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EU-Rotate_N – a Decision Support System – to Predict Environmental and Economic Consequences of the Management of Nitrogen Fertiliser in Crop Rotations

C. R. Rahn[1)], K. Zhang[1)], R. Lillywhite[1)], C. Ramos[2)], J. Doltra[2)], J.M. de Paz[3)], H. Riley[4)], M. Fink[5)], C. Nendel[5)], K. Thorup-Kristensen[6)], A. Pedersen[6)], F. Piro[7)], A. Venezia[7)], C. Firth[8)], U. Schmutz[8)], F. Rayns[8)] and K. Strohmeyer[9)]

([1)]Warwick HRI, University of Warwick, Wellesbourne, Warwick, England, [2)]Instituto Valenciano de Investigaciones Agrarias (IVIA), Moncada, Spain, [3)]Consejo Superior de Investigaciones Científicas (CSIC), Albal/Valencia, Spain, [4)]Bioforsk, Apelsvoll Research Centre, Kapp, Norway, [5)]Institut für Gemüse- und Zierpflanzenbau (IGZ), Großbeeren, Germany, [6)]Department of Horticulture, University of Aarhus, Research Centre Aarslev, Aarslev, Denmark, [7)]Consiglio per la ricerca e la sperimentazione in agricoltura, Istituto sperimentale per l'orticoltura (CRA-ORT), Pontecagnano, Italy, [8)]Henry Doubleday Research Association (HDRA), Ryton Organic Gardens, Coventry, England and [9)]BOLAP GmbH, Speyer, Germany)

Summary

A model has been developed which assesses the economic and environmental performance of crop rotations, in both conventional and organic cropping, for over 70 arable and horticultural crops, and a wide range of growing conditions in Europe. The model, though originally based on the N_ABLE model, has been completely rewritten and contains new routines to simulate root development, the mineralisation and release of nitrogen (N) from soil organic matter and crop residues, and water dynamics in soil. New routines have been added to estimate the effects of sub-optimal rates of N and spacing on the marketable outputs and gross margins. The model provides a mechanism for generating scenarios to represent a range of differing crop and fertiliser management strategies which can be used to evaluate their effects on yield, gross margin and losses of nitrogen through leaching. Such testing has revealed that nitrogen management can be improved and that there is potential to increase gross margins whilst reducing nitrogen losses.

Key words. vegetables – organic production – N-fertiliser management – nitrate leaching – modelling – gross margins

Introduction

Large amounts of nitrogen are applied to intensively cultivated land, especially where field vegetables are grown. Demyttenaere et al. (1990) and Goulding (2000) showed that growing field vegetable crops can lead to large amounts of potentially leachable nitrate being left in the soil after harvest. Since the value of the produce is high in comparison to the cost of additional fertiliser, the temptation to over-fertilise is high, leading to greater risks of nitrate pollution. Increasing environmental concerns about high nitrate levels in drinking water from such intensive land use now demands effective systems of fertiliser recommendation.

Neeteson and Carton (2001) reviewed the multiple pathways by which nitrogen applied to field vegetable crops could pollute the environment. Many EU directives and national regulations are now in place, which seek to regulate the use of fertilisers. Many of these were identified by an EU concerted action, the NUMALEC project (De Clercq et al. 2001).

In some countries, supermarkets are demanding that the produce they sell has been grown according to environmentally sound practices and have introduced assurance schemes as a result. Model based decision support systems can be valuable tools for consultants and farmers to help meet these increasingly tight standards and regulations.

Two existing decision support models: N Expert (Fink and Scharpf 1993) and WELL_N (Rahn et al. 1996) are available to supply fertiliser advice for field vegetable production in Germany and the UK respectively. WELL_N is based on routines in the N_ABLE model (Greenwood 2001). The N_ABLE model, however, only operates on single season crops and Rahn et al. (1992, 1998) demonstrated that crops can be more effectively fertilised if N fertiliser is managed over whole crop rotations.

A new model, EU-Rotate_N, was developed, with EU funding, as a tool for assessing the effects of different fertiliser and rotational practices on losses of nitrogen to the environment and gross margin returns across Europe. This paper describes the model, its validation using a German dataset, and demonstrates its use in examining the effects of different agricultural practices under Norwegian conditions.

Materials and Methods

The model consists of a number of modules which simulate: plant growth both below and above ground, nitrogen mineralisation from the soil and crop residues and subsequent N uptake. These processes are regulated by weather factors such as rainfall, temperature and radiation. Modules simulate the flow of water and nitrogen in the soil, into the plant and subsequent evapotranspiration or leaching. The modules operate on a daily basis, utilising data from soil properties, crop residues, fertiliser and weather data where appropriate (Fig. 1). The model can simulate any number of crops in the rotation with a maximum limit of 30 years.

Description of the soil

In the model, soil is divided into 40 vertical layers of 0.05 m thickness. After planting, these layers are split horizontally into 0.05 m wide cells. The number of cells horizontally depends on row width. When the crop is harvested or the residues are incorporated the horizontal cells are merged into one unit until the next crop is planted. Describing the soil in this way allows for more accurate simulation of root growth of row crops compared to the original N_ABLE model. While the crop is growing all the processes described below are simulated at the cell level.

The basic properties of the soil layers are provided by the user of the model and include the water content at permanent wilting point, field capacity, and at saturation. These hydraulic properties control water availability to the plant and allow calculation of drainage. Mineralisation and losses of nitrogen by denitrification are adjusted for water content. Other inputs include pH, which allows for simulation of N losses where urea fertilisers are used, and the organic matter content of the soil, which affects the supply of N from mineralisation. The clay and sand content is used to calculate denitrification, hydrolysis of urea, and ammonia volatilisation from the top layer.

The water module

Crop evapotranspiration is calculated using the FAO approach (Allen et al. 1998). The main parameters are those related to the evaporative demand of the atmosphere, summarized by the reference evapotranspiration (ET_0) and a crop coefficient that varies with crop development.

The effects of water stress on plant growth are considered and it is assumed that the reduction in dry matter accumulation due to water deficit is proportional to the transpiration reduction (Hanks 1983; Shani and Dudley 2001).

Water infiltration and redistribution in the soil follow a capacitance approach similar to the one in the N_ABLE model, but this has been modified using a drainage coefficient that allows the water transfer between layers above field capacity to be controlled pro-

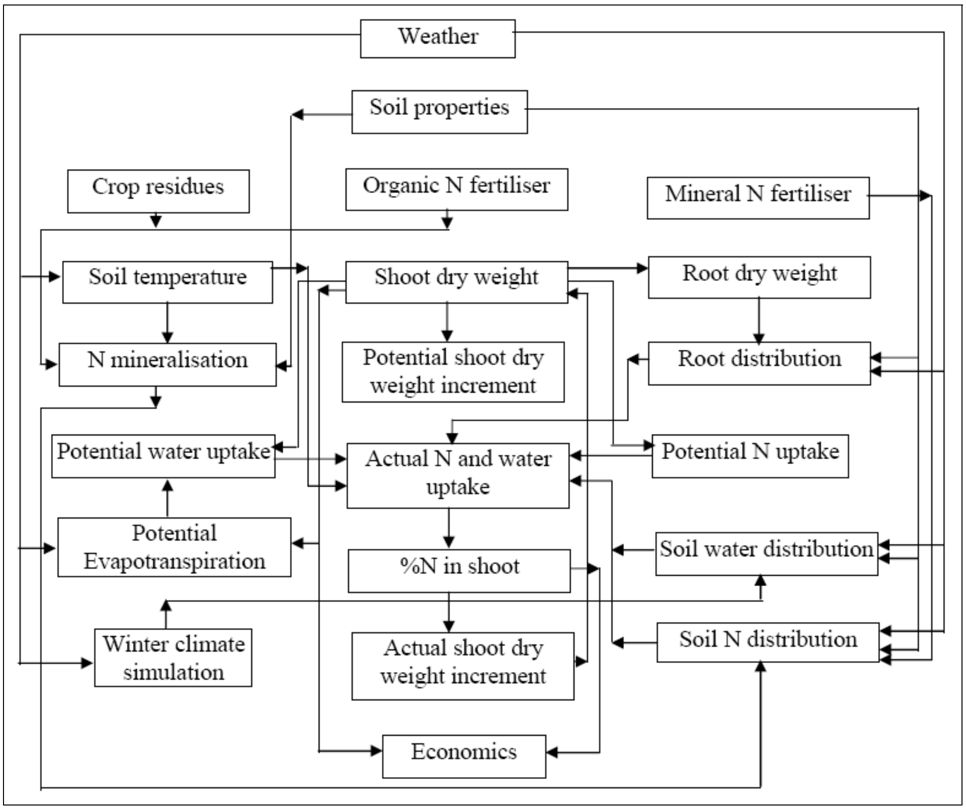

Fig. 1. The organisation of the main model modules.

gressively (in more than one day) and more or less rapidly depending on soil type (Ritchie 1998). Drainage at any depth is given as the downward water flow from the cell elements at this depth. The module also accounts for two-dimensional capillary flow by adopting a soil water normalised diffusion approach (Rose 1968; Ritchie 1998). The main parameters that define the hydraulic soil properties, such as the water content at field capacity and wilting point, are input by the user for the different soil layers. Values can be estimated from soil texture when not available (Saxton et al. 1986).

Runoff is calculated using the approach of the U.S. National Resource Conservation Service (NRCS, formerly the Soil Conservation Service) based on studies of small agricultural watersheds (< 800 ha) across the United States (Nrcs 2004).

Mineralisation module

The calculation of N mineralisation from organic matter is based on the routines used in the DAISY model (Hansen et al. 1990). Carbon dynamics in the soil are described by three pairs (slow or rapid decomposition) of conceptual pools (soil organic matter, soil microbial biomass and added organic matter). Decomposition rate coefficients are temperature and moisture dependent and reflect the environmental conditions of the simulated site; decay and respiration rates of soil microbial biomass are additionally influenced by soil clay content. Efficiency parameters determine the loss of CO_2 during the single turnover processes. N release as NH_4^+ is a consequence of C lost as CO_2 from the system that maintains fixed C to N ratios in the different pools. Processes of nitrification and denitrification are implemented to complete the turnover model.

Residues of crops simulated with the crop growth module enter the mineralisation routine with a dynamic C to N ratio determined by crop N content, harvest index and a factor determining the N content in crop residues relative to the N content in the harvested crop parts, which reflects the growth conditions of the crop during the season with respect to N supply. A fixed C to N ratio is assigned to the slow decomposing part of the material whereas the C to N ratio of the fast decomposable part will then vary depending on total N content in the plant material. Decomposition rate coefficients of both pools are also fixed (Abrahamsen and Hansen 2000). C to N ratios and partitioning coefficients for crop residues are derived from stepwise chemical digestion experiments (Jensen et al. 2005). Parameters for the release of N from manure and slurry were taken from the DAISY model (Abrahamsen and Hansen 2000).

N volatilisation from applied manures and slurries are described using an empirical relation implemented in the ALFAM model (Søgaard et al. 2002). A soil pH dependency factor was introduced by fitting data from He et al. (1999) to Michaelis-Menten kinetics and subsequently normalising the relation between pH and volatilisation half-life time to pH 7.0.

Hydrolysis of, and gaseous N loss from, applied urea fertiliser is calculated based on routines of the AMOVOL model (Sadeghi et al. 1988), taking into account the temperature dependent equilibrium between the ammonium ions in solution and gaseous ammonia, as well as the effect of soil organic matter, soil temperature and soil water content on the hydrolysis process itself. An atmospheric resistance parameter finally governs the loss of gaseous ammonia from the top soil.

Snow and frost module

The original snow model, developed at the University of Helsinki by Vehviläinen and Lohvansuu (1991), was used to calculate water equivalent, but modified by Karvonen (2003) to calculate snow depth, which is important for determining soil freezing and thawing. This has been further modified and calibrated by iterative simulation using a 10-year dataset from Norway, as described by Riley and Bonesmo (2005). The approach has been validated with independent data.

The soil frost module is based on two approaches, one for freezing and one for thawing. The approach for soil freezing was proposed by Olsen and Haugen (1997) and assumed uniform thermal properties throughout the profile; values are taken from the SOIL model (Jansson 1991). The module requires input of surface temperature as modified by the snow pack. The approach used for thawing is that of the ECOMAG model (Motovilov et al. 1999). Both freezing and thawing processes have been validated for Norwegian conditions.

The snow and frost calculation routines affect water infiltration and associated processes such as leaching. In brief, it is assumed that infiltration ceases when soil freezes. If the soil surface is frozen, it is assumed that precipitation is either stored in the snow pack, if present, or it is lost to surface runoff. During snowmelt and soil thaw, an amount of melt-water equal to the difference between field capacity and saturation is stored for later infiltration, whilst the remainder passes to surface runoff. When complete soil thaw occurs the stored melt-water passes through the profile.

Root module

The calculations in the root module consist of three main parts:

i) first the physical extension of the root system is calculated,
ii) then the total root length of the crop is calculated, and
iii) finally the distribution of the root system with depth and distance from the crop row is calculated. The root module has been described and tested in Pedersen et al. (2009).

The depth development of the root system (r_z) is calculated from the accumulated temperature sum (T_{cumul}) from crop planting. After a lag period (ddg_{lag}) the rooting depth increases linearly with accumulated temperature sum from its starting value (z_{start}), using the crop specific rooting depth development rate Kr_z. The length of the lag period and the rate of rooting depth development are controlled with crop specific parameter values. This approach to simulation of crop rooting depth is based on a number of studies showing good linear relationships between accumulated temperature sum and rooting depth (Thorup-Kristensen and Van Den Boogaard 1998; Kage et al. 2000; Kristensen and Thorup-Kristensen 2004; Thorup-Kristensen 2006a).

$$r_z = z_{start} + ((T_{cumul} - ddg_{lag}) \cdot Kr_z) \quad (1)$$

Horizontal root extension is calculated in the same way, but for each soil layer the calculation starts when the roots reach this layer rather than when the crop is planted. In this way horizontal root growth starts progressively later at larger depths.

Root biomass is calculated as a fraction of above-ground crop biomass. For all crops this fraction is reduced with higher crop biomass, but crops are parameterized into three classes with high, medium or low fractions of root biomass. The fraction of biomass allocated to the roots start at 0.65 at very low crop biomass for all root classes, fall to 0.5, 0.3, and 0.2 at 2 t ha^{-1} dry matter, and to 0.1, 0.05 and 0.02 when crop biomass exceed 9 t ha^{-1} for high medium and low fractions respectively. Total root length is then calculated from the simulated root biomass and a fixed specific root length which is used for all crops.

Most vegetable crops are grown as row crops. Simulated root length is distributed spatially into the 2D array of 0.05 by 0.05 m soil cells used in the model to simulate the effects of the row crop structure on crop rooting and uptake of water and nitrogen. Root distribution is calculated to a maximum depth of 2 m, and to a maximum width of half crop row distance. Gerwitz and Page (1974) proposed a logarithmic root length function declining from the topsoil downwards. The assumption of a logarithmic decline in root density has been used in simulation models (e.g. the Daisy model, Hansen et al. 1990), but in these models a rooting depth defined by a very low root density is assumed, and then the logarithmic function is used to distribute root length in the soil layers above the rooting depth. This inevitably leads to very low root densities in deeper soil layers. In our approach the root density at rooting depth is allowed to vary, meaning that we can simulate higher root densities in deep soil layers. Below rooting depth, root density is simulated to decline fast to zero, using a simple linear function. The steepness of the logarithmic decline within the root zone is controlled by one parameter for the vertical distribution (az) and another parameter for the horizontal distribution (ax). The root length at depth z is calculated as:

$$\text{rootlength}_z = L_0 e^{-az \cdot z} \quad (2)$$

where L_0 is root density at the soil surface, and z is the soil depth. Root density decline from beneath the crop row to the inter row soil is calculated by a similar function.

With some crops the plant to plant distance within the row is significant, but the effects of this cannot be simulated by the 2D approach used here, a 3D approach would be needed. During early growth this will lead to an overestimation of N availability, as the model will simulate that all N present close to the crop row will be available to the plants. To avoid this, we use the estimation of root width to calculate the fraction of the soil between plants within a row which is in contact with plant roots, and then reduce daily N uptake by this fraction.

Crop growth and critical N

Crop growth in EU-Rotate_N uses a total dry matter yield at harvest W_{max} in t ha^{-1} as a target yield. This approach overcomes difficulties that arise when trying to parameterise the large variety of different vegetable crops for photosynthesis-driven algorithms, but requires the user to provide the target. Each day the increment in plant dry matter is calculated from:

$$\Delta W = \frac{K_2 G_N G_T G_W W}{K_1 + W} \quad (3)$$

where W is the cumulative dry weight, and $K_1 = 1$ t ha^{-1}. G_T is the effective day degree for the day divided by the average day degree throughout the entire growing period, where the effective day degree is the average temperature for the day less a base temperature, with the limitation that if the average temperature exceeds 20 °C then it is set equal to 20 °C, Greenwood (2001). G_N and G_W are the growth coefficients dependent on crop %N and water supply respectively. K_2 is calculated from the integral of the above equation with G_N G_W and G_T set equal to 1. The equation is then

$$K_2 = \frac{K_1 \ln W_{max} + W_{max} - K_1 \ln W_P - W_P}{T_h - T_P} \quad (4)$$

where W_P is the dry weight at planting, W_{max} is the target total dry matter yield (t ha^{-1}), T_h is the time of final harvest and T_p is the time of drilling or planting in days from January 1st.

We use a unified equation to define critical %N (the minimum N content in the plant required for maximum growth) for different crops, i.e.

$$\%N_{Crit} = a \cdot (1 + b \cdot e^{-0.26W}) \quad (5)$$

where $\%N_{crit}$ is the critical %N, W = total dry matter yield (t ha^{-1}), and a and b are crop-specific coefficients. These coefficients are included for the crops used in the test of the model in Table 1 and are similar to those described in Greenwood (2001).

Luxury N consumption is permitted to take place. It is calculated as follows:

$$\%N_{max} = R_{lux}\ \%N_{crit} \quad (6)$$

where $\%N_{max}$ is the maximum possible crop %N, and R_{lux} (> 1) is the coefficient for luxury N consumption (examples shown in Table 1).

For each day a growth coefficient G_N is calculated as:

$$G_N = \min\left(\frac{\%N}{\%N_{crit}}, 1.0\right) \quad (7)$$

where %N is the actual %N in the dry matter of the whole plant (excluding fibrous roots).

Similarly, a growth coefficient G_W can be activated which regulates growth depending on water supply which is calculated as:

$$G_W = \frac{TR_{act}}{TR} \quad (8)$$

where TR_{act} and TR are the actual and potential transpiration rates.

Table 1. Main crop parameter values used for testing the operation of the EU-Rotate_N model over rotations shown in Table 2.

CROP	a	b	R_{lux}	Base	ddg_{lag}	Kr_z	a_z	HI	N_ratio
Dutch white cabbage	3.45	0.60	1.0	7	100	0.0014	1.5	0.65	0.9
Cabbage (summer)	2.60	1.10	1.0	7	100	0.0010	2.0	0.75	0.9
Cabbage (winter/spring)	2.60	1.10	1.0	7	100	0.0010	1.5	0.54	1.2
Calabrese	3.45	0.60	1.0	7	100	0.0010	2.0	0.28	0.6
Carrot	1.00	1.26	1.5	7	250	0.0007	3.0	0.83	2.0
Cauliflower	3.45	0.60	1.0	7	100	0.0010	2.0	0.45	0.9
Leek	2.00	4.00	1.4	7	350	0.0003	8.0	0.68	1.2
Lettuce butterhead	1.35	1.35	1.0	7	100	0.0010	3.0	0.80	0.8
Lettuce crisp	2.60	1.10	1.0	7	100	0.0010	2.0	0.80	0.8
Maize grain	0.60	9.00	1.0	7	100	0.0014	3.0	0.80	0.8
Onion	1.35	2.42	1.0	7	250	0.0003	8.0	0.75	2.0
Peas	1.35	3.00	1.0	7	100	0.0010	3.0	0.25	0.6
Potato (early)	1.35	3.00	1.5	7	100	0.0007	3.0	0.80	2.0
Potato (late)	1.35	3.00	1.5	7	100	0.0007	3.0	0.95	1.9
Radish	1.35	1.87	1.2	7	100	0.0010	3.0	0.50	1.4
Spinach	1.35	3.00	1.0	7	100	0.0010	3.0	0.71	0.8
Sugar beet	1.11	1.38	1.6	7	250	0.0010	2.0	0.70	2.8
Turnip	1.35	3.00	2.0	7	100	0.0010	2.0	0.47	1.5
Wheat	1.35	3.00	1.2	4	100	0.0010	3.0	0.51	0.3
Lamb's lettuce	1.35	3.00	1.2	4	250	0.0014	3.0	0.95	1.0
Kohlrabi	1.35	3.00	1.4	3	100	0.0014	3.0	0.70	1.5
Celery	1.35	3.00	1.3	6	250	0.0004	3.0	0.70	1.0
Celeriac	1.35	3.00	1.2	6	250	0.0004	3.0	0.71	2.0
Small radish (spring)	1.35	3.00	1.2	2	100	0.0010	3.0	0.84	0.8
Small radish (summer)	1.35	3.00	1.2	2	100	0.0010	3.0	0.85	0.8
Parsley	1.35	3.00	1.4	4	250	0.0010	3.0	0.75	0.6
Radicchio	1.60	3.00	1.3	7	100	0.0012	3.0	0.40	1.0
Spring onion	1.35	2.42	1.0	7	200	0.0003	8.0	0.90	1.0
Barley	1.35	3.00	1.2	4	100	0.0010	3.0	0.51	0.3
Rye and Triticale	1.35	2.00	1.2	4	100	0.0010	3.0	0.50	0.3
Maize (corn cob mix)	0.60	9.00	1.0	7	100	0.0014	3.0	0.70	0.8
Maize (silage)	0.60	9.00	1.0	7	100	0.0014	3.0	0.93	0.8

a and b are crop specific parameters for equation 5 (% N_{crit}); R_{lux} = coefficient for luxury consumption; Base=Base temperature (°C); ddg_{lag} = lag period before root growth begins (°C days); Kr_z = Vertical root penetration rate (m day^{-1} $°C^{-1}$); a_z = Form parameter for root development in vertical and horizontal directions (m); HI = Harvest Index [dry matter basis]; N Ratio = %N in residue DM / %N in harvested DM

N uptake

N uptake is calculated as a function of crop N demand on a specific day and the potential root N uptake on the same day. The simulated crop N demand is calculated in the crop growth part of the model. The potential supply from the soil is calculated as a function of the root length in each soil unit and the content of ammonium-N and nitrate-N in each soil unit to control root N uptake efficiency. This is calculated separately for ammonium and nitrate N. Equation 9 shows the calculation for potential ammonium N uptake.

$$N_{potNH_4} = \frac{rootlength \cdot S_N \cdot (NH_4 - S_1)}{S_2 + NH_4} \qquad (9)$$

with NH_4 being the soil ammonium concentration and S_N a crop specific parameter. Diffusion terms are not included in the simulation, since they are assumed to be very small over the relevant time spans for the simulations. N in the form of nitrate is highly mobile in the soil, and diffusion processes will only limit uptake on the very short term even at low root density. The value of S_1 determines the minimum amount of ammonium-N which can be left in the soil (e.g. THORUP-KRISTENSEN 2001, 2006b), and is set to prevent further uptake when less than 5 kg ammonium-N is present in the top 30 cm soil layer. S_2 reduces N uptake as these minimal values are approached.

A function is then used to balance actual N uptake according to crop N demand and potential root N uptake. At very high or low N supply relative to demand, the uptake will be fully controlled by crop N demand and

Table 2. Crop rotations monitored for model testing.

Nr.		Strategy	FEA	Soil type	SOM (%)	Total N (kg N ha^{-1})	Irrig. (mm)	Crop rotation 1st year	Crop rotation 2nd year
1		intensive	low	silt loam	1.4	570	210	Spring onion – Lamb's lettuce	Winter wheat
2		intensive	low	silt loam	1.3	1182	474	2×Small radish – Spring onion	Small radish – Winter rye
3	a	intensive	high	sandy loam	1.7	240	840	Kohlrabi – Radish	Spinach – Celery
	b					280	840	Kohlrabi – Radish	Spinach – Celeriac
4	a	intensive	high	loamy sand	1.0	590	755	Phacelia – Lettuce – Phacelia	Cauliflower – Phacelia
	b					590	755	Phacelia – Lettuce – Phacelia	Romanesco – Phacelia
5		agriculture	high	silt loam	1.4	450	620	Cauliflower – Cauliflower	Sugar beet
6	a	intensive	low	clay loam	1.5	470	685	Broccoli – Lamb's lettuce	Onion
	b					470	685	Broccoli – Lamb's lettuce	Cauliflower
7	a	organic	high	sandy loam	1.5	65	145	Potato – Weeds – Winter rye	Lettuce
	b					65	205	Potato – Weeds – Winter rye	Kohlrabi
8		organic	high	sandy loam	1.5	250	320	Onion – Spinach – Spinach	Maize
9	a	organic	moderate	silt loam	1.8	120	165	Pea (ind.) – Lamb's lettuce	Parsley
	b					141	165	Pea (ind.) – Lamb's lettuce	Carrot
10		intensive	high	silt loam	1.5	216	350	3×Parsley	Potato – Spinach
11		intensive	low	clay loam	2.3	520	725	2×Broccoli	Potato
12		extensive	high	sandy loam	1.5	260	150	Onion – Mustard	Potato
13		extensive	high	silt loam	1.4	330	195	Lettuce – Sudan grass	Potato – Sudan grass
14		extensive	very high	clay loam	1.5	220	195	Turnip	Radicchio – Ryegrass
15		experiment		sand	1.2	200	503	Carrot – Winter wheat	Lucerne
16		experiment		sand	1.2	380	644	Leek – Winter wheat	Lucerne
17		experiment		sand	1.2	190	334	Spring rye	Carrot
18		experiment		sand	1.2	340	427	Spring rye	Leek
19		experiment		sandy clay loam	2.2	154	251	Carrot	Spring wheat
20		experiment		sandy clay loam	2.2	305	175	Broccoli	Spring wheat
21		experiment		sandy clay loam	2.2	141	100	Spring wheat	Carrot
22		experiment		sandy clay loam	2.2	287	80	Spring wheat	Broccoli

FEA = Farmer's environmental awareness, SOM = Soil organic matter content, Irrig.=Irrigation potential root N supply respectively. When N demand is close to potential N uptake, the simulated uptake will be below either value.

$$N_{up} = N_{demand} \cdot \left(1 - e^{\left(-\frac{N_{pot}}{N_{demand}}\right)}\right) \quad (10)$$

Often, the calculated actual N uptake will be lower than the potential root N supply. When this is the case, the actual depletion of soil N will be reduced proportionally from the potential value in all soil cells. Finally a specific calculation is made of N taken up from below 0.9 m in the soil. This is made as N leaching loss and other N balance figures are shown mainly for the 0–0.9 m soil layer in much of the model output, and it is therefore necessary to have an output showing how much N is taken up from below this zone.

Fertility building crops

As it is difficult to specify an appropriate target yield for a fertility building crop an alternative approach is used. The user specifies Good, Medium or Bad growth to determine crop growth rates rather than final DW production. The increment in plant dry matter on each day is calculated from:

$$\Delta W = \min(G_{type}\, G_N\, G_T\, W, \Delta W_{type}) \quad (11)$$

where W is the cumulative dry weight, G_{type} and ΔW_{type} is set to one of three possible values (Good, Medium, Bad), which categorize growing conditions. Growth rate, varies from 2 to 6% per day for poor and good crops with a maximum dry weight increment of between 20 and 60 kg/ha dry matter for poor and good crops respectively. G_N and G_T are the growth coefficients dependent on the crop %N and day degree. The calculation of the growth coefficient G_N is the same as that for a cash crop.

The growth coefficient G_T is calculated:

$$G_T = \begin{cases} 1.0 \\ \dfrac{\text{day degree} - \text{base temperature}}{10.0 - \text{base temperature}} \\ 0 \end{cases} \quad (12)$$

if day degree > 10.0
base temperature ≤ day degree ≤ 10.0
day degree < base temperature

Another crop parameter, litter loss, specifies the percentage of biomass which is returned to the upper layer of the soil each day; it is then mineralised as a crop residue. This is particularly significant for longer term leys. The user can specify dates at which the crop is mown – on these occasions 50 % of the biomass is either mulched or removed from the field.

Most fertility building crops are legumes and nitrogen fixation is the main source of nitrogen in organic cropping systems. A crop parameter specifies whether the crop is N fixing or not (this also applies to cash crops). The growth of N fixing crops is not limited by nitrogen in the soil as any deficiency in soil supply is met by fixation of N from the air.

Annual crops are killed after an appropriate period of time, for example, after the 1st of March, regardless of the 'harvest date' set by the user. Crops are also killed if the temperature drops below a specified value, Phacelia is killed when the temperature drops below −5 °C.

Modelling of the growth of undersown crops begins at the harvest of the crop canopy with an appropriate dry matter and nitrogen content; the user can choose between Good, Medium and Bad performance as an understorey to provide different starting Dry matter yields which are 2000, 1000, 500 kg ha^{-1} for Good, Medium and Bad crops respectively.

Estimation of marketable yield

Two strategies were adopted to convert total dry matter yield (TDM) into yield of marketable produce.

For the first, our own published and un-published field research data were collected, where both total dry matter and marketable yields were measured across Europe. The algorithms developed allow direct conversion of total dry matter yield (TDM) into fresh marketable yield (MFY) at any given N supply and take into account the effects of both sub- and supra-optimal supply of N.

$$MFY = TDM \cdot R(N_{av}) \quad (13)$$

$R(N_{av})$ being the ratio of marketable yield to total dry matter yield and N_{av} the available nitrogen in soil and plant to 90 cm. The ratio $R(N_{av})$ is specific for each crop and depends on the proportion of available N used for each crop. The formula for $R(N_{av})$ is a linear or polynomial relationship of available nitrogen (N_{av}).

$$R(N_{av}) = r_0 + r_1 \cdot N_{av} + r_2 \cdot N_{av}^2 + r_3 \cdot N_{av}^3 \quad (14)$$

The terms r_0, r_1, r_2, and r_3 are empirically chosen for each crop. For a simple constant relationship r_1, r_2 and $r_3 = 0$. For a linear relationship r_2 and $r_3 = 0$. Otherwise, the relationship is non-linear. For some crops, more polynomial terms may be needed because of different behaviour in the sub- and supra-optimum ranges.

In a second approach, the single plant fresh weight is calculated by using the harvest index (HI) to calculate the dry weight of the harvested parts. Then, with the dry matter content (c_{DM}) and the plant population (n), an average single plant fresh weight yield (PFY) is produced:

$$PFY = \frac{TDM \cdot HI}{n \cdot c_{DM}} \quad (15)$$

A normal distribution of plant fresh weights are assumed with a coefficient of variation (e.g. 20 %) and a lower and upper limit of marketable plant fresh weight can be set (e.g., the EU trade specifications). With this information, an average fresh weight of marketable plants within these specifications is calculated. Using the plant population again, the marketable yield (MFY) and the residues left post-harvest are calculated. A more detailed description of this approach can be found in Nendel et al. (2009).

Plants with a single product per plant use the second approach; other crops, such as those with multiple products or multiple harvests, use the direct conversion approach. After calculation of marketable yield the fraction of N harvested or left in the field as crop residues is then calculated. The ratio of N in the marketed part of the crop to the whole crop is taken from Table 1.

Gross margin calculation

With the marketable yield modelled, the calculation of the crop gross margin (GM) uses the standard equation:

$$GM = MFY \cdot Price - (VC_{ind} + VC_{dep} + VC_{Nfert}) \quad (16)$$

where the variable costs dependent (VC_{dep}) and independent (VC_{ind}) of marketable yield is provided by the user in the model run files. VC_{ind} should include, for example, cost per hectare of seed, transplants, fleece, irrigation, crop protection, and weed control. It should also include the cost of fertiliser application, but not the fertiliser itself. Variable costs dependent (VC_{dep}) on the marketable yield should be provided per unit (e.g. tonnes) marketed and are then multiplied by the modelled marketable yield. They consist of packaging and drying, transport, harvest casual labour and market commission cost. The variable costs (VC_{Nfert}) are the costs of inorganic and organic fertilisers, dependent on the fertiliser amounts and the prices of the fertilisers.

The triggered amount of N fertiliser and number of applications are multiplied by the cost of fertiliser and the cost per application as specified in the input file. Subsidies are not considered in the gross margin calculation. Rotational gross margin is cumulative gross margin of all crops in the rotation (including the negative gross margin of cover crops) divided by the number of years simulated.

Model use

The model requires input data in plain text format to describe soil properties, the initial soil mineral N and initial soil water content conditions. It can then be supplemented by blocks of text for each individual crop. These blocks contain planting and harvesting dates and the management of crop residues. The fertilisation and irrigation of these crops can be controlled by a range of fixed and automatic triggers. The automatic triggers can be used to fertilise or irrigate when certain threshold values are met. To run the model five other text format files are required, one containing meteorological data, and four others containing parameters for mineral, organic fertilisers, crop growth and crop residues. The model, along with example files, can be downloaded from www.warwick.ac.uk/go/eurotaten.

Testing the model

The model was tested against field data acquired from a range of sites in each country participating in the EU-Rotate_N project. Within this short paper it is impossible to reproduce all the results so an example of the validation on an independent data set in Germany is presented.

The Palatinate region in South-West Germany covers the area from the banks of the Rhine in the East to the rising hills of the Palatinate Forest in the West. The Palatinate is one of the economically most important and at the same time one of the most diverse field vegetable production areas in Germany. 19 biannual crop rotations on 14 farms have been monitored from April 2003 until the end of 2004. Growers followed different production strategies, including fertilizer regimes of various intensities. Five rotations were grown on organic farms. A wide range of crops, including all major arable and horticultural crops, was represented. In addition, simulations were performed for 8 rotations similarly monitored at two research stations in eastern Germany, 4 on sand and 4 on clay soils. All crops were grown with a single (non-limiting) level of nitrogen fertilizer, reflecting actual user practice. Details of the crop rotations under observation are given in Table 2.

During the vegetable growing period, soil was sampled every two weeks. Each time, soil samples from 15 points on each plot were taken from 0–30 cm, 30–60 cm, and 60–90 cm depth. In 2004, the frequency of sampling was less as non-vegetable crops such as cereals, maize, sugar beets and fertility building crops were grown. In the soil samples, soil moisture and mineral N content were determined. Total crop dry matter was determined at harvest of each crop Nitrogen content of these samples was determined in a Vario EL element analyser (elementar Analysengeräte GmbH, Hanau, Germany) (Table 2).

To simulate the monitored crop rotations the model was initialised by running it on the same crop rotations twice in advance. This was carried out in order to initialise the starting properties of the soil organic matter pools before the testing against measured data was carried out. Observed yields were set as crop target yield parameters. Weather data observed at the Karlsruhe weather station (Dwd 2003) was used. Soil hydraulic parameters were determined from texture information according to the German Soil Survey Manual (Ag Bodenkunde 1994). Crop parameters that were used are shown in Table 1.

Model performance for soil mineral nitrogen and soil moisture was calculated by comparing measured and predicted values for the three soil layers. For above-ground biomass dry matter and nitrogen concentrations, measured and predicted values at harvest were compared. The following model assessment statistics were used: root mean square error and mean absolute error (RMSE and MAE; Wilmott and Matsuura 2005), model bias (MBE; Addiscott and Whitmore 1987), model efficiency (EF; Nash and Sutcliffe 1970) and index of agreement (d; Wilmott 1981). Two example rotations with different N regimes were selected to demonstrate the applicability of the model:

(i) an organic farm crop rotation on a loamy soil (Rotation 8 in Table 2), where the use of organic fertilisers occasionally leads to very high soil mineral N contents, and

(ii) a conventional, extensive crop rotation on sand (Rotation 15 in Table 2), where all year round ground cover and minimal fertiliser rates result in low soil mineral N levels.

Case studies – Norway

A case study was selected where early vegetable crops were planted within a 6 year rotation with spring cereals as break crops. The case study was selected in contrasting soil types in the southern coastal regions of Norway to illustrate the effects of N management on nitrate require-

Table 3. Statistical evaluation of model performance assessed over 27 sites in Germany: root mean squared error (RSME), mean absolute error (MAE), mean bias error (MBE), modelling efficiency (EF), and index of agreement (d).

		Soil mineral N (kg N ha^{-1})	Soil water (kg kg^{-1})	Dry matter yield (t ha^{-1})	N concentration (%)
n	no unit	2383	771	89	85
RMSE	unit	62.72	0.07	2.02	1.07
MAE	unit	42.38	0.05	0.97	0.81
MBE	unit	−9.87	0.00	−0.75	−0.16
EF	no unit	−0.14	0.51	0.79	0.47
d	no unit	0.71	0.87	0.95	0.82

ment and N leaching. The study was based on two choices of N management.

A survey of grower practice revealed that levels of N fertilizer applied to vegetables often exceed the rates specified by the Norwegian Institute for Agricultural and Environmental Research. The reasons for this include a desire to safeguard against deficiencies as well as a tendency to overestimate the expected/target yield level (to which current recommendations are linked). Growers make little use of mineral N measurements to check for early season N supply, as small field size and limited time in spring combine to make this method impracticable and costly. A modelling approach is an effective way of taking into account previous leaching losses and N mineralization from crop residues. The following two scenarios are compared:

- 'Current recommendations' (set according to yield level, based mainly on Fystro et al. 2006)
- 'Current grower practice' (based on survey if available, otherwise estimated).

Results

Testing the model

Testing the model against field data of 27 highly diverse crop rotations yielded an index of agreement (d) which indicates that 71 % of the variations in soil mineral N, 82 % of the variations in crop N concentration and more than 87 % of the variations in soil water content can be explained by the model, see Table 3.

For dry matter yield, 95 % of the variation was explained by the model. However, this was expected as maximum target yields were an input to the model. On the basis of the statistical tests referred to in the materials and methods section, overall bias (MBE) is relatively low. The performance of the simulations for soil mineral N were variable on individual rotations but the model was still able to simulate the differences in soil mineral N between the two contrasting rotations (Fig. 2). Compared to the observations, the model is able to simulate both production systems with an average Index of agreement of 0.65 for Rotation 8 and 0.33 for Rotation 15. MBE for Rotation 8 was 28.2 kg N ha^{-1} (0–30 cm), −21 (30–60 cm) and −12 kg N ha^{-1} (60–90 cm) and for Rotation 15 3 (0–30 cm), −3 (30–60 cm) and −3 kg N ha^{-1} (60–90 cm), respectively (rotation numbers in Table 2).

Case Study Norway

To parameterise the soil mineralization routine, the EU-Rotate_N model was run without any crops to check that the rates of release of N from soil organic matter were similar to those measured in the field. Once parameterised, the model was run for 3 cropping rotations in the southern coastal region of Norway. Table 4 shows the simulation results. Survey results revealed that growers often applied up to 36 % more N than recommended as good practice. With recommended management practices nitrate concentrations in the drainage water were nearer the 50 mg L^{-1} EU limit for drinking water. The model simulated that on light soils (CS) gross margin increased by 14 %, suggesting that higher grower N rates may be economically but not environmentally justified as simulated leaching was increased by 19 %.

Examination of the detailed outputs showed that there was a leaching peak during the cultivation of the third cauliflower crop and that using currently recommended rates the crop could fail – hence the reason for the higher application rates. Further investigation showed that if the lower rate of nitrogen was split into 3 rather than 2 applications and applied to coincide with crop demand, increases in gross margin could be achieved without applying any additional fertiliser (Table 5). Leaching losses could also be reduced. The most effective treatment to increase gross margin was splitting the N into 6 applications as it made it much more available to the growing crop. A technique such as fertigation might be used to deliver this approach but the capital cost (not included) might outweigh the benefit.

Discussion

The EU-Rotate_N model enables the effect of different strategies of fertilisation and crop management over rotations for both field vegetable and major arable crops to be tested. The example simulations demonstrated that the model is able to predict the soil mineral N dynamics for two contrasting production systems. The model was able to simulate the higher amounts of soil mineral N in the rotation with large inputs of organic N compared with the rotation receiving more optimised inputs of mineral fertiliser N. In the case studies the value of the model to match demand of crops more closely to supply in order to reduce N losses was demonstrated.

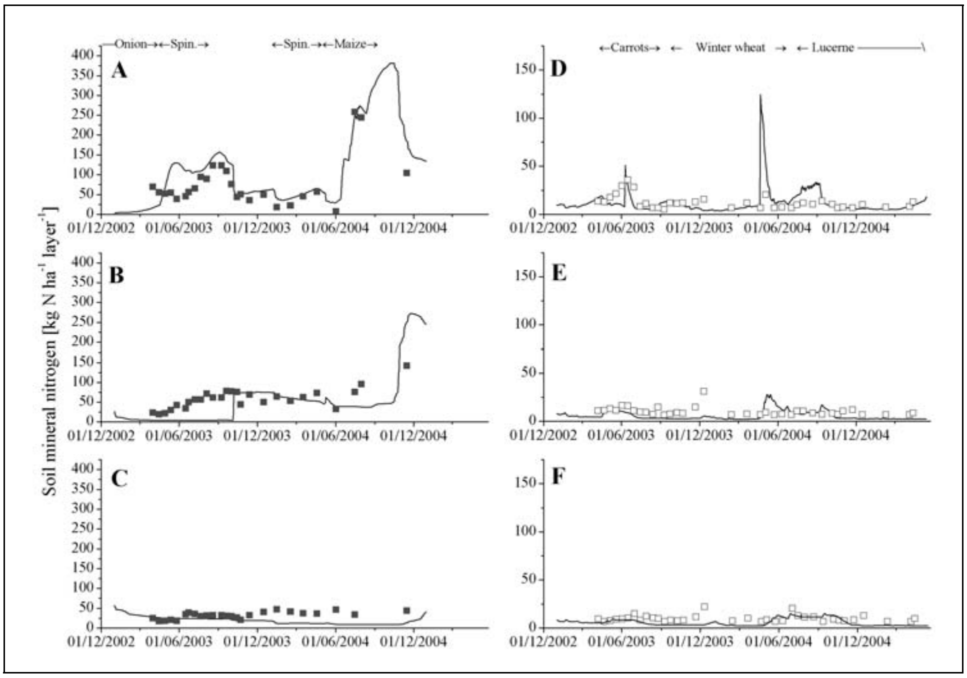

Fig. 2. Soil mineral nitrogen dynamics in 0–30 cm (A, D), 30–60 cm (B, E) and 60–90 cm (C, F) in two different crop rotations (A, B, C: Rotation 8: onion – spinach – spinach – maize on a light sandy loam soil in South-Western Germany; D, E, F: Rotation 15: carrot – winter wheat – lucerne on a sandy soil in Eastern Germany). Symbols: observed data; solid lines: model simulation.

Table 4. Key annual N-flows (kg ha^{-1}) and gross margins (Euro ha^{-1} $year^{-1}$) simulated for various early vegetable crops grown in 6-year rotations with spring cereals in coastal regions of Southern Norway, with currently recommended N fertilizer rates (A), and assumed grower N fertilizer rates (B). (All data are means of all six years in the rotation, calculated for the period 2000–2005).

Soils	Sandy loam	Sandy loam	Sand
Rotation name	AS[1)]	BS[1)]	CS[1)]
Currently recommended rates			
Total N fertilizer	110	142	144
Net N mineralisation	59	71	65
Total N uptake	109	133	118
Marketable N offtake	82	99	90
Leaching below 90 cm	77	99	109
[2)]% Time leaching > 0.1	14.1	15.4	16.1
[3)]Drainage below 90 cm (mm)	762	749	799
Average nitrate concentration (mg l^{-1})	45	58	60
Gr. margin (Euro ha^{-1})	3850	2200	1717
B – Assumed grower N rates			
Total N fertilizer	150	183	183
Total N uptake	125	153	143
Marketable N offtake	94	114	107
Leaching below 90cm	105	123	130
[2)]% Time leaching > 0.1	14.4	15.8	16.2
Average nitrate[2)] concentration (mg l^{-1})	61	73	72
Gr. margin (Euro ha^{-1})	3933	2350	1967

[1)]AS: early potato – early carrot – spring wheat – summer onion – early carrot – spring barley; BS: summer cabbage – early potato – spring wheat – early cauliflower – early potato – spring barley; CS: summer cabbage – early potato – spring wheat – early cauliflower – early potato – spring barley

[2)]Proportion of the rotation time expressed as a % when leached nitrogen was greater than 0.1 kg ha^{-1} day^{-1}.

[3)]Drainage same for both A+B case studies

Table 5. The simulated effect of different fertilizer management strategies on environmental and economic outputs of Cauliflower crops grown on Sand soils in southern Norway.

Practice	Timing and amount of fertilizer (kg ha^{-1} N)	Leaching on 13/05/03 (kg ha^{-1} N)	Gross margin cauliflower crop (Euro)
Recommended rate (2 splits)	10/04 @ 196.0 20/05 @ 43.0	33	−548
Grower practice	10/04 @ 237.0 20/05 @ 52.5	26	555
Modified recommended practice (3 splits)	10/04, 5/05, 30/05 @ 80.0	12	1360
Regular feeding (6 applications)	10/04, 30/04, 10/05, 20/05, 30/05, 9/06 @ 40.0	14	2170

Most of the modules are based on existing models which have already been extensively validated but few studies have validated the operation of the entire model. Currently few datasets covering rotations are available for such a validation to be carried out but this situation should improve in the future.

One of the new modules simulates the growth of roots for field vegetable and some arable crops that are grown in wide rows using a two dimensional approach, the single dimension approach for water and N uptake being inadequate (Schröder et al. 1996; Thorup-Kristensen and Van Den Boogaard 1998, 1999). Since the range of plant morphology in field vegetable crops makes modelling of growth and development of leaf area for photosynthesis too complex (Baranauskis 2005) EU-Rotate_N uses the target yield approach used in the N_ABLE and WELL_N models (Greenwood 2001). This enables the simulation of dry matter accumulation in a large variety of field vegetables with different morphologies as well as in multiple harvest crops such as cucumbers or courgettes. This simplification does lead to a limitation that target yield has to be estimated before the model can be run, however suitable values for target yields can be obtained from previous experiments or can be based on growers expert knowledge.

The model also simulates recovery of N that has leached below the depth of shallow rooted crops by crops with deeper roots allowing the planning of rotations to minimise N losses. The importance of N supply to successive crops through decomposing crop residues, left in the field by the preceding one, is often poorly described in dynamic process-based models for agricultural systems (Kersebaum et al. 2007). Automatically triggered fertilisation and irrigation events allow the calculation of long-term scenarios to assess different strategies for improving the N efficiency in vegetable crop rotations. Such strategies were demonstrated under drip and furrow irrigation systems used by Mediterranean producers (Doltra et al. 2007), within highly variable input production systems (Nendel 2009) or within organic low-input production systems (Schmutz et al. 2006, 2008).

Rotation planning is particularly important in organic production systems where the application of permitted fertilisers and manures must also be optimised. Very simple approaches has been used for predicting N availability in organic systems (Padel 2002; Cuttle 2006), approaches which avoid many of the difficulties associated with the EU-Rotate_N approach of handling the recycling of N as a result of litter loss and mowing residues. However, such simple approaches are also less able to deal with complex rotations and frequent short term fertility building crops common in field vegetable production. A more sophisticated approach has been used in the NDICEA model (Koopmans and Bokhorst 2002; Van Der Burgt et al. 2006), originally developed for use under Dutch conditions. This model does allow rotations to be built up but it does not take into account reductions in yield attributable to lack of water or N, neither does it include any of the economic aspects of EU-Rotate_N.

The ability to calculate gross margins across crop rotations will support farmers in balancing environmental and economic objectives. This is in contrast to typical practice, where evaluations of the economic and environmental impact (in terms of N leaching) of farmer's decisions or political measures range from very simple approaches based on yield and N leaching assessment with the help of non-feedback functions (Hasler 1998) to quite advanced approaches using dynamic soil-crop-atmosphere models for specific problems at different scales. The most frequently employed models in this context are EPIC (Hughes et al. 1995; Teague et al. 1995; Kelly et al. 1996), SOIL-SOILN (Vatn et al. 1999, 2002), FASSET (Berntsen et al. 2003), CropSyst (Fares 2003; Morari et al. 2004) and STICS (Schnebelen et al. 2004). However, these models do not include any economic assessments. An ecological and economical evaluation of different fertiliser strategies on a regional level using EU-Rotate_N was presented by Nendel (2009).

Conclusions

The case study demonstrated how the EU-Rotate_N model can be used as a tool to illustrate the effects of different management strategies on yield and nitrogen losses. It is clear that, following recommended practice which includes assessments of available N in the soil, can reduce the amounts of applied fertiliser in most cases, thereby reducing N losses, particularly by leaching. The simulations in southern Norway illustrate that the model will in some situations recommend higher N rates than those based on National Recommendations, e.g. in situations where there is a risk of significant N leaching loss during crop growth. Helping farmers in general to reduce N inputs, but also sometimes to increase fertilisation of crops where needed due to soil and weather conditions, will be a major advantage of using the model for N advice. However, the model could be further used to refine the management practices to minimise N leaching. These practices could be tested in the field and demonstrated to farmers.

The EU-Rotate_N decision support system provides a platform for evaluating the impact of implementing National Fertiliser Recommendations on crop, environmental and economic outputs of varied crop rotations, which could subsequently allow the identification of leaky points and beneficial practices to plug them. Contrasting beneficial practices, which can reduce the environmental impact with "reasonable" economic costs can be tested against each other. Fluctuations in input and output prices, subsidies and tax effects can also be analysed, providing a dynamic feedback that could help both farmers and policymakers in the future.

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Addresses of authors: Dr Clive Rahn (corresponding author), K. Zhang and R. Lillywhite, Warwick HRI, University of Warwick, Wellesbourne, Warwick, CV35 9EF, England, C. Ramos and J. Doltra, Instituto Valenciano de Investigaciones Agrarias (IVIA), Ctra. Moncada – Apdo. Oficial, 46113 Moncada, Spain, J.M. de Paz, Consejo Superior de Investigaciones Científicas (CSIC). Apdo. Oficial, 46470 Albal/Valencia, Spain, H. Riley, Bioforsk, Apelsvoll Research Centre, 2849 Kapp, Norway, M. Fink and C. Nendel, Institut für Gemüse- und Zierpflanzenbau (IGZ), Theodor-Echtermeyer-Weg 1, 14979 Großbeeren, Germany, C. Nendel (present address:) Leibniz-Centre for Agricultural Landscape Research, Institute for Landscape System Analysis, Eberswalder Straße 84, 15374 Müncheberg, Germany, K. Thorup Kristensen and A. Pedersen, Department of Horticulture, University of Aarhus, Research Centre Aarslev, Kirstinebjergvej 10, 5792 Aarslev, Denmark, F. Piro and A. Venezia, Consiglio per la ricerca e la sperimentazione in agricoltura – Istituto sperimentale per l'orticoltura (CRA-ORT). Via dei Cavalleggeri 25, Casella Postale 48, 84098 Pontecagnano, Italy, C. Firth, U. Schmutz and F. Rayns, Henry Doubleday Research Association (HDRA), Ryton Organic Gardens, Coventry, CV8 3LG, England and K. Strohmeyer, BOLAP GmbH, Obere Langgasse 40, 67346 Speyer, Germany, e-mail: clive.rahn@warwick.ac.uk.