supplied or that the deeper samples at Hunts Mill (0–60 cm) resulted in a mixing of topsoil and subsoil layers, and a subsequent overestimate of the mineral N content in the subsoil layer.

NPK balance for each of the rotations applied at the organic trial sites

Modeled nutrient balances derived from NDICEA are presented in Table 4 for each of the stockless rotations. The results include an estimate of the change in soil organic matter, with a negative number indicating mining of existing reserves and a positive number indicating an assimilation of N to soil organic matter (i.e., an increase in organic matter stocks).

Table 4 illustrates that the amount of N supplied through biological fixation could potentially support the crop removal at the EFRC trial, although due to losses from the system, in particular leaching, much of this N is lost. The negative values for organic N indicated a mining of organic matter over the course of the experiment. This decline was observed through field measurements with organic matter levels dropping from 32 to 25 g kg^{-1} of soil, probably as a result of starting the trial after a 5–6 yr ley. Organic matter levels would be expected to rise again on return to a longer-term ley period, as is a standard organic practice. The increase in organic matter levels from the implementation of a 1-year fertility building ley was reflected in the NDICEA model, which showed a rise during this period, although the subsequent decline was more than the offset gain. When a nutrient demanding crop was introduced into the rotation (e.g., potatoes in EFRC B) the deficit for all three nutrients increased to the extent that further use of external inputs (e.g., composts or manures) would be required, in particular for P and K. The high P and K offtake of beans similarly contributed to the large deficit of these two nutrients within the balance for rotation EFRC C.

A similar picture is presented for the rotation at ADAS Terrington. Despite the large contribution of N through fixation, there are considerable losses from leaching and denitrification, resulting in a negative N balance. It may be possible to address this problem through better use of over-winter cover crops (cover crops performed poorly over the course of the experiment with only one crop yielding over 1 t DM ha^{-1}). The deficits for P within this trial are also unsustainable in the long-term and would need to be addressed through imports or reducing the exploitative phase of the rotation. The K deficits for this site are also substantial; however, it may be possible that weathering of K stocks in the mineral pool could redress this (Khan et al., 2014).

Lower rates of leaching were found for both Hunts Mill plots, although considerable deficits of P and K were also found despite the addition of green waste compost on area 1. The K deficits could be addressed through the buffering capacity of K-bearing minerals (Khan et al., 2014); however, the P deficit represents a more fundamental issue for the maintenance of crop yields in the longer term (Cordell et al., 2009). The results for Hunts Mill area 6 also illustrate that it is possible to maintain a fairly balanced system with regard to N through the effective use of late summer/autumn-sown green manures (i.e., without the use of a ley/break crop), although the overall deficit for N may result in a reduction in offtake or the need to use imported composts or manure.

Most of the stocked rotations were found to be more balanced with regard to N and P supply and loss (see Table 5). However, all of the SRUC sites faced a large K deficit, due to the high offtake from grass/clover silage, the potato crop (only at Woodside) and the use of straw for bedding, which were not offset by the manure application. Similar results were found within the nutrient balances for Tulloch and Woodside calculated by Watson et al. (2000) although lower offtake was estimated within this study due to the lower assumptions on P and K content within NDICEA. Despite the K deficit, no trend in K levels was found over time at Tulloch or Woodside, although the soil samples were restricted to the first 30 and 45 cm due to the presence of indurated layers at deeper levels, largely impenetrable to soil augers or crop roots. It is possible that soil K levels at these sites were being supplemented by reserves within parent material, in addition to potential inputs from crop residues (these inputs are ignored in standard soil K measurements and in part explains why test values are unrelated to crop K balances; Khan et al., 2014). These and other factors lead Khan et al. (2014) to suggest that measurements of available soil K are an unreliable indicator and that producers should use strip trials to determine site-specific fertilizer management. At both Woodside sites, the rate of N leaching was higher than at Tulloch, despite a lower annual rainfall. This was in part related to the lighter soil texture and the relatively low yield of the grass/clover leys at Woodside 37 (4–6 t DM ha^{-1}, Taylor et al., 2006) which was related to the high soil moisture deficit. The low grass/clover yield at Woodside 37 also led to a negative N balance overall, due to a lower rate of biological N fixation. Much of the excess N at the other SRUC sites was locked up as organic matter (illustrated as a positive value under ‘Change in organic N’ in Table 5). This was observed within the trial through a small increase in soil organic matter levels observed at Tulloch, although the

Table 4. Nutrient balance of stockless organic rotations/trial sites expressed in kg ha yr^{-1}.

	EFRC A			EFRC B			EFRC C			ADAS			HuntsMill Area 1			HuntsMill Area 6		
	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
Fertilizer applied		8			8			8			8		8	5	18			
Deposition	20		4	20		4	20		4	30	1	5	20		3	20		3
Biological fixation	44			59			59			84			42			21		
Total supply	64	8	4	79	8	4	79	8	4	114	9	5	70	5	22	41	0	3
Volatilization	0			0			0						0			0		
Denitrification	47			54			44			26			24			7		
Leaching	57			57			52			28			18			15		
Product removal	36	8	6	63	17	32	55	14	26	77	15	45	35	9	55	33	10	62
Total loss	140	8	6	174	17	32	151	14	26	131	15	45	77	9	55	55	10	62
Nutrient balance	−76	0	−2	−95	−9	−28	−72	−6	−22	−17	−6	−40	−7	−4	−33	−14	−10	−59
Change in soil organic N	−93			−100			−60			0			−1			−13		
Change in soil mineral N	17			5			−12			−17			−6			−1		

measured organic matter levels at Woodside remained relatively constant. Volatilization rates were low across all of the stocked rotations in Table 5 as a result of incorporating applied manure on the same day as application on the trial sites.

Nutrient (NPK) balance for typical rotations applied using site conditions of the organic trials

Nutrient balances are presented in Table 6 for each of the typical rotations described in Table 3. The results presented below are mean values across all six sites and associated soil/weather conditions.

The stocked complex rotation described above seems to represent a well-balanced system with regard to N and P supply and offtake. However, the model predicted a relatively large K deficit with offtake exceeding supply. As discussed earlier, this could be addressed through K delivery from the weathering of minerals depending on the underlying geology, climatic conditions and site management (Simonsson et al., 2007; Khan et al., 2014), or through imported compost and/or mineral sources. The higher proportion of nutrient-demanding crops (e.g., potatoes) within the stocked simple rotation creates a larger K deficit compared with the stocked complex example. As with the stocked experimental sites in Table 5, volatilization rates were low for all of the stocked rotations in Table 6, as a result of selecting same-day incorporation of manure applied within NDICEA, and the low stocking density (i.e., 0.3 LSU ha^{-1}). The volatilization losses would be expected to increase if incorporation was delayed for any reason.

The stockless complex rotation has a deficit for all three nutrients. Two years of a red clover ley plus 1 yr of spring beans did not provide enough N to support 4 yr of crop offtake due to a high rate of leaching and denitrification. The presence of nutrient demanding crops contributes to the deficit (i.e., potatoes lead to a high N and K demand and beans to a high K offtake). The stockless simple rotation faces less of a deficit with respect to N, due to a higher input of biologically fixed N from the inclusion of peas which have a higher rate of N fixation than beans within NDICEA, and the use of the grass/vetch overwinter green manures following the spring crops. In addition, there is an absence of nutrient demanding crops (e.g., potatoes) however the rate of leaching is still high. The relatively low deficit of P within all of the typical rotations is a result of the application of rock phosphate. All of the modeled rotations would face a P deficit on a similar scale to the K balance without the use of this input.

Implications for improved organic management

In common with previous studies, the work presented here found considerable rates of N leaching within the

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Table 5. Nutrient balance of stocked organic rotations/trial sites expressed in kg ha yr^{-1}.

	Tulloch T50			Tulloch T67			Woodside W50			Woodside W37			Hunts Mill Area 1			Hunts Mill Area 6		
	N	**P**	**K**	**N**	**P**	**K**	**N**	**P**	**K**	**N**	**P**	**K**	**N**	**P**	**K**	**N**	**P**	**K**
Fertilizer applied	63	17	63	83	22	81	63	17	62	38	10	37	48	13	53	62	16	61
Deposition	12	1	7	12	1	7	12	1	7	12	1	7	20		4	20		3
Biological fixation	57			109			112	0	0	60			25			9		
Total supply	132	18	69	204	24	88	187	18	69	110	11	44	93	13	57	91	16	65
Volatilization	7			8			6			5			5			5		
Denitrification	3			3			12			11			15			14		
Leaching	26			30			49			45			29			29		
Product removal	59	17	96	57	36	188	78	19	92	61	17	79	43	10	59	42	11	71
Total loss	95	17	96	98	36	188	145	19	92	122	17	79	92	10	59	90	11	71
Nutrient balance	37	1	−27	106	−12	−100	42	0	−23	−12	−5	−35	1	4	−2	1	4	−6
Change in organic N	32			101			43			6			1			1		
Change in mineral N	5			5			1			−18			0			0		

Table 6. Nutrient balance of typical organic rotations/trial sites expressed in kg ha yr^{-1}.

	Stocked complex				Stocked simple				Stockless complex				Stockless simple			
	N	***se (+/−)***	**P**	**K**	**N**	***se (+/−)***	**P**	**K**	**N**	***se (+/−)***	**P**	**K**	**N**	***se (+/−)***	**P**	**K**
Fertilizer applied	32	*0*	12	23	26	*0*	14	21			8				9	
Deposition	17	*3*		5	17	*2*		5	17	*3*		5	16	*2*		5
Biological fixation	142	*9*			117	*9*			93	*10*			130	*11*		
Total supply	190	*9*	12	28	160	*10*	14	26	109	*10*	8	5	146	*11*	9	5
Volatilization	2	*0*			2	*0*			0	*0*			0	*0*		
Denitrification	21	*2*			17	*2*			31	*3*			26	*2*		
Leaching	35	*9*			39	*9*			50	*10*			57	*11*		
Product removal	79	*0*	13	37	72	*0*	14	42	49	*0*	10	37	55	*0*	10	16
Total loss	137	*8.7*	13	37	130	*10*	14	42	130	*10*	10	37	138	*11*	10	16
Nutrient balance	53	*7*	−1	−9	30	*9*	0	−16	−21	*3*	−2	−32	8	*3*	−1	−11
Change in organic N	51	*8*			28	*8*			−3	*10*			20	*9*		
Change in mineral N	2	*8*			2	*7*			−18	*9*			−12	*7*		

Note: se = standard error (se is only calculated for N as the P and K balances are unaffected by the site conditions).

rotations assessed (Berry et al., 2003; Torstensson et al., 2006; Kirchmann et al., 2007). In some cases, this exceeded the amount lost by product removal (e.g., the stockless simple rotation described in Table 3). High rates of leaching under organic management are related to difficulties associated with matching crop N demand with N availability, particularly following incorporation of the ley when N availability exceeds demand (Torstensson et al., 2006; Aronsson et al., 2007; Bergström et al., 2008). The use of organic manures can also make it difficult to predict N availability, compared with applications of mineral fertilizer (Cassman et al., 2002), making it more difficult to maximize N recovery and crop yields under organic management (Seufert et al., 2012). As a result of these factors, lower use efficiency has been reported for organic cropping in comparisons with conventional systems (Torstensson et al., 2006; Bergström et al., 2008).

The effective use of over winter green manures and undersowing of leys in cereal crops will help to reduce losses and thus enhance overall N efficiency (Kaffka and Koepf, 1989; Torstensson et al., 2006) and the lowest rates of leaching within this study were found for the rotations incorporating undersown crops and cover crops (e.g., ADAS Terrington, Warwick University Hunts Mill). Poor cover-crop establishment (e.g., at the ADAS and Elm Farm experiment) was experienced as a result of competition from weeds and slow emergence which reduced the benefit obtained (ADAS, 2006). Poor cover-crop establishment can also be related to competition from the cash crop, adverse weather conditions and low soil temperatures at the time of sowing (Snapp et al., 2005) In particular, the occasional occurrence of poorly performing cover crops presents an important challenge for the long-term sustainability of stockless systems, which rely on keeping the N supplied through

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biological fixation within the system. Although with careful rotation design, such systems are, in theory, sustainable from an N management perspective (Schmutz et al., 2007), in practice these systems appear to be highly vulnerable to poor establishment during the cover-cropping period.

The use of cover crops is not limited to organic farms, and higher N use efficiencies can be obtained by using this method alongside targeted mineral fertilizer application(s) to meet crop demand (and thus increase yield) whilst minimizing losses (Torstensson et al., 2006). Such tightly controlled systems could represent a suitable approach to developing highly N-efficient production systems, through a combination of organic practices and targeted fertilizer application (Cassman et al., 2002; Godfray, 2014). Similar targeted approaches could still be used on organically managed land, through the use of organic fertilizers with a high N availability (e.g., poultry manure and digestate from slurry-based anaerobic digestion) to supply readily available N at key points in the rotation (Berry et al., 2002; Möller and Stinner, 2009b). However, the application of such sources can increase the occurrence of nitrophilous weeds and their use within organic systems has been questioned as the high N availability leads to feeding the plant instead of the soil (Möller, 2009a) and a reduction in the amount of organic matter applied in the case of digestate (Oelofse et al., 2013; Stinner et al., 2008). The use of perennial crops can also help to reduce leaching in organic systems by keeping the soil covered and improving N synchrony (Di and Cameron, 2002; Cox et al., 2002), although lower yields, weed susceptibility and pest and disease management issues may limit uptake (Pimentel et al., 2012). A lack of technical information, suitable varieties and socioeconomic constraints (e.g., lower consumer demand compared with staple annual crops) also limit the potential for a wider adoption of perennial cropping (Pimentel et al., 2012; Valdivia et al., 2012).

Organic farmers can also reduce N leaching considerably through improved management of manures and slurries. In particular, careful storage, application timing and choice of application method will help to maximize N recovery and minimize losses where slurries and manures are applied (Smith et al., 2002; Webb et al., 2010). Manure analysis can also improve on farm nutrient use efficiency and help to reduce losses by improving understanding of nutrient supply from organic sources (Watson et al., 2005). In some regions, there may be opportunities for farmers to work together to measure the nutrient use efficiency of their systems through a combination of manure and livestock dietary analysis combined with soil sampling (Verhoeven et al., 2003; Le Gal et al., 2011). Such participatory approaches can be effective in allowing improvement options to be identified and for the fine-tuning of production systems. Again the use of such methods is not restricted to organic farms; however, the inability of such farms to access manufactured N fertilizer makes the implementation of such measures all the more important for the effective prediction of N supply.

With regard to P, the modeled systems able to achieve a sustainable balance were using external inputs of rock phosphate to offset losses. Although rock phosphate can help to offset losses, a reliance on this source may result in limited P bioavailability to meet crop demand, due to slow rates of solubilization (Edwards et al., 2010). In addition, the use of such a fertilizer clearly does not fit well with the International Federation of Organic Agriculture Movements (IFOAM) organic principles (IFOAM, 2006), which emphasize the importance of reducing inputs to increase the long-term sustainability of farming systems. Despite this aim, the use of imported manure, straw and/or rock phosphate is common on organic farms, particularly for the supply of P and K (Kirchmann et al., 2008; Oelofse et al., 2010; Nowak et al., 2013). In many cases, manure and straw are sourced from conventional farms, which has led to the conclusion that organic farms are being 'propped-up' by conventional agriculture, and that as a result a large-scale conversion to organic management would be unsustainable (Kirchmann et al., 2008; Oelofse et al., 2010; Nowak et al., 2013). Organic monogastric systems (in particular poultry) also often require imported feed (e.g., soy) to supply protein and essential amino acids (Dekker et al., 2011) and so these systems are supplemented by internationally imported P and K.

The use of household waste and sewage sludge on organic farms could represent a possible solution to reduce the reliance on conventional manure and/or rock phosphate on organic cropping farms, in particular for the sustainable supply of P. Source separated urine also presents an opportunity to apply readily available N and P (Kirchmann et al., 2008; Germer et al., 2011; Karak and Bhattacharyya, 2011). The use of such sources clearly fits with the organic ideal of closing the system as far as possible (Oelofse et al., 2013), although in this case the 'system' expands beyond the farm gate to the consumer (Oelofse et al., 2010). Although there have been many cases of household waste recycling on organic farms to supply nutrients to the soil (Darnhofer, 2005; Altieri et al., 1999; Luske and van der Kamp, 2009), the use of sewage sludge or urine is strictly prohibited on organic land in Europe, despite the fact that its use seems to be a rational and scientifically supported method of closing the nutrient cycle. Developments in the area of struvite (magnesium ammonium phosphate) recovery from waste water treatment plants could present a possible solution, allowing for application of a refined and slow release mineral fertilizer product, however this product is not currently on the list of permitted fertilizer within the European Commission organic regulation (European Council., 2007). This is an area that needs further scrutiny from a scientifically based perspective as it would appear that historical concerns about the toxic effects of applying urine and sewage sludge to agricultural land may no longer be justified (Smith, 2009; Karak and Bhattacharyya, 2011), although public perception concerning the risks to human health remains an issue in some areas (Robinson et al., 2012). Increasing the co-operative use of manure between (organic) livestock and arable farmers has also been suggested as a possible route for reducing the use of conventional manures on organic land and, within farming in general, the co-operative use of manure between specialized livestock and arable holdings could contribute to the prevention of stockpiling of nutrients and associated losses on intensive livestock holdings (Wilkins, 2008; El-Hage Scialabba and Müller-Lindenlauf, 2010). In particular, this approach has been encouraged in Denmark by a decision to phase out the use of conventional manure and straw on organic land by 2021, partly in recognition of the conflict between principle and practice and partly to prevent the import of genetically modified organisms into organic systems via manure (Oelofse et al., 2013). In addition, the transition strategy in Denmark has highlighted the importance of crop rotation design (in particular to improve understanding on nutrient supply and losses), the development of crop cultivars for low-nutrient environments, and the development of biogas plants that can run on plant-based feedstock (in particular grass/clover harvested from leys) in recognition of the limited supply of organic manure (Jørgensen and Kristensen, 2010; Oelofse et al., 2013).

Potassium deficits were observed across all of the rotations however on many soils, this does not present an issue given vast reserves of mineral K within parent material which may be released for plant uptake by weathering (Khan et al., 2014). Despite this potential, Holmqvist et al. (2003) found that weathering and bioavailability from the mineral fraction can vary greatly (between 3 and 80 kg K $ha^{-1} yr^{-1}$ on a range of soil types in Norway, Sweden and Scotland), although the modeled predictions in this study did not take into account the dynamic and localized biological weathering by plant roots illustrated by x-ray diffraction studies (e.g., Hinsinger et al., 1991; Khan et al., 2014) and the potential contribution of mycorrhizal fungi to K availability (Hoffland et al., 2002). Nevertheless, improved knowledge of site-specific geochemical and mineralogical data, in addition to soil rhizosphere interactions could be a useful aid to develop site-specific fertilizer recommendations and nutrient balances (Holmqvist et al., 2003; Andrist-Rangel et al., 2007). With respect to mineral reserves of K on the sites assessed in this study, only EFRC, IBERS and ADAS Terrington could be expected to supply a considerable amount of K from the clay fraction (Buckman and Brady, 1984), although sand- and silt-sized muscovite and biotite can also be a major source of plant-available K on lighter soils (Mengel et al., 1998) and the presence of these and other K-bearing minerals may have offset some or all of the K offtake at Hunts Mill and the Scottish sites (Andrist-Rangel et al., 2010). Despite the high deficits, there was no apparent trend in available K levels over time at most of the experimental sites considered, although Hunts Mill showed a slight decline over the course of the study and the K measurements at Tulloch (taken in the winter) may have been affected by the preceding silage crop (Watson et al., 2000). Other studies have demonstrated a decline in soil P and K levels following conversion to organic management (Loes and Øgaard, 1997; Torstensson et al., 2006) and positive yield responses have been observed following K applications in long-term experiments in Australia and the UK (Bar-Yosef et al., 2015) and within rice production systems, following several years of intensive cropping (Greenland, 1997). It is thus important to use nutrient budgets together with soil analysis to help understand the buffering capacity of soils and the management of P and K on individual fields. It should also be remembered that the bank-balance (i.e., supply minus offtake) concept of nutrient management can have major limitations, as N fertilization in excess of crop removal can lead to a depletion of soil carbon reserves by enhancing microbial decomposition (Khan et al., 2007; Mulvaney et al., 2009). This approach can also lead to an uneconomical fertilizer usage in the case of K that may also have an adverse effects on soil quality and productivity (Khan et al., 2014) although a range of management factors (e.g., N supply and tillage system) can mask the effect of K fertilization on crop yield (Bar-Yosef et al., 2015). It has also been suggested that crop yield and quality reductions following K fertilizer application are more likely to be related to K–Mg and K–Ca antagonism in plant uptake and/or K immobilization in the soil (Bar-Yosef et al., 2015), rather than toxicity in the plant and root zone, or a depletion of the soil structure (Khan et al., 2014).

In summary, it is clear from the analysis and modeling within this study that most typical organic cropping systems in the UK will require nutrient inputs to maintain an NPK balance. It should also be remembered that most organic farms import fewer nutrients than their conventional counterparts (Hansen et al., 2000; Torstensson et al., 2006; Trydeman Knudsen et al., 2006). Although this approach naturally leads to lower yields, and can lead to lower N efficiencies within cropping systems (Torstensson et al., 2006), it can also offer a useful way to balance production and environmental concerns (Gomiero et al., 2011; Francis and Porter, 2011). For example, organic farms often require less fossil energy on a per hectare or kilogram of product basis, in particular through the absence of imported mineral N fertilizer (Smith et al., 2015). The use of grass/clover leys and manures for fertility building on organic farms also contributes to greater soil organic carbon concentrations and stocks on organically managed land (Gattinger et al., 2012). In addition, organic methods (e.g., use of clover and other legumes to supply N) can be used effectively on conventional farms to increase efficiencies and reduce the environmental impacts of the agriculture sector as a whole (Pretty et al., 2005; Gaudin et al., 2013; Godfray, 2014).

Conclusion

An assessment of the NDICEA model has found that it is a useful tool for UK organic farmers to assess the amount of N supplied and lost through their rotations, although the model should be calibrated to improve accuracy for UK conditions where measured crop NPK, soil N and organic matter values are available. The modeling of the NPK balance within organic trials found that in most cases sufficient N is being supplied through biological fixation to support the cropping, although leaching in higher rainfall areas and on lighter soil types may prevent the N from becoming available to the crop(s). The study has also shown that careful rotation design is particularly important within stockless organic systems to reduce losses and avoid the requirements for external inputs as far as possible. Although, adequate N balances are theoretically achievable within stockless organic cropping systems, these systems are highly vulnerable to cover crop failure, poor crop yields and low rates of N fixation within the fertility building period. Negative P and K balances were found for most of the experimental stockless systems and the typical stockless rotations modeled within this study. For P, the systems seem to be dependent on imported rock phosphate for the maintenance of a small surplus or deficit. The much larger K deficits could be addressed through weathering and subsequent bioavailability of mineral K stocks, depending on site and management conditions. On soils with naturally low K deposits within parent material, K inputs in the form of fertilizer or feed may be required to offset removal, or a reduction in K demanding crops (e.g., potatoes) may be necessary.

NPK balances on organic farms are a useful method for exploring the extent to which organic methods can be applied effectively to improve nutrient use efficiencies within agricultural systems. It is likely that the greatest N use efficiencies can be achieved through a combination of organic production methods (e.g., use of cover crops and clover to supply N) combined with conventional farming practices (e.g., use of mineral fertilizer at key points in the rotation to meet crop demands fully and increase yields). In addition, the need to obtain minerals from sustainable sources leads to the conclusion that deriving these from suitably defined wastewater treatment could close the nutrient loop for organic farms, but this would require a change in international standards.

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