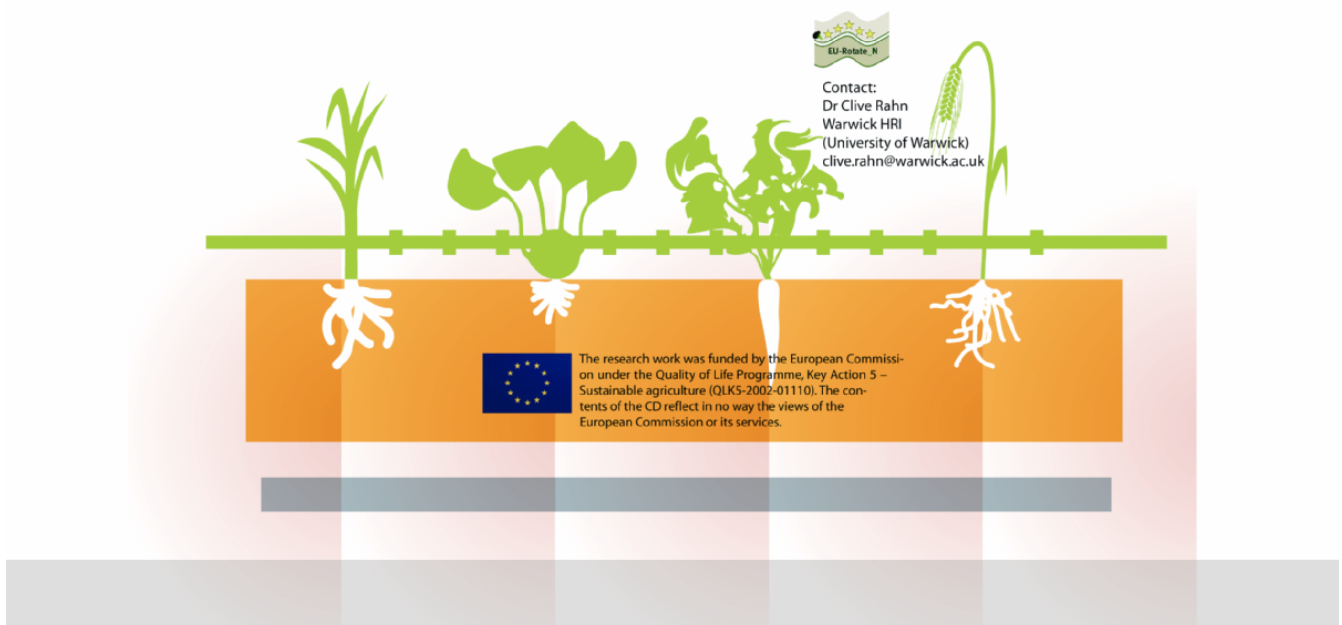


BRIEF DESCRIPTION OF THE EU-ROTATE_N MODEL

8/08/2007

EU-Rotate_N



EU-Rotate_N is a four year project, funded by the European Commission within the Fifth Framework Programme, and is co-ordinated by Dr Clive Rahn at Warwick HRI. Partner organizations include HDRA UK, IGZ and BOLAP Germany , IVIA and CSIC Spain, Bioforsk Norway, DJF Denmark and ISOR Italy.

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The Integrated Model - description of the model sub-routines.

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Where the model sub-routines are based on existing models or existing published algorithms these are referenced to the original source. Where new sub routines have been added which are based on new science such as the root routines these are described in more detail.

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1 Model structure and timestep

The model consists of a number of subroutines to simulate the growth both below and above ground, nitrogen mineralisation from the soil and crop residues, subsequent N uptake and balance between supply and demand to regulate growth. These will all be regulated by weather factors such as rainfall, temperature and radiation. Routines simulate the flow of water and nitrogen into the plant, subsequent evapotranspiration or leaching.

The sub-routines operate in the following order, utilising data from soil properties, residues, fertiliser and weather data where appropriate.

1. The soil N mineralization: calculates soil N mineralization in the top 30cm soil depth from soil organic matter, crops residues and organic and inorganic N fertilisers;
2. The potential maximum increment in shoot dry weight: calculated on the assumption of no restriction from N-deficiency and water stress;
3. The potential maximum N-uptake: calculated from the product of potential maximum dry weight and the critical %N for a crop of that size;
4. The root distribution: calculates the rooting depth and width, and root length distribution in the root zone;

5. The actual N uptake: calculates the amount of N that the roots can take from the root zone;
6. The actual %N in the plant: calculated from the N uptake, the amount of N in the plant on the previous day, and the dry weight of the plant calculated for the previous day;
7. The snow dynamics and frost depth: calculates the snow depth, depths of frost and of any thawed layer above the frost layer, actual infiltration water for winter climate;
8. The surface runoff: calculates the surface runoff caused by heavy rain;
9. The potential transpiration and evaporation rate: calculated from the reference transpiration and a crop coefficient varying with crop development using a FAO approach;
10. The water drainage and redistribution: calculates soil water distribution in the entire soil domain from infiltration and soil properties;
11. The water removal: calculates the amounts of water that the roots can extract from the root zone and via evaporation;
12. The actual shoot dry weight increment: calculated from its current dry weight, the calculated %N and reduction in transpiration.
13. At harvest the amount of marketable crop and its gross margin is calculated using the Economics module.

Modules 1-12 are daily routines. Whether modules 7 & 8 are called is dependent on the information in the input file. During growth modules 1-12 are called on a daily basis, while modules 1, 7-11 are called when the model simulates fallow crops. At harvest module 13 is also called.

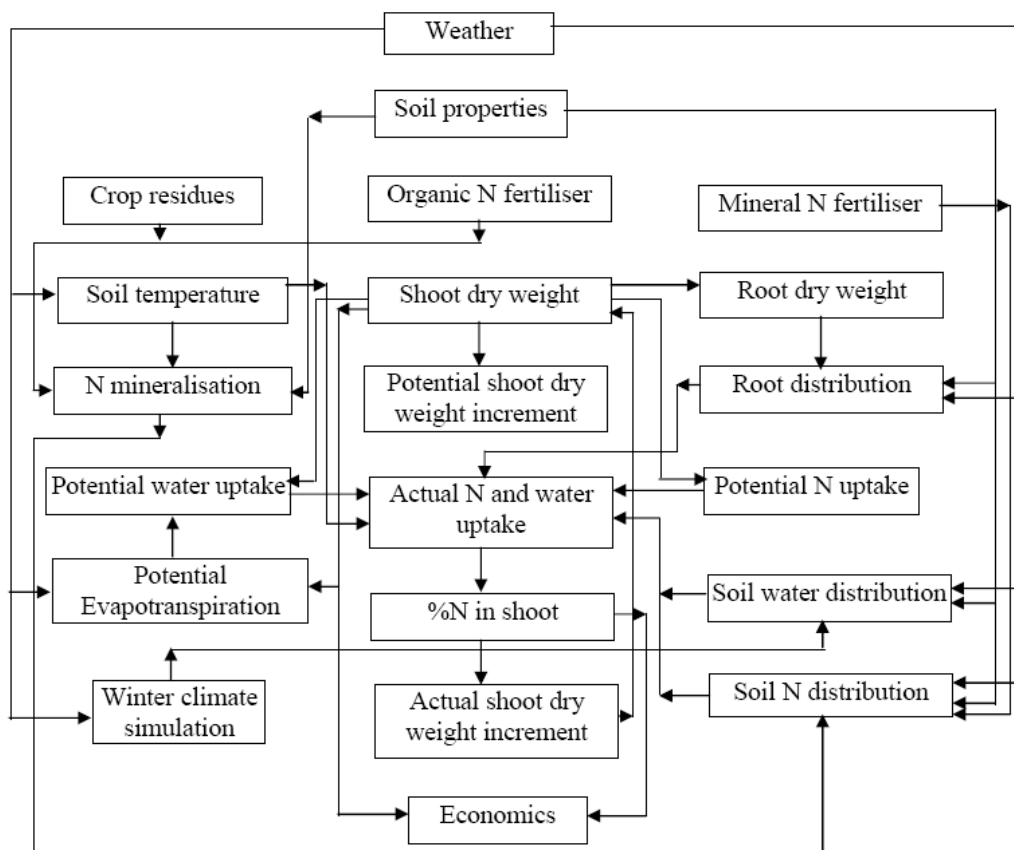


Figure 1: The organisation of the main model sub_modules

2 Description of the soil

In the model the soil is divided into 40 5 cm thick vertical layers. After planting these layers are split horizontally into 5cm wide cells.. The number of cells horizontally depends on row width. As soon as the crop is harvested OR when the residues are incorporated the horizontal elements are merged into one unit until the next crop is planted. The description of the soil in this way allows for more accurate simulation of root growth than was possible in the original N_ABLE model. While the crop is growing all the processes described below are all simulated at the element level.

The 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 the saturated level. These control water availability to the plant and allow calculation of drainage. Mineralisation and losses of nitrogen by denitrification is adjusted for water content. Other inputs include pH which allows for the simulation of N losses where urea fertilisers are used. The amount of organic matter levels affects the supply of N from mineralisation. Clay and sand contents are used to calculate urea solution and hydrolysis, ammonia volatilisation from top layer, decay rate coefficients, denitrification.

3 The water module

The water module has different parts that calculate basically the following:

- Crop evapotranspiration (soil evaporation and transpiration)
- Effective water infiltration (applied water minus runoff)
- Drainage
- Water redistribution in soil

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

The effects of water stress on plant growth are considered assuming 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 soil follows a capacitance approach, similar to the one in the N_ABLE model but that has been modified using a drainage coefficient that allows the water transfer between layers above field capacity to be done progressively (in more than one day) and more or less rapidly depending on soil type (Ritchie, 1998). Drainage at any depth is given as the water downward flow of the cell elements at this depth. The module also accounts for upward/downward capillary flow by adopting a soil water normalised diffusion approach (Rose, 1968 and 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, although default values depending on soil texture are available.

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

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4 Mineralisation Module

Nitrogen (N) release from soil organic matter and from different kinds of N containing materials added to the soil for fertilising is calculated in a module that hosts the following routines:

- N mineralisation from both soil bound and freshly added organic matter
- N volatilisation from added manures and slurries
- Hydrolysis of urea and volatilisation of NH_3

The concept of N mineralisation from organic matter is based on the routines used in the DAISY model (Hansen et al., 1990). Three pairs of conceptual pools (soil organic matter, soil microbial biomass added organic matter), each representing a rapidly decomposable and a slowly decomposable class of N containing organic substances, respectively, describe C dynamics in the soil. Decomposition rate coefficients are temperature and moisture dependent and reflect the environmental conditions of the simulated site. Decay and maintenance rates of soil microbial biomass are additionally influenced by soil clay content. Efficiency parameters determine the loss of CO_2 during the single turn-over 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 turn-over model.

Residues of crops simulated with the crop growth model enter the mineralisation routine with a dynamic C to N ratio, which reflects the growth conditions of the crop during season with respect to N supply. The variable C to N ratio is assigned to the rapidly decomposing part of the material, while the remaining part is considered to decompose slowly, having a fixed C to N ratio. Decomposition rate coefficients of both pools are also fixed (Abrahamsen, 2000). C to N ratios and partitioning coefficients for crop residues are derived from stepwise chemical digestion experiments (Jensen et al. 2005). Manure and slurry properties are taken from DAISY parameterisations (Abrahamsen, 2000).

N volatilisation from soil 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 ammonium ions, solved and gaseous ammonia as well as the effect of soil organic matter, soil temperature and soil water potential on the hydrolysis process itself. An atmospheric resistance parameter finally governs the loss of gaseous ammonia from the top soil.

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5 Snow and Frost Module

Routines have been developed that allow the calculation of snow depth and density, water storage in snow and water melting from the snow pack, using daily input of air temperature.

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

The chosen soil frost model is based on two approaches, one for freezing and one for thawing. The approach for soil freezing was proposed by Olsen and Haugen (1997), at the Norwegian University of Life Sciences, Ås, assuming uniform thermal properties throughout the profile. Values for the latter properties are taken from the Swedish SOIL model (Jansson, 1991). The model requires input of surface temperature as modified by the snow pack. The approach used for thawing is that in the ECOMAG model developed at the University of Oslo (Molotov et al., 1999). We have validated both freezing and thawing processes for Norwegian conditions.

The snow and frost calculation procedures, including all parameters used, are described in detail in a programming note (Riley, 2004a). This note also describes how these processes interact with water infiltration and associated processes such as leaching. In brief, it is assumed that infiltration ceases when soil freezes. During snowmelt and soil thaw, an amount of water equal to the difference between field capacity and total porosity is stored for later infiltration, whilst the remainder passes

to surface runoff. An example of the interaction of frost with runoff appeared in an article in the second project newsletter (Riley, 1994b).

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6 Root Module

The root model calculation consists of three main parts: 1) first the physical extension of the root system is calculated, 2) then the total root length of the crop is calculated, and 3) finally the distribution of the root system depending on depth and distance from the crop row is calculated.

The depth development of the root system is calculated from the accumulated temperature sum from crop planting. After a lag period (ddglag) the rooting depth increases linearly with temperature sum. The length of the lag period and the rate of rooting depth development are controlled with crop specific parameter values. A crop specific base temperature (Tmin) for calculation of root growth is also used, and Tmax is then set to Tmin+20 °C. 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 (Kristensen & Thorup-Kristensen, 2004; Thorup-Kristensen, 2001; Thorup-Kristensen, 2006; Thorup-Kristensen, 1998; Thorup-Kristensen & Van den Boogaard, 1998; Thorup-Kristensen & Van den Boogaard, 1999; Kage et al., 2000).

$$rz=zstart+((cumuT-ddglag)*Krz) \quad (1)$$

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.

$$rx=xstart+((cumuT-ddglag)*Krx) \quad (2)$$

Crop root length is then calculated as a function of 1) crop biomass, 2) crop growth stage, and 3) the parameter value of root class “Rtclss”. The root biomass is calculated as a function of aboveground crop biomass, a fraction which declines with crop size, but increases with Rtclss ($1 < 2 < 3$), to allow for crops with different root/shoot ratios. Total root length is then calculated from the simulated root biomass and a fixed specific root length which is used for all crops.

Root length is distributed spatially into a 2D array of soil units. Root models in crop/soil simulation models are mostly 1D; i.e. root density varies only with depth. However, most vegetable crops are grown as row crops, and the 2D approach was used to be able 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 max width of half crop row distance. The soil units used in this array are 0.05 by 0.05 m.

The root length declines by a logarithmic function from the topsoil downwards, as originally proposed by Gerwitz and Page (1974), and from the crop row to the interrow soil. However, contrary to Gerwitz and Page (1974) we include a value for rooting depth, under which root density declines fast to zero. In the modified forms of the Gerwitz and Page equation used in other models, a rooting depth has also been included, but in these approaches the root density at maximum rooting depth has been constant, meaning that subsoil root density will always be low, and variation in root length will practically only be found in the topsoil. With our approach we allow higher root densities in the subsoil, but compared to the original equation from Gerwitz and Page (1974) our setup allows relatively high root density at the simulated rooting depth without leading to significant root density also in layers below that. In our approach the steepness of the logarithmic decline is controlled by one parameter for the vertical distribution (az) and another parameter for the horizontal distribution (ax).

$$\text{rootlength}(i,j)=(lz(i)*\exp(-ax*x)) \quad (3)$$

Ideally, the model should have been a 3D model, to simulate also the effect of plant distance within the crop row. At the early growth stages where root width is less than plant to plant distance within the row, an arbitrary function is used to reduce N uptake capacity accordingly.

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7 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 received from 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, the content of ammonium-N and nitrate-N in each soil unit and the value S_N read from the croptable parameter file, to control root N uptake efficiency. Diffusion terms are not included in the simulation, as with N uptake this is not assumed to be significant 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. Here the equation for potential ammonium-N uptake is shown; this calculation is made for each soil unit and summed for the whole soil volume. The value of S_1 determines the minimum amount of ammonium-N which can be left in the soil:

$$N_{potnh4} = ((\text{rootlength} * S_N * (\text{nnh4} - S_1)) / (S_2 + \text{nnh4})) \quad (4)$$

A minimum level of N left in the soil is included for both ammonium-N and nitrate-N, as experimental data show, that even though crops with high N demand compared to the soil N supply may reduce soil N to very low levels, some soil N is always measured in the soil analyses, especially in the topsoil layers (e.g. Thorup-Kristensen, 2001, 2006). S_2 reduces N uptake as these minimal values are reached.

A function is then used to balance actual N uptake according to crop N demand and potential root N uptake. When crop N demand and potential root N uptake are close to each other, the simulated N uptake will be below either value, but at very high or low

N supply relative to demand, the uptake will be fully controlled by crop N demand and potential root N supply respectively.

$$N_{up} = N_{demand} * (1 - \exp(-1 * (N_{pot} / N_{demand}))) \quad (5)$$

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 units. At last, 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 from the 0-0.9 m soil layer in much of the model output, and it is therefore necessary also to have an output showing how much N is taken up from below this zone.

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Ref Type: Journal (Full)

8 Crop growth and critical N

Each day the increment in plant dry matter is calculated from:

$$\Delta W = \frac{K_2 G_N G_T G_W W}{K_1 + W} \quad (6)$$

where W is the cumulative dry weight, K_2 is calculated as described below. $K_1 = 1 \text{ t ha}^{-1}$. 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 . G_N and G_W are the growth coefficients dependent on crop %N and water supply. 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

$$K_2 = \frac{K_1 \ln W_{\max} + W_{\max} - K_1 \ln W_P - W_P}{T_h - T_P} \quad (7)$$

where W_P is the dry weight at planting. T_h is the time of final harvest and T_P is the time of drilling or planting in days from Jan 1st.

We use a unified equation to define critical %N for different crops, i.e.

$$\%N_{\text{crit}} = a(1 + be^{-0.26W}) \quad (8)$$

where $\%N_{crit}$ is the critical $\%N$, and a and b are the coefficients, varying from crops (see the crop table of the model).

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

$$\%N_{max} = R_{lux} \%N_{crit} \quad (9)$$

where $\%N_{max}$ is the maximum possible crop $\%N$, and $R_{lux} (\geq 1)$ is the coefficient for luxury N consumption (see the crop table).

For each day a growth coefficient G_N is calculated as:

$$G_N = \min\left(\frac{\%N}{\%N_{crit}}, 1.0\right) \quad (10)$$

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

Similarly, a growth coefficient G_W is calculated as:

$$G_W = \frac{TR_{act}}{TR} \quad (11)$$

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

9 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 rather than a numerical value and the actual numbers for each crop are read from the crop table. The increment in plant dry matter on each day is calculated from:

$$\Delta W = \min(GG_N G_T W, \Delta W_{type}) \quad (12)$$

where W is the cumulative dry weight, G and ΔW_{type} is set to one of three possible values (good, medium, bad) to define the growth rate and the dry weight increment, 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:

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

Another crop parameter 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 added to the soil.

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

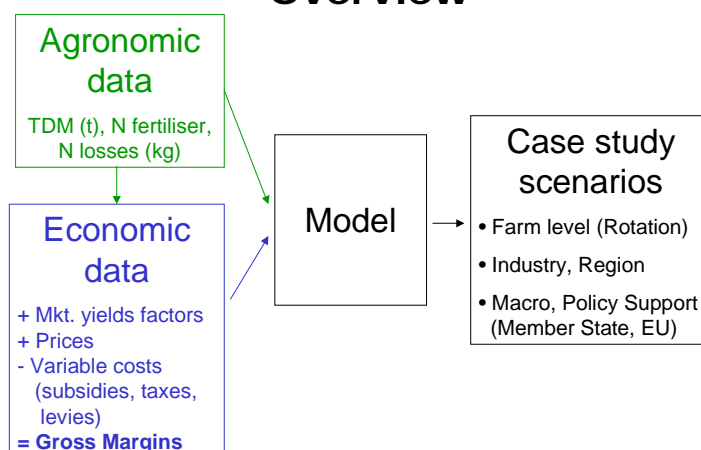
Annual crops are killed after an appropriate period of time (specified in the Crop Table) regardless of the ‘harvest date’ set by the user. Crops are also killed if the temperature drops below a specified value.

Modelling of the growth of undersown crops begins at the harvest of the overstory with an appropriate dry matter and nitrogen content as specified in the Crop Table; the user can choose between Good, Medium and Bad performance as an understory to give different starting conditions.

10 Economics Module

At present soil- and plant, models rarely contain economic components, because natural and social sciences often use different approaches to modelling. In the EU-Rotate_N model we did not attempt building a separate economic model, rather integrated the economics into a sub-model, so that EU-Rotate_N can run with or without the economic part (Schmutz et. al. 2004). The main entry into the economic model is the total dry matter (TDM), which includes roots, and all above ground dry matter. TDM is an output of the current agronomic model. This parameter however, does not give an indication of the above ground dry matter or fresh matter, nor is there an indication of size or shape of the marketable vegetable parts. Therefore, one of the challenges was finding appropriate algorithms to calculate a marketable yield, which is a major input in any farm economic model. This gives also a figure for the dry matter removed, and the remaining residues (post-harvest) are used as an input for the mineralisation sub-model.

Overview



Simplified model overview and link to economic data

Conversion of total dry matter in marketable yield

Marketable yields are not fixed: the percentage of total yield marketable depends on “soft” or social factors. Among those are market channels, production systems (organic or conventional), eating cultures (e.g. some countries prefer small, other large vegetables, a full-flavoured taste in one may be considered bitter in another). Only a few “hard” figures can be used such as the EU trade classifications, which makes certain vegetables un-marketable if below or above the specifications. Considering these, two strategies were developed - one more empirical the other more theoretical.

(1) For the empirical conversion “Direct conversion” our own research, published and un-published field research data were collected, where both total dry matter and marketable yields were measured across Europe. From this an algorithm was derived converting total dry matter into marketable yield at any given N supply level considering the effects of both sub- and supra-optimal supply of N. A unified algorithm with different crop specific parameters is used for each annual vegetable with a single harvest. There are three main types of vegetable crops: some with a simple constant relationship at all available N levels, some with linear increasing or decreasing relationship depending on available N. Some are more complicated with a non-linear relationship. Other vegetable crops are perennial, like artichokes, or with multiple harvests and need different algorithms than annual, single harvest crops.

“Direct conversion” is a direct conversion of total dry matter (TDM) into marketable yield (MKTY) with one factor R, sourced from empirical data.

$$\text{MKTY} = \text{TDM} \times R \cdot f(N_{av}) \quad (14)$$

With:

- R the ratio of marketable yield to total dry matter for optimum nitrogen supply and spacing
- N_{av} the available nitrogen (N)

The ratio R is individual for each crop and depends on the available N supply used for each crop. The formula for R is a linear or polynomial relationship of available nitrogen (Nav).

$$R = r_0 + r_1 \times N_{av} + r_2 \times N_{av}^2 + r_3 \times N_{av}^3 + r_4 \times N_{av}^4 \quad (15)$$

The terms r0, r1 and r2 are empirically gained for individual crops. For a simple constant relationship: r1 = 0 and r2 = 0. For a linear relationship: r2 = 0. Otherwise, the relationship is non-linear. For some crops, more polynoms may be needed because of different behaviour in sub- and supra-optimum conditions and therefore r3, r4 ...rx are added.

(2) In a second approach, the single plant fresh weight is calculated. This is done using the harvest index to calculate the dry weight of the harvested parts. Then, with the dry matter content and the plant population, an average single plant fresh weight is produced. Assuming a normal distribution of plant fresh weights and a coefficient of variation of e.g. 20% 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 and the residues left post-harvest are calculated.

$$\text{av. single plant fresh weight} = \text{TDM} \times \text{HI} \times \text{plant population}^{-1} \times \%dm^{-1} \quad (16)$$

A normal distribution with a given coefficient of variation is used to simulate the %-gradeout, then the marketable yield in tonnes is calculated. For each crop, a default model choice (approach 1 or 2) is stored in the crop table, but the experienced user can change this.

Prices, variable costs and gross margin calculation

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

$$GM = \text{MKTY} \times \text{Price} - VC_{ind} - VC_{dep} - VC_{N\ fert} \quad (17)$$

The variable costs independent (VC_{ind}) of marketable yield are recorded per hectare and consist of seed and transplants costs, fertiliser costs excluding N fertiliser, fleece, irrigation, crop protection, weed control. Variable costs depending (VC_{dep}) on the marketable yield are recorded per tonne marketed and multiplied by MKTY. They consist of packaging and drying, transport, harvest casual labour and market commission. The variable costs of inorganic and organic fertilisers ($VC_{N\ fert}$) are calculated using the physical data generated by the model. The triggered amount of 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.

For the calculations, own figures or standardised figures stored in a separate economic data file can be used. In this database, the countries Norway, Denmark, Germany, UK, Italy and Spain are considered. The market channels considered are pre-pack for supermarket, wholesale, direct marketing and processing. The growing systems considered are conventional and organic. The database holds about 300 crop entries of all relevant horticultural crops, including fertility-building crops, across Europe. The data are current prices and standardised variable cost data published in each country for conventional and organic farming systems (e.g. Lampkin et al., 2004; Nix, 2004; Agro Business Consultants Ltd., 2005). The level of data availability and the depth of detail vary among countries.

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