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Converting simulated total dry matter to fresh marketable yield for field vegetables at a range of nitrogen supply levels

C. Nendel · U. Schmutz · A. Venezia · F. Piro · C.R. Rahn

C. Nendel (✉)
Institute for Vegetable and Ornamental Crops,
Theodor-Echtermeyer-Weg 1, 14979 Großbeeren, Germany
Present address: Leibniz-Centre for Agricultural Landscape Research, Institute for Landscape System Analysis,
Eberswalder Straße 84, 15374 Müncheberg, Germany
e-mail: nendel@zalf.de

U. Schmutz
Henry Doubleday Research Association,
Ryton Organic Gardens, Coventry, CV8 3LG, UK

A. Venezia · F. Piro
Centro di Ricerca per l'Orticoltura,
Via dei Cavalleggeri 25, Casella Postale 48,
84098 Pontecagnano, Italy

C.R. Rahn
Warwick HRI,
Wellesbourne, CV35 9EF, UK

Abstract

Simultaneous analysis of economic and environmental performance of horticultural crop production requires qualified assumptions on the effect of management options, and particularly of nitrogen (N) fertilisation, on the net returns of the farm. Dynamic soil-plant-environment simulation models for agro-ecosystems are frequently applied to predict crop yield, generally as dry matter per area, and the environmental impact of production. Economic analysis requires conversion of yields to fresh marketable weight, which is not easy to calculate for vegetables, since different species have different properties and special market requirements. Furthermore, the marketable part of many vegetables is dependent on N availability during growth, which may lead to complete crop failure under sub-optimal N supply in tightly calculated N fertiliser regimes or low-input systems. In this paper we present two methods for converting simulated total dry matter to marketable fresh matter yield for various vegetables and European growth conditions, taking into consideration the effect of N supply: (i) a regression based function for vegetables sold as bulk or bunching ware and (ii) a population approach for piecewise sold row crops. For both methods, to be used in the context of a dynamic simulation model, parameter values were compiled from a literature survey. Implemented in such a model, both algorithms were tested against experimental field data, yielding an Index of Agreement of 0.80 for the regression strategy and 0.90 for the population strategy. Furthermore, the population strategy was capable of reflecting rather well the effect of crop spacing on yield and the effect of N supply on product grading.

Key words

Dry matter yield; marketable yield; vegetables; model; nitrogen

Introduction

For the simultaneous analysis of economic and environmental performance of agricultural production different paths have been followed, each having their own advantages and drawbacks. Sectoral status analyses often ignore interactions on the process level or summarise them using purely economical indicators (e.g. Galdeano-Gomez 2008). Farm level approaches often use static models (e.g. Bateman et al. 1999; Cembali et al. 2007; Münier et al. 2004), which in few cases are based on previously obtained results of dynamic ones (e.g. Pacini et al. 2004). If environmental practices in agriculture are assessed for their profitability, the farmer’s management options in the field are often not considered (e.g. Managi and Karemera 2005). This is applicable to evaluate the performance of the respective economic sector. However, it does not provide feedback relations to (i) support the farmer’s choice for market channels, crops and fertiliser management or (ii) to indicate directions for the development of codes for Good Agricultural Practice. Performance evaluation of vegetable production inevitably requires knowledge on the effect of N fertiliser on yield and the farm’s net return. As the system is complex, dynamic soil-plant-environment simulation models for agro-ecosystems are often applied to predict crop yield and the environmental impact of production (Kersebaum et al. 2007). However, only simple models with a limited performance range have been available for field vegetable production systems up until now (Fink and Scharpf 1993; Greenwood 2001; Rahn et al. 1996).

Decisions on estimating N fertiliser applications are mainly governed by two factors: at policy level, environmental issues often determine legislative acts to control N fertiliser use in agriculture, whereas at the farm level decisions are governed by economic considerations. Both factors are included in a variety of models in different ways, depending on the scale of the simulation. Agricultural sector models have been combined with dynamic nutrient leaching models and used at national (Lehtonen et al. 2007) or watershed level (Faeth et al. 1991; Ribaudo et al. 2001; Schou et al. 2000). However, at field level, more details have to be considered and for this reason, soil-plant-environment models are often equipped with additional modules which allow simultaneous evaluations of the economical and environmental impact of crop management decisions (e.g. Hughes et al. 1995; Lindgren and Elmquist 2005; Rejesus and Hornbaker 1999; Vatn et al. 1999). In most cases, the simulated total above-ground crop dry matter (TDM) is used to calculate economic returns, which is feasible for many agricultural systems.

Crop growth models that produce TDM as an output can generally be categorised as process-based models driven by photosynthesis and empirical models that often use alternative drivers (Marcelis et al. 1998). The objective behind functional process models is to explain crop growth using the most important feedback regulation mechanisms. Most commonly, the leaf area index development of the crop is simulated according to its ontogenesis, providing a framework for photosynthesis to be calculated from radiation (Wang et al. 2002). Assimilates produced from this process are then distributed – either actively or driven by sink demand – to the different plant organs. This approach enables us to explicitly calculate the mass of the crop's marketable part, and renders a conversion step obsolete if the dry matter content is known or calculable. Numerous process models have been developed for all kinds of vegetable crops (Marcelis et al. 1998). However, a generic, process-based crop growth model for a large number of field-grown vegetables has not yet been presented. Such a task is hampered by the fact that field vegetables have a broad range of morphologies, including those for which a leaf area index in terms of a photosynthetic active surface is difficult to determine (cabbages, lettuces, leek, etc.). A canopy approach has previously been applied for such crops (Gutierrez et al. 1994; van Henten 1994). The EU-Rotate_N model (Rahn et al. 2007) requires a target yield to describe the growth of field vegetables. This approach restricts the simulation of the crop's response to radiation and heat, limiting the model application to situations in which a rough idea of the expected yield exists. However, using this approach in combination with the critical N concept (Greenwood et al. 1986; Plenet and Lemaire 1999), nitrogen uptake and fate can be simulated generically for most vegetables.

The use of TDM as a basis for economic calculations leads to considerable problems for field vegetable production systems. First, the relationship between TDM and marketable fresh weight yield (MFY) is highly variable due to a large number of species (Marcelis et al. 1998) and secondly, some vegetables can produce large amounts of unmarketable material that is not harvested and is reincorporated as crop residues into the field. In addition, the TDM-MFY relationship is often dependent on the N supply to the crop but unfortunately it does not always follow simple optimum curves as i.e. for cereals. This is due to the fact that some crops do not produce any marketable parts when the N supply drops below a certain threshold (Rather and Schenk 2005; Thompson et al. 2000). Excessive N levels can also lead to the marketable part of some vegetable crops becoming unmarketable, developing hollow stems, fuzzy curds, black midribs or other disorders (Berard 1990; Scaife and Wurr 1990).

The implementation of the EU nitrates directive (The Council of the European Communities 1991) has reduced the amount of N being applied to agriculture and resulted in N management in crop production becoming increasingly complex. Eventually this may result in vegetables receiving sub-optimal nutrient supply under unfavourable weather conditions. Consequently, decision support systems will need to support the possible effects of sub-optimal N supply on crop growth and thus on farm net returns. This is especially important when modelling low-input production systems such as organic vegetable farming, where sub-optimal N conditions occur frequently. In these systems, crop spacing is used to adjust for N utilization and yield.

This paper presents two strategies to overcome the specific problems of yield conversion for field vegetable production, with some results of their use in a model aimed at supporting environmentally sound vegetable production planning across Europe. Each strategy has its own advantages and disadvantages, which will be discussed.

Material and Methods

Yield data

Marketable and total dry matter yield data obtained from experiments with different N fertiliser levels were extracted from previously unpublished field vegetable experiments undertaken as part of the EU-Rotate_N project (www.warwick.ac.uk/go/eurotaten) or during the default work programme of regional research stations. The research stations located at Großbeeren (Germany), Hanover (Germany), Kise (Norway), Landvik (Norway), Piikkiö (Finland), Pontecagnano (Italy), Ryton (UK), Valencia (Spain), Wannweil (Switzerland), Wellesbourne (UK) and Årslev (Denmark) provided experimental data on various field vegetables, including a range of currently grown cultivars. Additional monitoring data from managed farm sites were collected at Bobenheim, Böbingen, Kleinniedesheim, Lustadt and Zeiskam (all Germany). All of the experiments include measurements of the soil mineral nitrogen content at sowing or planting time, which is used to roughly estimate the total N supply to the crop by adding it to the fertiliser amount applied during the course of the experiment. For this method, it is assumed that no leaching of N out of the rooting zone occurs. Furthermore, all of the experiments include measurements of crop fresh marketable yield and above-ground dry matter at harvest. The fertiliser treatments cover a range of N supply in which profitable vegetable production commonly occurs. Almost all of the experiments include a zero fertiliser treatment, which enables crop production to be assessed in low fertiliser regimes that meet the requirements of EU legislation. All in all, the levels of detail for the various crops differ quite considerably. For many crops, detailed field experiments from various countries, including multiple N treatments, are available. For some crops, only single field experiments or published field research designed for other research questions where the raw data could be used for our purpose are available. For the remainder, expert knowledge was used to obtain a preliminary value for the model. Here, further research and experimental data is required to back up the estimate. In those cases, crop parameters were defined based on experimental results for similar species (parsnip, broad beans, spring onion). A summary of the data used for algorithm development and parameterisation is given in Table 1.

Strategy I: Regression approach

A feasible method of converting simulated above-ground total dry matter (TDM) into marketable fresh weight yield (MFY), for which prices are available, is the use of a conversion factor. This method follows the idea of the harvest index, which is used to estimate grain yield from total crop biomass (Hay 1995). For most field vegetables, the relationship between TDM and MFY is a function of the N supply to the crop.

$$\hat{m}_{MFY}(N_{av}) = f(N_{av}) \cdot \hat{m}_{TDM}(N_{av}) \qquad \text{(Equation 1)}$$

with

$\hat{m}_{MFY}(N_{av})$ = marketable fresh weight yield estimator for specific level of available N

$\hat{m}_{TDM}(N_{av})$ = simulated above-ground dry matter for specific level of available N

$f(N_{av})$ = conversion function

N_{av} = plant-available nitrogen in soil

From the empirical data three different types of N supply dependent TDM-MFY relationships were classified according to best-fit of various trend and regression types (Table 2): Type A includes all vegetable crops for which the conversion function is linear (Figure 1A). Type B describes vegetable crops that have a linear ratio only at an optimum region but different ratios under sub- and supra-optimum conditions (Figure 1B). Finally, type C covers all vegetables which show no TDM-MFY relation (Figure 1C).

((Table 2))

((Figure 1))

For all type A and B vegetables the conversion function can be described with a polynomial function of the type

$$f\left(N_{av}\right) = r_0 + r_1 \cdot N_{av} + r_2 \cdot N_{av}^{\ 2} \qquad \text{(Equation 2)}$$

with r_0, r_1 and r_2 being crop specific parameters. Parameter values were estimated for all vegetables for which sufficient data was available from the literature survey or from own experiments (data not shown), using SigmaPlot 5.0 (SPSS Inc., Chicago, IL, USA). Parameter sets for those vegetables to be converted following Strategy I, are compiled in Table 3. In these particular cases, r_2 equals 0.

((Table 3))

Strategy II: Population approach

The regression approach has a number of drawbacks: it does not consider that (i) different crop spacing can affect the marketable yield as the absolute number of plants changes, (ii) some vegetables do not produce any marketable yield when N supply is restricted and (iii) very small or very large produce may be rejected by the consumer and will not be offered for sale. Consequently a more complex approach is presented as an alternative strategy for crops with a single marketable product: this population approach is based on the concept that crop yield follows a normal distribution in respect of the size of the marketable part. A given coefficient of variation describes the size distribution within the population. Minimum and maximum size boundaries determine the fraction of the population’s marketable produce that is suitable for marketing. Identifying non-marketable produce allows the simulation model to treat this biomass as crop residue to be recycled in the system.

In a first step, dry matter yield (DMY) is calculated from simulated TDM using the crop specific harvest index *HI* as

$$\hat{m}_{DMY}(N_{av}) = \hat{m}_{TDM}(N_{av}) \cdot HI(N_{av}) \qquad \text{(Equation 3),}$$

describing the fraction of TDM that is commonly harvested and thus not left in the field as crop residue. DMY is now transferred into a single-plant fresh matter yield (PFY) by

$$\hat{m}_{PFY}(N_{av}) = \frac{\hat{m}_{DMY}(N_{av})}{n \cdot c_{DM}} \qquad \text{(Equation 4),}$$

with

n = number of plants per area unit, calculated from row and planting distances

c_{DM} = typical dry matter concentration of the harvested fraction

The size of the harvested part (i.e. curds, heads, etc.) is normally distributed and can thus be described using $\hat{m}_{PFY}(N_{av})$ as mean fresh weight of a single plant product at harvest with a given coefficient of variation (*CV*, standard deviation related to mean). A lower market limit (L_{low}), describes the minimum weight of a product that can be sold at market and subsequently a grade-out probability p_G can be calculated for the population.

$$p_G(N_{av}) = \frac{1}{\sqrt{2\pi\bar{s}}} \cdot e^{-\left(\frac{L_{low} - \hat{m}_{PFY}(N_{av})}{2\bar{s}^2}\right)} \qquad \text{(Equation 5)}$$

with

$\bar{s} = \hat{m}_{PFY}(N_{av}) \cdot CV$ being the standard deviation of the sizes within the population of harvested plant parts.

In the same way an upper market limit (L_{up}) is established which is used to grade out harvested produce that is too big to be marketable. MFY is then calculated from PFY, corrected by the grade-out probability.

$$\hat{m}_{FMY}(N_{av}) = n \cdot \hat{m}_{PFY}(N_{av}) \cdot (1 - p_G(N_{av})) \qquad \text{(Equation 6)}$$

This approach requires the following crop specific data: row spacing, plant spacing, c_{DM}, L_{low}, L_{up}, *CV*, and *HI*, all of which need to be determined experimentally or acquired from expert knowledge. Since only very limited empirical data on *CV* values were found on most crops, the average *CV* of 0.3 was used for all crops, except for carrots. Parameter sets for those vegetables to be converted following Strategy II, are compiled in Table 4.

((Table 4))

The EU-Rotate_N simulation model

The EU-Rotate_N model (Rahn et al. 2007) is based on a dynamic process-based simulation of the crop-soil-environment interaction in field vegetable production systems. N movement in soil is driven by water balance and transport according to a capacity approach (Ritchie 1998), where the water content at saturation, field capacity and wilting point define the hydraulic soil properties. Crop growth simulation follows a simple target yield approach, with the daily growth increment being linearly reduced in case of water or N deficiency. Nitrogen mineralisation from organic matter is based on the routines used in the DAISY model (Hansen et al. 1991). Crop residues are assigned a dynamic C to N ratio, which reflects the growth conditions of the crop with respect to N supply (Jensen et al. 2005).

Root growth is calculated using a heat sum approach and distributed spatially in a 2D soil cell grid, allowing for the simulation of spacing effects in row crops. Crop and soil-specific rooting depth enables the simulation of deep and shallow rooted crops, and their characteristic N exploitation from the soil. N uptake is calculated as a function of crop N demand, which in turn follows the critical N concept of Greenwood (2001). Fertility-building crops are simulated using fixed growth rates and parameters for litter loss, N fixation processes and winter kill.

An economic analysis of the simulation results is based on costs related (planting, base fertilisers, irrigation, crop protection, weed control, hail insurance) and not related (packing, drying, transport, commission, labour, fuel) to yield, costs for N fertilisers and applications and on prices for marketable parts of the crop, which are stored in the model's database. In order to link the TDM model output to the MFY prices, the algorithms for both conversion strategies are embedded in the EU-Rotate_N model. An example economic analysis was presented by Nendel (2009). The simulations presented below are conducted with the EU-Rotate_N simulation model.

Testing the algorithms

Simulation of marketable yield in a crop rotation experiment in Italy

The two conversion strategies were tested against a crop rotation experiment carried out on the CRA-ORT experimental station at Pontecagnano, Italy (40°38' N, 14°52' O). The experiment has been conducted with four two-yearly rotations of four vegetable crops, each grown at three nitrogen levels and two times per year (spring-summer versus autumn-winter seasons) until completion of four cropping cycles. The crops included broccoli, cabbage, spinach, lettuce and fennel. Broccoli did not prove sufficiently robust to withstand cold season winds during the first crop series and was thereafter substituted with cabbage, which was used from the second to the fourth series. The nitrogen fertilizer levels were based on average farmer's practice and applied as 100% and 130%, respectively. A zero fertilizer treatment completed the experimental design.

A split-plot field layout was used, with the rotations in main plots and the N rates in subplots, with two replicates in adjacent blocks. Among others, observations included above-ground TDM and MFY. The experiment started in November 2003 and was completed by July 2005. The EU-Rotate_N model was applied to reproduce the rotations, using the observed yields set as target yields. By default, the model displays MFY as the results of both conversion strategies.

Both conversions were compared against the observed MFY data for one replicate of the experiment, including 16 crops at three N levels, by computing the limits of agreement, a predictive interval for the difference between simulated and observed yield for a new crop among the tested species, following Bland and Altman (1986). The outcome p_i for a new crop i yielded by two alternative estimation methods m (1, 2) can be modelled as:

$$p_{mi} = \alpha_m + \mu_i + e_{mi},\ e_{mi} \sim N(0, \sigma_m^2) \qquad \text{(Equation 7)}$$

The differences $d_i = p_{1i} - p_{2i}$ are identically distributed with mean $\alpha_1 - \alpha_2$ and variance $\sigma_1^2 + \sigma_2^2$, so the 95% prediction interval for a new difference is $\alpha_1 - \alpha_2 \pm \left(1.96 + \sqrt{\left(\sigma_1^{\ 2} + \sigma_2^{\ 2}\right)}\right)$.

Besides this numerical summary, plotting the differences d_i versus the averages $\bar{p}_{\cdot i}$ evidences the extent of the agreement between the two methods and the types of departure from it. Results are displayed by plotting means versus differences (Bland-Altman plot).

Simulation of marketable yield in a plant spacing experiment in Germany

The Strategy II algorithm’s ability to predict the effects of different plant spacings on individual product weight was tested against data from a spacing experiment with white cabbage (Variety “Quisto”), carried out at Großbeeren, Germany (52°20’ N, 13°19’ O), in 1995. Applying the EU-Rotate_N model, fertilisation and irrigation were triggered automatically to ensure that simulated growth was not restricted by either water or N deficiency. Local weather data from Potsdam (52°23' N, 13°03' O) was used for the simulation. The target yield parameter which drives dry matter accumulation in the EU-Rotate_N model was calibrated against the total dry matter measurements from the experimental data using the least root mean squared error (RMSE) as a fitting criterion. Within the simulation the effect of crop spacing on crop dry matter was controlled by a 2D root model algorithm, which takes competing water and nutrient requirements between plants into consideration. The calculation of MFY (head fresh weight) and crop residues (leaf fresh weight) occurs at harvest time (September 27, 1995) in the modelling procedure.

Simulation of product grading in an N fertiliser experiment in Germany

Individual products being too big or too small to meet market requirements are commonly graded out and not offered to the consumer (gradeout procedure). To demonstrate the ability of the Strategy II algorithms to reproduce product gradeout, an N fertiliser experiment with cauliflower (Variety "Fremont") carried out at Großbeeren, Germany in 1996, was simulated using the EU-Rotate_N model. Simulated N treatments and irrigation matched the original field experiment and marketable yield gradeout was calculated at harvest time (August 1, 1996). Gradeout parameters were $\hat{m}_{PFY}(N_{av})$, a default CV of 0.3 and a default HI of 0.45. L_{low} for gradeout in simulation and experiment was set to an individual head weight of 600g; L_{up} was not set.

Results

Simulation of marketable yield in a crop rotation experiment in Italy

MFY as converted by the model is compared to field data for the regression (Figure 2A) and the population approach (Figure 2B). While the simulations for most vegetables produce almost identical results for both methods, MFY of fennel was widely underestimated with the regression method, indicating that the regression method is not applicable for fennel (Figure 3).

((Figure 2))

((Figure 3))

Simulation of marketable yield in a plant spacing experiment in Germany

The results of the simulation for head and leaf fresh matter weight, total N content and TDM are shown in Figure 4. Since the simulated crop was well supplied, both spacing variants were simulated with little variation in TDM development or N content (Figure 4, C and D). The differences in yield simulation as displayed in Figures 4 A and B are based on the alteration of the model's row distance variable only.

((Figure 4))

Simulation of product grading in a N fertiliser experiment in Germany

The simulation results for three fertiliser scenarios (Figure 5, D – F) were compared to the gradeout rates of the harvested heads in the experiment (Figure 5, A – C). The model was able to reflect the general trend observed in the experimental data, in which lower N supply yielded smaller heads and a larger fraction of heads graded too small. The large difference between observed and simulated gradeout within the 120 kg N ha^{-1} treatment is caused by three individuals being only marginally lighter than L_{low}.

((Figure 5))

Discussion

The comparison of both conversion methods against field data from Italy reveals that for most of the tested crops both methods yield similar results. However, for fennel the regression approach did not work sufficiently well, spoiling the over-all performance evaluation of this method (Figure 2A). Here, the pattern (Figure 3) indicates that in this example a different parameterisation would lead to a better result. As demonstrated for fennel, the two alternative approaches can not be applied simultaneously to all vegetables. From Figure 1 C, it is obvious that type C classified vegetables can not be described using a polynomical conversion function, since the relationship is poor. Type C crops almost solely produce marketable parts which are sold piecewise to the consumer. A crop that is sold by fruit, head, bulb or curd is strongly dependent on quality parameters like head weight or diameter, colour, shape, and appearance. Judging their market value by fresh weight alone is inappropriate. Consequently, the regression approach is not applicable for type C vegetables, especially for crops that require multiple harvests (i.e. aubergine, courgette). Also in the A and B categories we find crops that are often sold piecewise to the consumer, (i.e. cauliflower, red and white cabbage, celeriac). Although the regression approach would most likely give reasonable results for those crops, the application of the population approach would be preferred for its added advantages.

Most vegetable crops are grown in rows with set distances between the individual plants, so altering the planting distance within or between the rows can affect the growth of the individual plant considerably (Csizinszky 1996; Falzari et al. 2006; Ferrari et al. 2008; Jett et al. 1995). The main reason for lowering plant density is to increase the supply of nutrients, water and radiation to the individual plants (Francescangeli et al. 2006; Hussaini et al. 2000). Applying the population approach means that the simulated TDM gives greater individual head weights if the number of individuals per area is small (i.e. increased row or planting distance), which is consistent with field observations. For industry production (i.e. canning, processing, frozen foods) the crops are mostly grown at higher spacing to achieve large units, while for direct or whole sale market channels smaller units are desired so tighter spacing is used (e.g. Jett et al. 1995). How this can be implemented in the context of a crop growth simulation model was shown with white cabbage as an example (Figure 2).

The major advantage of the population approach is the ability to consider product gradings. In practice, produce that is too light or too small is graded out and left in the field along with the crop residues. The same fate often awaits produce that is too heavy or large. In extreme situations a whole crop could be graded unmarketable, due to lack of N, even though heads, curds, bulbs or fruits have been produced (Figure 5 C). Equally, over-supply of N can cause problems such as bolting, resulting in unsaleable products (i.e. lettuce, cauliflower, fennel). Figure 5 illustrates the ability of the algorithms to reflect these relations using cauliflower as an example, which could be even better if a higher number of individuals was available.

In the EU-Rotate_N model, all vegetables are allocated to one of the three categories which describe the relationship between TDM and MFY. In general, two categories of crops will be converted via the regression approach (Table 3): (i) crops that produce more than one marketable part per plant (i.e. beans, tomatoes, cereals, maize) and (ii) small crops whose planting density is rarely varied and that are normally sold as bulk or bunching ware (i.e. small radish, beetroot, spinach). All other crops share some common production techniques which can vary according to the desired market channel (i.e. carrot: narrow space → bunching carrots for direct or pre-pack sale; wide space → large carrots grown for storage or processing). These crops will be converted using the population approach (Table 4). Crops for which no data were available to support the direct conversion approach will also be converted this way (bell/sweet pepper, courgette/zucchini and eggplant/aubergine). In the case of some root crops (beetroot, turnip, swede, sugar beet and radish), Strategy I proved the better method, since here spacing variations are of minor practical importance and parameters to support Strategy II are not well founded from literature and experiments.

Conclusion

The vast number of species used for vegetable production and the broad range of their properties makes it difficult to apply a generic approach for economic analysis of scenarios obtained from process simulations for vegetable growth and yield. The algorithms presented here constitute a key link between process simulations of water and nutrient dynamics in agro-ecosystems and the calculation of net returns on marketable produce, which in turn form the basis of any economic evaluation of management strategies in vegetable production. Integration of the algorithms into the dynamic, process-based simulation model for horticultural crop rotations for European horticulture, EU-Rotate_N, enables the model to simultaneously assess both ecological and economic consequences of different nitrogen management practices in field vegetable production, providing valuable information for farm managers and policy makers on different scales. Along with existing decision support approaches for horticulture: NDICEA (Koopmans and Bokhorst 2002; van der Burgt et al. 2006), ORGPLAN (Padel 2002), and FBC (Cuttle 2006), it presents a major contribution to the best available practise in modelling horticultural production systems and offers a range of possibilities beyond the power of economic status analyses.

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Table 1: Summary of field experiments on the total aboveground and marketable yields of vegetables over a range of nitrogen supply rates. Literature resources are printed in *italic*, the remainder are unpublished field experiments. FMY = farm yard manure.

Crop name	Number of experiments	Countries covered	Number of nitrogen treatments	Range of rootzone nitrogen supply rates	Resources
Artichoke	3	Italy	13	49 – 651	*Bianco et al. 1996; Elia et al. 1991; Foti et al. 2005*
Beetroot	9	Germany	44	102 – 403	Hanover 1984-98; Großbeeren 1998
Bell/Sweet pepper	1	Turkey	3	70 – 210	*Kirnak et al. 2003*
Broccoli	15	Germany, Norway	57	60 – 462	Hanover 1981-98; Großbeeren 1996, 2001; Kise 1999-2001
Brussels Sprouts	8	Germany	31	225 – 508	Hannover 1981-83; Großbeeren 1999
Carrot	13	Denmark, Germany, UK	80	45 – 204	Årslev 1988-90; Hanover 1986-91; Wellesbourne 1996
Carrot (Industry)	4	Germany	16	63 – 353	Großbeeren 1993
Cauliflower	15	Germany, Norway, UK	76	41 – 456	Hanover 1979-94; Großbeeren 1996, 2001; Wellesbourne 1993; Kise 1995-2001
Celeriac	2	Germany	4	108 – 260	Hanover 1988; Lustadt 2004
Celery	7	Finland, Germany, Italy	37	61 – 341	Hanover 1980-96; *Evers et al. 1997; Temperini et al. 2000*
Chinese cabbage	9	Germany	41	130 – 408	Hanover 1985-97
Courgette/Zucchini	1	UK	1	1.3 t ha^{-1} FMY	Ryton 2003
Cucumber (Pickling)	3	Finland	3	140 – 151	Piikkiö 2001-03
Eggplant/Aubergine	2	Italy, Turkey	6	95 – 450	*Kirnak et al. 2002; Rosati et al. 2002*
Endive	1	Turkey	4	0 – 180	*Ugur et al. 2004*
Fennel	4	Italy	12	73 – 847	Pontecagnano 2003-05
French Beans	3	Germany	18	45 – 300	Hanover 1979-94
Garlic	1	Brazil	5	0 – 250	*Resende et al. 2000; Rosen and Tong 2001*
Kale	3	Germany	10	50 – 300	Hanover 1993-98

Kohlrabi	16	Germany	63	37 – 320	Hanover 1987-94; Großbeeren 1994-95;
Lamb's lettuce	5	Germany	26	37 – 581	Großbeeren 2004-05, Zeiskam 2003; Kleinniedesheim 2003
Leek	18	Denmark, Germany, UK	99	44 – 451	Hanover 1979-98; Wellesbourne 1996; Årslev 1988-90
Lettuce (Butterhead)	11	Germany	50	27 – 232	Hanover 1980-88; Großbeeren 1994; 1999
Lettuce (Crisp)	9	Germany	38	24 – 263	Hanover 1982-97
Onion	8	Argentina, Germany, Norway, Poland, Spain	42	11 – 200	Hanover 2002-03; Großbeeren 2000; Kise 1990-96, Valencia 1999; *Gaviola et al. 1998; Rumpel 1998*
Parsley	3	Germany, Poland, Switzerland	10	28 – 229	Kleinniedesheim 2004, Wannweil 1987, *Rumpel and Kaniszewski 1994*
Pea	2	Germany	2	58 – 100	Großbeeren 1996; Kleinniedesheim 2003
Potato (Early)	3	Germany, Norway	33	30 – 210	Kise 1993-94, Bobenheim 2004
Potato	4	Italy, Spain	10	276 – 449	Valencia 1999; *Colauzzi et al. 2003; Scaziota et al. 2002*
Radicchio	3	Germany, Italy	17	49 – 405	Böbingen 2003; *Pimpini et al. 2000; Pimpini et al. 2002*
Radish	3	Germany, Serbia, USA	8	0 – 274	Lustadt 2003; *Djurovka et al. 1997; Santos et al. 1998*
Red cabbage	3	Germany	8	46 – 428	Hannover 1996-98
Savoy cabbage	5	Germany	29	110 – 447	Hannover 1988-90
Small radish (Spring)	8	Germany	8	120 – 394	Großbeeren 1998-2001; Zeiskam 2003
Small radish (Summer)	13	Germany	13	99 – 636	Großbeeren 1998-2001; Zeiskam 2003-04
Spinach	4	Germany	17	41 – 429	Hanover 1993-94; Großbeeren 1996
Squash	1	Italy	6	0 – 300	*Damato et al. 1998*
Swede	1	Norway	5	30 – 190	Kise 1995-96
Tomato (Processing)	2	Italy, USA	10	0 – 269	*Andersen et al. 1999; Parisi et al. 2006*
Turnip	4	Germany, India	22	6 – 400	Hanover 2002; *Inam 2002*
White cabbage	9	Denmark, Germany, UK	48	50 – 467	Årslev 1988-89; Hanover 1984-87; Wellesbourne 1996
White cabbage (Summer)	4	Norway	44	13 – 393	Landvik 1990-91
White cabbage (Winter)	4	Norway	44	13 – 393	Landvik 1990-91
White cabbage (Industry)	3	Germany, UK	9	165 – 455	Großbeeren 1994

Table 2: Classification of vegetable crops into different types of relation between total dry matter content and marketable fresh matter yield.

Type A crops (linear)	
Apiaceae	Carrots, Parsley, Parsnips, Celeriac
Brassicaceae	Broccoli, Cauliflower, Brussels sprouts, Turnip, Radish
Chenopodiaceae	Beetroot
Fabaceae	Broad and French bean, Cowpea
Liliaceae	Garlic
Poaceae	Sweet corn
Solanaceae	Main and Early potatoes
Type B crops (curvelinear or linear only at optimum region)	
Apiaceae	Carrots (Industry), Celery
Brassicaceae	Kohlrabi, Kale, Red cabbage, Savoy cabbage, White cabbage, Swedes
Chenopodiaceae	Spinach
Liliaceae	Leek, Onions
Type C crops (not related, multi harvest, perennial)	
Asteraceae	Butterhead and Iceberg lettuce, Artichoke
Brassicaceae	Chinese cabbage
Cucurbitaceae	Courgettes, Cucumber, Melon, Squash, Pumpkin
Fabaceae	Runner bean
Solanaceae	Aubergine, Tomato,

Table 3: Empirical parameters for vegetables and main agricultural crops which total above-ground dry matter is to be converted to marketable fresh matter yield using the regression approach (Strategy I).

Crop name	r_0	r_1		r_0	r_1
Artichoke	2.1	0	Parsley	8.3	0
Barley	0.61	0	Peas	1.4	0
Beetroot	5.45	0	Potato (Early)	2.36	-0.0014
Broccoli	3.5	0	Potato	10	0
Broccoli	2.5508	-0.0026	Radish	9	0
Brussels sprouts	1.9516	-0.0015	Rye/Triticale	0.6	0
Cucumber (Pickling)	13.7	0	Spinach	10.189	0.0172
French beans	4	0	Spring onion	9	0
Kale	5	0	Sugar beet	3.04	0
Lamb's lettuce	10.6	0	Swede	10.88	-0.026
Maize (CCM)	1.2	0	Sweet corn	0.7	0
Maize (Silage)	3	0	Tomato (Processing)	9.429	0.0115
Maize (Grain)	1	0	Turnip	5.84	0
Oat	0.61	0	Wheat	0.61	0
Oil seed rape	0.38	0			

Table 4: Empirical parameters for vegetables and main agricultural crops which total above-ground dry matter is to be converted to marketable fresh matter yield using the population approach (Strategy II).

Crop name	Dry matter content (c_{DM}) %	Harvest index (HI) %	Minimum fresh weight (L_{low}) g	Maximum fresh weight (L_{up}) g	Population coefficient of variance (CV)
Bell/Sweet pepper	10.0	70	90		0.3
Carrot	12.0	83	50	250	0.5
Cauliflower	10.0	45	600		0.3
Celeriac	15.0	71	100	1000	0.3
Celery	10.0	70	150		0.3
Chinese cabbage	3.6	70	350		0.3
Courgette/Zucchini	10.0	70	50	450	0.3
Eggplant/Aubergine	10.0	70	100		0.3
Endive	4.0	80	150		0.3
Fennel	10.0	80	80		0.3
Garlic	40.0	80	60		0.3
Kohlrabi	10.0	70	80	500	0.3
Leek	12.2	68	35		0.3
Lettuce (Butterhead)	4.0	80	150		0.3
Lettuce (Crisp)	4.0	80	300		0.3
Melon	7.0	80	1500		0.3
Onion	10.4	75	20		0.3
Parsnip	17.0	95	50		0.3
Radicchio	5.0	40	200		0.3
Red cabbage	9.3	65	350		0.3
Savoy cabbage	9.3	65	350		0.3
Small radish (Spring)	4.8	84	4	20	0.3
Small radish (Summer)	4.2	85	4	20	0.3
Squash	10.0	80	0		0.3
Water melon	7.0	80	1500		0.3
White cabbage	9.3	65	350		0.3
White cabbage (Summer)	7.8	75	350		0.3
White cabbage (Winter)	12.0	54	350		0.3
White cabbage (Industry)	9.3	65	350		0.3

Figure 1: Examples of the relation between total above-ground dry matter (TDM) and marketable fresh matter yield (MFY) for different levels of plant available N as defined as N in soil and plant at harvest, showing linear (A), curvilinear (B), or no (C) relationships.

Figure 2: Bland-Altman plots for differences between marketable yields converted from simulated total dry matter using the regression approach (A) and the population approach (B) versus observed marketable yields from different experimental crop rotations.

Figure 3: Marketable yields converted from simulated total dry matter: Plotting the regression approach results versus the population approach results for simulations of different experimental crop rotations.

Figure 4: Simulation of a plant spacing experiment with white cabbage "Quisto": Mean individual marketable yield (A) and crop residues (B) are calculated by the model first at harvest time. Above-ground crop N content (C) and dry matter development (D) are continuously simulated. Data show measured values at 30 × 50 cm (■) and 50 × 50 cm (□) spacing, calculated final fresh matter yield at 30 × 50 cm (◆) and 50 × 50 cm (◇) spacing and dynamic simulations for 30 × 50 cm (—) and 50 × 50 cm (---) spacing.

Figure 5: Simulation of an N fertiliser experiment with cauliflower "Fremont". Measured individual head weight distribution for a 240 kg N ha^{-1} (A), 120 kg N ha^{-1} (B) and 0 kg N ha^{-1} (C) treatment (n = 24). Normal distribution based on simulated mean head weight and a cauliflower default coefficient of variation (0.3) for a 240 kg N ha^{-1} (D), 120 kg N ha^{-1} (E) and 0 kg N ha^{-1} (F) fertiliser scenario. Lower boundary for gradeout was set to an individual head weight of 600g.