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3
4 **EU-Rotate_N - A Decision Support System To Predict Environmental**
5 **And Economic Consequences Of The Management Of Nitrogen**
6 **Fertiliser In Crop Rotations**

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23

24

25 **Summary**

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

37

38 Key Words: vegetables, organic production, N-fertiliser management, nitrate leaching,
39 modelling, gross margins.

40

41 **Introduction**

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

49 NEETESON and CARTON (2001) reviewed the multiple pathways by which nitrogen applied to field
50 vegetable crops could pollute the environment. Many EU directives and national regulations are
51 now in place, which seek to regulate the use of fertilisers. Many of these were identified by an
52 EU concerted action, the NUMALEC project (DE CLERCQ et al. 2001).

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

57 Two existing decision support models: N Expert (FINK and SCHARPF 1993) and WELL_N (RAHN
58 et al. 1996) are available to supply fertiliser advice for field vegetable production in Germany and
59 the UK respectively. WELL_N is based on routines in the N_ABLE model (GREENWOOD 2001).
60 The N_ABLE model, however, only operates on single season crops and RAHN et al. (1992,
61 1998) demonstrated that crops can be more effectively fertilised if N fertiliser is managed over
62 whole crop rotations.

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

68

69 **Materials and Methods**

70
71 The model consists of a number of modules which simulate: plant growth both below and above
72 ground, nitrogen mineralisation from the soil and crop residues and subsequent N uptake. These
73 processes are regulated by weather factors such as rainfall, temperature and radiation. Modules
74 simulate the flow of water and nitrogen in the soil, into the plant and subsequent
75 evapotranspiration or leaching. The modules operate on a daily basis, utilising data from soil
76 properties, crop residues, fertiliser and weather data where appropriate (Figure 1). The model can
77 simulate any number of crops in the rotation with a maximum limit of 30 years.

78

79 *<Figure 1>: The organisation of the main model modules.*

80

81 **Description of the soil**

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

88

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

96

97 **The water module**

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

101
102 The effects of water stress on plant growth are considered and it is assumed that the reduction in
103 dry matter accumulation due to water deficit is proportional to the transpiration reduction (HANKS
104 1983; SHANI and DUDLEY 2001).

105
106 Water infiltration and redistribution in the soil follow a capacitance approach similar to the one in
107 the N_ABLE model, but this has been modified using a drainage coefficient that allows the water
108 transfer between layers above field capacity to be controlled progressively (in more than one day)
109 and more or less rapidly depending on soil type (RITCHIE 1998). Drainage at any depth is given
110 as the downward water flow from the cell elements at this depth. The module also accounts for
111 two-dimensional capillary flow by adopting a soil water normalised diffusion approach (ROSE
112 1968; RITCHIE 1998). The main parameters that define the hydraulic soil properties, such as the
113 water content at field capacity and wilting point, are input by the user for the different soil layers.
114 Values can be estimated from soil texture when not available. (SAXTON et al. 1986)

115
116 Runoff is calculated using the approach by the U.S. National Resource Conservation Service
117 (NRCS, formerly the Soil Conservation Service) based on studies of small agricultural
118 watersheds (< 800 ha) across the United States. (NRCS 2004)

119
120 ***Mineralisation module***

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

129 pools. Processes of nitrification and denitrification are implemented to complete the turnover
130 model.

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

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

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

150

151 ***Snow and frost module***

152 The original snow model, developed at the University of Helsinki by VEHVILÄINEN and
153 LOHVANSUU (1991), was used to calculate water equivalent, but modified by KARVONEN (2003)
154 to calculate snow depth, which is important for determining soil freezing and thawing. This has
155 been further modified and calibrated by iterative simulation using a 10-year dataset from
156 Norway, as described by RILEY and BONESMO (2005). The approach has been validated with
157 independent data.

158

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

165
166 The snow and frost calculation routines affect water infiltration and associated processes such as
167 leaching. In brief, it is assumed that infiltration ceases when soil freezes. If the soil surface is
168 frozen, it is assumed that precipitation is either stored in the snow pack, if present, or it is lost to
169 surface runoff. During snowmelt and soil thaw, an amount of melt-water equal to the difference
170 between field capacity and saturation is stored for later infiltration, whilst the remainder passes to
171 surface runoff. When complete soil thaw occurs the stored melt-water passes through the profile.

172

173 **Root module**

174 The calculations in the root module consist of three main parts: i) first the physical extension of
175 the root system is calculated, ii) then the total root length of the crop is calculated, and iii) finally
176 the distribution of the root system with depth and distance from the crop row is calculated. The
177 root module has been described and tested in PEDERSEN et al. (2009).

178

179 The depth development of the root system (r_z) is calculated from the accumulated temperature
180 sum (T_{cumul}) from crop planting. After a lag period (ddg_{lag}) the rooting depth increases linearly
181 with accumulated temperature sum from its starting value (z_{start}), using the crop specific rooting
182 depth develop rate Kr_z . After a lag period (ddg_{lag}) the rooting depth increases linearly with
183 accumulated temperature sum from its starting value (z_{start}). The length of the lag period and the
184 rate of rooting depth development are controlled with crop specific parameter values. This
185 approach to simulation of crop rooting depth is based on a number of studies showing good linear
186 relationships between accumulated temperature sum and rooting depth (KRISTENSEN and
187 THORUP-KRISTENSEN 2004; THORUP-KRISTENSEN 2006; THORUP-KRISTENSEN and VAN DEN
188 BOOGAARD 1998; KAGE et al. 2000).

189

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

191

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

195

196 Root biomass is calculated as a fraction of aboveground crop biomass. For all crops this fraction
197 is reduced with higher crop biomass, but crops are parameterized into three classes with either
198 high, medium or low fractions of root biomass. The fraction of biomass allocated to the roots
199 start at 0.65 at very low crop biomass for all root classes, fall to 0.5, 0.3, and 0.2 at 2 Mg dry
200 matter ha⁻¹, and to 0.1, 0.05 and 0.02 when crop biomass exceed 9 Mg ha⁻¹ for high medium and
201 low fractions respectively. Total root length is then calculated from the simulated root biomass
202 and a fixed specific root length which is used for all crops.

203

204 Most vegetable crops are grown as row crops. Simulated root length is distributed spatially into
205 the 2D array of 0.05 by 0.05 m soil cells used in the model to simulate the effects of the row crop
206 structure on crop rooting and uptake of water and nitrogen. Root distribution is calculated to a
207 maximum depth of 2 m, and to a maximum width of half crop row distance. GERWITZ and PAGE
208 (1974) proposed a logarithmic root length function declining from the topsoil downwards. The
209 assumption of a logarithmic decline in root density has been used in simulation models (e.g. the
210 Daisy model, HANSEN et al. 1990), but in these models a rooting depth defined by a very low root
211 density is assumed, and then the logarithmic function is used to distribute root length in the soil
212 layers above the rooting depth. This inevitably leads to very low root densities in deeper soil
213 layers. In our approach the root density at rooting depth is allowed to vary, meaning that we can
214 simulate higher root densities in deep soil layers. Below rooting depth, root density is simulated
215 to decline fast to zero, using a simple linear function. The steepness of the logarithmic decline
216 within the root zone is controlled by one parameter for the vertical distribution (az) and another
217 parameter for the horizontal distribution (ax). The root length at depth z is calculated as:

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

219

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

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

228
229

230 **Crop growth and critical N**

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

235

$$236 \quad \Delta W = \frac{K_2 G_N G_T G_W W}{K_1 + W} \quad (3)$$

237

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

244

$$245 \quad K_2 = \frac{K_1 \ln W_{\max} + W_{\max} - K_1 \ln W_P - W_P}{T_h - T_P} \quad (4)$$

246

247 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
248 of final harvest and T_p is the time of drilling or planting in days from Jan 1st.

249
250 We use a unified equation to define critical %N (The minimum N content in the plant required for
251 maximum growth) for different crops, i.e.

$$252 \quad \quad \quad \% N_{crit} = a \cdot (1 + b \cdot e^{-0.26W}) \quad (5)$$

254
255 where $\%N_{crit}$ is the critical %N, W = total dry matter yield ($t\ ha^{-1}$), and a and b are crop-specific
256 coefficients. These coefficients are included for the crops used in the test of the model in Table 1 and
257 are similar to those described in GREENWOOD (2001).

258
259 Luxury N consumption is permitted to take place. It is calculated as follows:

$$260 \quad \quad \quad \% N_{max} = R_{lux} \% N_{crit} \quad (6)$$

262
263 where $\%N_{max}$ is the maximum possible crop %N, and R_{lux} (>1) is the coefficient for luxury N
264 consumption (examples shown in Table 1)
265).

266
267 For each day a growth coefficient G_N is calculated as:

$$268 \quad \quad \quad G_N = \min\left(\frac{\% N}{\% N_{crit}}, 1.0\right) \quad (7)$$

270
271 where %N is the actual %N in the dry matter of the whole plant (excluding fibrous roots).

272
273 Similarly, a growth coefficient G_W can be activated which regulates growth depending on water
274 supply which is calculated as:

275

276
$$G_w = \frac{TR_{act}}{TR} \quad (8)$$

277

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

279

<<Table 1>>

280

281

282

283 ***N uptake***

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

290

291
$$N_{potNH_4} = \frac{rootlength \cdot S_N \cdot (NH_4 - S_1)}{S_2 + NH_4} \quad (9)$$

292

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

301

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

304 crop N demand and potential root N supply respectively. When N demand is close to potential N
305 uptake, the simulated uptake will be below either value.

306

$$307 \quad N_{up} = N_{demand} \cdot \left(1 - e^{\left(-\frac{N_{pot}}{N_{demand}} \right)} \right) \quad (10)$$

308

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

315

316

317 ***Fertility building crops***

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

322

$$323 \quad \Delta W = \min(G_{type} G_N G_T W, \Delta W_{type}) \quad (11)$$

324

325 where W is the cumulative dry weight, G_{type} and ΔW_{type} is set to one of three possible values (good,
326 medium, bad), which categorize growing conditions. Growth rate, varies from 2 to 6% per day for
327 poor and good crops with a maximum dry weight increment of between 20 and 60 kg/ha dry matter
328 for poor and good crops respectively.. G_N and G_T are the growth coefficients dependent on the crop
329 %N and day degree. The calculation of the growth coefficient G_N is the same as that for a cash crop.
330 The growth coefficient G_T is calculated:

331

$$G_T = \begin{cases} 1.0 & \text{if } \textit{day degree} > 10.0 \\ \frac{\textit{day degree} - \textit{base temperature}}{10.0 - \textit{base temperature}} & \textit{base temperature} \leq \textit{day degree} \leq 10.0 \\ 0 & \textit{day degree} < \textit{base temperature} \end{cases} \quad (12)$$

333
 334 Another crop parameter, litter loss, specifies the percentage of biomass which is returned to the
 335 upper layer of the soil each day; it is then mineralised as a crop residue. This is particularly
 336 significant for longer term leys. The user can specify dates at which the crop is mown – on these
 337 occasions 50% of the biomass is either mulched or removed from the field.

338
 339 Most fertility building crops are legumes and nitrogen fixation is the main source of nitrogen in
 340 organic cropping systems. A crop parameter specifies whether the crop is N fixing or not (this also
 341 applies to cash crops). The growth of N fixing crops is not limited by nitrogen in the soil as any
 342 deficiency in soil supply is met by fixation of N from the air.

343
 344 Annual crops are killed after an appropriate period of time for example after the 1st of March.
 345 regardless of the ‘harvest date’ set by the user. Crops are also killed if the temperature drops below a
 346 specified value, Phacelia is killed when the temperature drops below -5 °C..

347
 348 Modelling of the growth of undersown crops begins at the harvest of the crop canopy with an
 349 appropriate dry matter and nitrogen content; the user can choose between Good, Medium and Bad
 350 performance as an understorey to provide different starting Dry matter yields which are 2000, 1000,
 351 500 kg/ha for good medium and bad crops respectively.

352
 353 ***Estimation of marketable yield***

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

356
 357 For the first, our own published and un-published field research data were collected, where both
 358 total dry matter and marketable yields were measured across Europe. The algorithms developed

359 allow direct conversion of total dry matter yield (TDM) into fresh marketable yield (MFY) at any
360 given N supply and take into account the effects of both sub- and supra-optimal supply of N.

361

$$362 \quad MFY = TDM \cdot R(N_{av}) \quad (13)$$

363

364 $R(N_{av})$ being the ratio of marketable yield to total dry matter yield and N_{av} the available nitrogen
365 in soil and plant to 90 cm. The ratio $R(N_{av})$ is specific for each crop and depends on the
366 proportion of available N used for each crop. The formula for $R(N_{av})$ is a linear or polynomial
367 relationship of available nitrogen (N_{av}).

368

$$369 \quad R(N_{av}) = r_0 + r_1 \cdot N_{av} + r_2 \cdot N_{av}^2 + r_3 \cdot N_{av}^3 \quad (14)$$

370

371 The terms r_0 , r_1 , r_2 , and r_3 are empirically chosen for each crop. For a simple constant relationship
372 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
373 some crops, more polynomial terms may be needed because of different behaviour in the sub-
374 and supra-optimum ranges.

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

$$378 \quad PFY = \frac{TDM \cdot HI}{n \cdot c_{DM}} \quad (15)$$

379 A normal distribution of plant fresh weights are assumed with a coefficient of variation (e.g.
380 20%) and a lower and upper limit of marketable plant fresh weight can be set (e.g., the EU trade
381 specifications). With this information, an average fresh weight of marketable plants within these
382 specifications is calculated. Using the plant population again, the marketable yield (MFY) and the
383 residues left post-harvest are calculated. A more detailed description of this approach can be
384 found in NENDEL et al. (2008).

385

386 Plants with a single product per plant use the second approach; other crops, such as those with
387 multiple products or multiple harvests, use the direct conversion approach. After calculation of

388 marketable yield the fraction of N harvested or left in the field as crop residues is then calculated.
389 The ratio of N in the marketed part of the crop to the whole crop is taken from the Crop shown in
390 Table 1.

391

392 **Gross margin calculation**

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

$$395 \quad GM = MFY \cdot Price - (VC_{ind} + VC_{dep} + VC_{Nfert}) \quad (17)$$

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

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

409

410 **Model use**

411 The model requires input data in plain text format to describe soil properties, the initial soil
412 mineral N and initial soil water content conditions. It can then be supplemented by blocks of text
413 for each individual crop. These blocks contain planting and harvesting dates and the management
414 of crop residues. The fertilisation and irrigation of these crops can be controlled by a range of
415 fixed and automatic triggers. The automatic triggers can be used to fertilise or irrigate when

416 certain threshold values are met. To run the model five other text format files are required, one
417 containing meteorological data, and four others containing parameters for mineral and organic
418 fertilisers, crop growth and crop residues. The model, along with example files, can be
419 downloaded from

420 www.warwick.ac.uk/go/eurotaten

421 ***Testing the model***

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

425 The Palatinate region in South-West Germany covers the area from the banks of the Rhine in the
426 East to the rising hills of the Palatinate Forest in the West. The Palatinate is one of the
427 economically most important and at the same time one of the most diverse field vegetable
428 production areas in Germany. 19 biannual crop rotations on 14 farms have been monitored from
429 April 2003 until the end of 2004. The growers followed different production strategies, including
430 fertilizer regimes of various intensities. Five rotations were grown on organic farms. A wide
431 range of crops, including all major arable and horticultural crops, was represented. In addition,
432 simulations were performed for 8 rotations similarly monitored at two research stations in eastern
433 Germany, 4 on sand and 4 on clay soils. All crops were grown with a single (non-limiting) level
434 of nitrogen fertilizer, reflecting actual user practice. Details of the crop rotations under
435 observation are given in 21.

436

437 << Table 2 >>

438

439 During the vegetable growing period, soil was sampled every two weeks. Each time, soil samples
440 from 15 points on each plot were taken from 0-30 cm, 30-60 cm, and 60-90 cm depth. In 2004,
441 the frequency of sampling was less whilst non-vegetable crops such as cereals, maize, sugar beets
442 and fertility building crops were grown. In the soil samples, soil moisture and mineral N content
443 were determined. Total crop dry matter was determined at harvest of each crop Nitrogen content

444 of these samples was determined in a Vario EL element analyser (elementar Analysengeräte
445 GmbH, Hanau, Germany).

446 .

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

454

455 Model performance for soil mineral nitrogen and soil moisture was calculated by comparing
456 measured and predicted values for the three soil layers. For above-ground biomass dry matter and
457 nitrogen concentrations, measured and predicted values at harvest were compared. The following
458 model assessment statistics were used: root mean square error and mean absolute error (RMSE
459 and MAE; WILMOTT and MATSUURA 2005), model bias (MBE; ADDISCOTT and WHITMORE
460 1987), model efficiency (EF; NASH and SUTCLIFFE 1970) and index of agreement (d; WILMOTT
461 1981). Two example rotations with different N regimes were selected to demonstrate the
462 applicability of the model: (i) an organic farm crop rotation on a loamy soil (Rotation 8 in 2),
463 where the use of organic fertilisers occasionally leads to very high soil mineral N contents, and
464 (ii) a conventional, extensive crop rotation on sand (Rotation 15 in 2), where all year round
465 ground cover and minimal fertiliser rates result in low soil mineral N levels.

466

467 ***Case studies - Norway***

468 A case study was selected where early vegetable crops were planted within a 6 year rotation with
469 spring cereals as break crops. The case study was selected in contrasting soil types in the southern
470 coastal regions of Norway to illustrate the effects of N management on nitrate requirement and N
471 leaching. The study was based on two choices of N management.

472

473 A survey of grower practice revealed that levels of N fertilizer applied to vegetables often exceed
474 the rates specified by the Norwegian Institute for Agricultural and Environmental Research. The

475 reasons for this include a desire to safeguard against deficiencies as well as a tendency to
476 overestimate the expected/target yield level (to which current recommendations are linked).
477 Growers make little use of mineral N measurements to check for early season N supply, as small
478 field size and limited time in spring combine to make this method impracticable and costly. A
479 modelling approach is an effective way of taking into account previous leaching losses and N
480 mineralization from crop residues. The following two scenarios are compared:

- 481 • ‘Current recommendations’ (set according to yield level, based mainly on FYSTRO et al.
482 2006)
- 483 • ‘Current grower practice’ (based on survey if available, otherwise estimated)

484 **Results**

485 ***Testing the model***

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

490

491 <<Table 3>>

492

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

503 << Figure 2 >>

504
505 **Case Study Norway**
506 To parameterise the soil mineralization routine, the EU-Rotate_N model was run without any
507 crops to check that the rates of release of N from soil organic matter were similar to those
508 measured in the field. Once parameterised, the model was run for 3 cropping rotations in the
509 southern coastal region of Norway. Table 4 shows the simulation results. Survey results revealed
510 that growers often applied up to 36% more N than recommended as good practice. With
511 recommended management practices nitrate concentrations in the drainage water were nearer the
512 50 mg/litre EU limit for drinking water. The model simulated that on light soils (CS) gross
513 margin increased by 14%, suggesting that higher grower N rates may be economically justified
514 but not environmentally as simulated leaching was increased by 19%.

515
516 Examination of the detailed outputs showed that there was a leaching peak during the cultivation
517 of the third cauliflower crop and that using currently recommended rates the crop could fail –
518 hence the reason for the higher application rates. Further investigation showed that if the lower
519 rate of nitrogen was split into 3 rather than 2 applications and applied to coincide with crop
520 demand, increases in gross margin could be achieved without applying any additional fertiliser
521 (Table 5). Leaching losses could also be reduced. The most effective treatment to increase gross
522 margin was splitting the N into 6 applications as it made it much more available to the growing
523 crop. A technique such as fertigation might be used to deliver this approach but the capital cost
524 (not included) might outweigh the benefit.

525
526 <Table 4>

527 <Table 5>

528
529 **Discussion**

530 The EU-Rotate_N model enables the effect of different strategies of fertilisation and crop
531 management over rotations for both field vegetable and major arable crops to be tested. The
532 example simulations demonstrated that the model is able to predict the soil mineral N dynamics

533 for two contrasting production systems. The model was able to simulate the higher amounts of
534 soil mineral N in the rotation with large inputs of organic N compared with the rotation receiving
535 more optimised inputs of mineral fertiliser N. In the case studies the value of the model to match
536 demand of crops more closely to supply in order to reduce N losses was demonstrated.

537
538 Most of the modules are based on existing models which have already been extensively validated
539 but few studies have validated the operation of the entire model. Currently few datasets covering
540 rotations are available for such a validation to be carried out but this situation should improve in
541 the future.

542
543 One of the new modules simulates the growth of roots for field vegetable and some arable crops
544 that are grown in wide rows using a two dimensional approach the single dimension approach for
545 water and N uptake being inadequate (SCHRÖDER et al. 1996; THORUP-KRISTENSEN and VAN DEN
546 BOOGAARD 1998, 1999). Since the range of plant morphology in field vegetable crops makes
547 modelling of growth and development of leaf area for photosynthesis too complex
548 (BARANAUSKIS 2005) EU-Rotate_N uses the target yield approach used in the N_ABLE and
549 WELL_N models (GREENWOOD 2001). This enables the simulation of dry matter accumulation in
550 a large variety of field vegetables with different morphologies as well as in multiple harvest crops
551 such as cucumbers or courgettes. This simplification does lead to a limitation that target yield
552 has to be estimated before the model can be run, however suitable values for target yields can be
553 obtained from previous experiments or can be based on growers expert knowledge.

554
555 The model also simulates recovery of N that has leached below the depth of shallow rooted crops,
556 by crops with deeper roots allowing the planning of rotations to minimise N losses. The
557 importance of N supply to successive crops through decomposing crop residues, left in the field
558 by the preceding one, is often poorly described in dynamic process based -models for agricultural
559 systems (KERSEBAUM et al. 2007). Automatically triggered fertilisation and irrigation events
560 allow the calculation of long-term scenarios to assess different strategies for improving the N
561 efficiency in vegetable crop rotations. Such strategies were demonstrated under drip and furrow
562 irrigation systems used by Mediterranean producers (DOLTRA et al. 2007), within highly variable

563 input production systems (NENDEL 2009) or within organic low-input production systems
564 (SCHMUTZ et al. 2006, 2008)

565
566 Rotation planning is particularly important in organic production systems where the application
567 of permitted fertilisers and manures must also be optimised. Very simple approaches has been
568 used for predicting N availability in organic systems (PADEL 2002, CUTTLE 2006), approaches
569 which avoid many of the difficulties associated with the EU-Rotate_N approach of handling the
570 recycling of N as a result of litter loss and mowing residues. However, such simple approaches
571 are also less able to deal with complex rotations and frequent short term fertility building crops
572 common in field vegetable production. A more sophisticated approach has been used in the
573 NDICEA model (KOOPMANS and BOKHORST 2002; VAN DER BURGT et al. 2006), originally
574 developed for use under Dutch conditions. This model does allow rotations to be built up but it
575 does not take into account reductions in yield attributable to lack of water or N, neither does it
576 include any of the economic aspects of EU-Rotate_N.

577
578 The ability to calculate gross margins across crop rotations will support farmers in balancing
579 environmental and economic objectives. This is in contrast to typical practice, where evaluations
580 of the economic and environmental impact (in terms of N leaching) of farmer's decisions or
581 political measures range from very simple approaches based on yield and N leaching assessment
582 with the help of non-feedback functions (HASLER 1998) to quite advanced approaches using
583 dynamic soil-crop-atmosphere models for specific problems at different scales. The most
584 frequently employed models in this context are EPIC (HUGHES et al. 1995; TEAGUE et al. 1995;
585 KELLY et al. 1996; JOHNSON, SOIL-SOILN (VATN et al. 1999, 2002), FASSET (BERNTSEN et al.
586 2003), CropSyst (FARES 2003; MORARI et al. 2004) and STICS (SCHNEBELEN et al. 2004).
587 However, these models do not include any economic assessments. An ecological and economical
588 evaluation of different fertiliser strategies on a regional level using EU-Rotate_N was presented
589 by NENDEL (2009).

590

591 **Conclusions**

592

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

604
605 The EU-Rotate_N decision support system provides a platform for evaluating the impact of
606 implementing national fertiliser recommendations on crop, environmental and economic outputs
607 of varied crop rotations, which could subsequently allow the identification of leaky points and
608 beneficial practices to plug them. Contrasting beneficial practices, which can reduce the
609 environmental impact with “reasonable” economic costs can be tested against each other.
610 Fluctuations in input and output prices, subsidies and tax effects can also be analysed, providing
611 a dynamic feedback that could help both farmers and policymakers in the future.

612
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617

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800 **Tables**

801

802 **Table 1** Main crop parameter values used for testing the operation of the EU-Rotate_N model over

803 rotations shown in Table 2

804

805

806 **Table 2** Crop rotations monitored for model testing. FEA = Farmer's environmental awareness, SOM =

807 Soil organic matter content.

808

809 **Table 3** Statistical evaluation of model performance assessed over 27 sites in Germany: root mean squared

810 error (RSME), mean absolute error (MAE), mean bias error (MBE), modeling efficiency (EF), and index

811 of agreement (d).

812

813 **Table 4.** Key annual N-flows (kg/ha) and gross margins (Euro/ha per year) simulated for various

814 early vegetable crops grown in 6-year rotations with spring cereals in coastal regions of Southern

815 Norway, with currently recommended N fertilizer rates (A), and assumed grower N fertilizer

816 rates (B). (All data are means of all six years in the rotation, calculated for the period 2000-2005)

817 ¹ Proportion of the rotation time expressed as a % when leached nitrogen was greater than

818 0.1 kg/ha/day.

819 ² Drainage same for both A+B case studies

820

821 **Table 5.** The simulated effect of different fertilizer management strategies on environmental and

822 economic outputs of Cauliflower crops grown on Sand soils in southern Norway

823

824 **Figures**

825

826 **Figure 1:** The organisation of the main model modules.

827

828 **Figure 2**

829 Soil mineral nitrogen dynamics in 0-30 cm (A, D), 30-60 cm (B, E) and 60-90 cm (C, F) in two

830 different crop rotations (A, B, C: Rotation 8: onion – spinach – spinach – maize on a light sandy

831 loam soil in South-Western Germany; D, E, F:Rotation 15: carrot – winter wheat – lucerne on a

832 sandy soil in Eastern Germany). Symbols: observed data; solid lines: model simulation.

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834 s

Table 1

CROP	a	b	Rl _{UX}	Base	ddg _{lag}	Kr _z	a _z	HI	N_ratio
Dutch_White_Cabbage	3.45	0.6	1	7	100	0.0014	1.5	0.65	0.9
Cabbage_Summer	2.6	1.1	1	7	100	0.001	2	0.75	0.9
Cabbage_Wint/Spring	2.6	1.1	1	7	100	0.001	1.5	0.54	1.2
Calabres	3.45	0.6	1	7	100	0.001	2	0.28	0.6
Carrot	1	1.26	1.5	7	250	0.0007	3	0.83	2
Cauliflower	3.45	0.6	1	7	100	0.001	2	0.45	0.9
Leek	2	4	1.4	7	350	0.0003	8	0.68	1.2
Lettuce_Butterhead	1.35	1.35	1	7	100	0.001	3	0.8	0.8
Lettuce_Crisp	2.6	1.1	1	7	100	0.001	2	0.8	0.8
Maize_grain	0.6	9	1	7	100	0.0014	3	0.8	0.8
Onion	1.35	2.42	1	7	250	0.0003	8	0.75	2
Peas	1.35	3	1	7	100	0.001	3	0.25	0.6
Potato_Early	1.35	3	1.5	7	100	0.0007	3	0.8	2
Potato_Late	1.35	3	1.5	7	100	0.0007	3	0.95	1.9
Radish	1.35	1.87	1.2	7	100	0.001	3	0.5	1.4
Spinach	1.35	3	1	7	100	0.001	3	0.71	0.8
Sugar_Beet	1.11	1.38	1.65	7	250	0.001	2	0.7	2.8
Turnip	1.35	3	2	7	100	0.001	2	0.47	1.5
Wheat	1.35	3	1.2	4	100	0.001	3	0.51	0.3
Lamb's_Lettuce	1.35	3	1.2	4	250	0.0014	3	0.95	1
Kohlrabi	1.35	3	1.4	3	100	0.0014	3	0.7	1.5
Celery	1.35	3	1.3	6	250	0.0004	3	0.7	1
Celeriac	1.35	3	1.2	6	250	0.0004	3	0.71	2
Small_Radish_Spring	1.35	3	1.2	2	100	0.001	3	0.84	0.8
Small_Radish_Summer	1.35	3	1.2	2	100	0.001	3	0.85	0.8
Parsley	1.35	3	1.4	4	250	0.001	3	0.75	0.6
Radicchio	1.6	3	1.3	7	100	0.0012	3	0.4	1
Spring_onion	1.35	2.42	1	7	200	0.0003	8	0.9	1
Barley	1.35	3	1.2	4	100	0.001	3	0.51	0.3
Rye_and_Triticale	1.35	2	1.2	4	100	0.001	3	0.5	0.3
Maize_(corn_cob_mix)	0.6	9	1	7	100	0.0014	3	0.7	0.8
Maize_(silage)	0.6	9	1	7	100	0.0014	3	0.93	0.8

a and b are crop specific parameters for equation 5 - %N, R_{lux} = coefficient for luxury consumption, Base=Base temperature Degree °C , ddg_{lag} = lag period before root growth begins Degree °C days. r_z 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

Table 2

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

Table 3

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

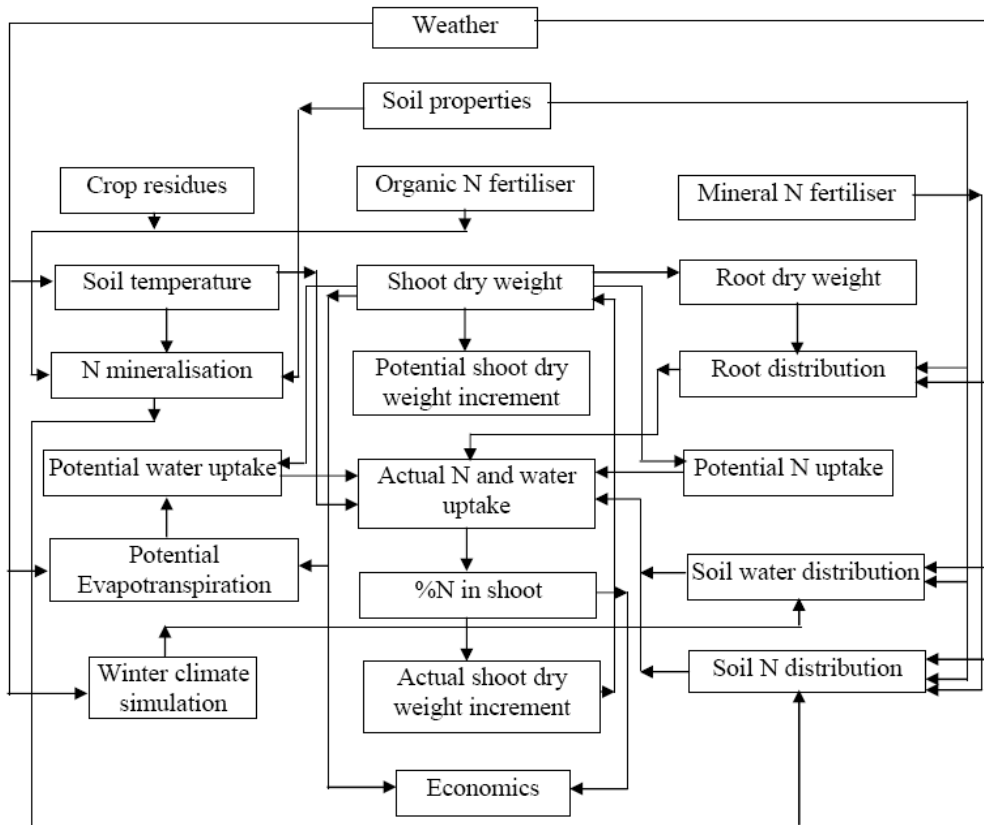
Table 4

Soils	Sandy. loam	Sandy. loam	Sand
Rotation name	AS	BS	CS
	early potato	sum. cabbage	sum. cabbage
	early carrot	early. potato	early. potato
	spring wheat	spring wheat	spring wheat
	summer. onion	early cauliflower	early cauliflower
	early carrot	early potato	early potato
	spring barley	spring barley	spring barley
A – 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 90cm	77	99	109
¹ % Time leaching >0.1	14.1	15.4	16.1
² Drainage below 90 cm (mm)	762	749	799
Average Nitrate concentration mg/l	45	58	60
Gr. margin (Euro./ha)	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
¹ % Time leaching >0.1	14.4	15.8	16.2
Average Nitrate ¹ concentration mg/l	61	73	72
Gr. margin (Euro/ha)	3933	2350	1967

Table 5

Practice	Amount and timing fertilizer kg/ha N	Leaching on 13/5/03 kg/ha N	Gross Margin Cauliflower crop Euro
Recommended Rate (2 splits)	10/4 @ 196 20/5 @ 43	33	- 548
Grower Practice	10/4 @ 237 20/5 @ 52.5	26	555
Modified Recommended Practice (3 splits)	10/4, 5/5, 30/5 @ 80 kg/ha N	12	1360
Regular Feeding 6 applications	10/4,30/4,10/5.20/5,30/5, 9/6 @ 40 kg/ha N	14	2170

Figure 1



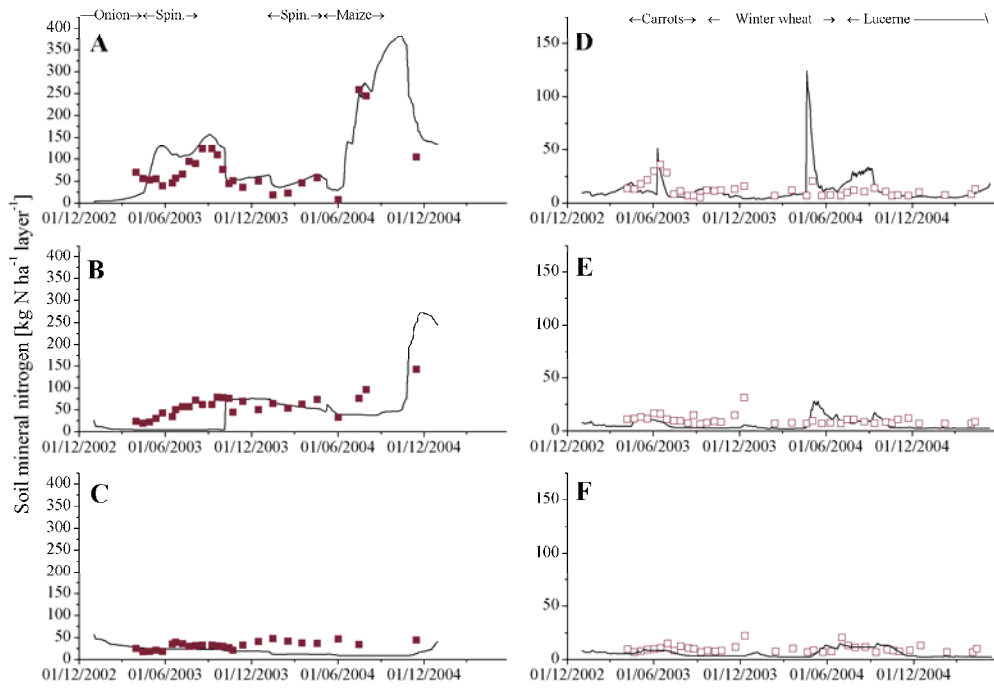


FIGURE 2