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Developing and testing a model for open field horticultural crops to enable use of a 'just-in-time' fertilization management

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Abstract: Today more than ever, increased crop production depends on judicious use of resources. In addition, issues such as climate change, climatic variability and environmental sequestration have become ever important. The objective of this study is to provide user-friendly ways for farmers to control the amount of nitrogen fertilizer in a very precise manner, in order to avoid overuse of fertilizer, which is not only harmful to the environment, but also a major production cost factor. This should however, be realized without suffering from production or quality losses. This is especially so in the case of intensive open field horticultural crops, where abundant to extreme use of fertilizers is very widespread. As such, cauliflower has been chosen as the research object in this study. Taking into account that in the future, governments will undertake action by the means of fines, it is in the interest of the horticultural farmer to be able to handle these issues in a sustainable manner.

An experimental site was set up, allowing real time follow-up of all fertilization and irrigation inputs and outputs. Four different nitrogen application rates and four fertilization treatments, from broadcasting to fertigation, resulted in a four by four completely randomized factorial design, replicated in two blocks. The fertilization rates were set in a way that luxury nitrogen availability as well as restricted availability was present in the experiment. Drainage water per plot was being retained so that the water volume could be sampled during growth and measured regularly for nitrogen content. Destructive growth analysis of plant biomass, both leaves and curd, was carried out on a fortnightly basis. At harvest time, about 83 days after planting, plants were sampled commercially (i.e. with leaf crown) and non-commercially (i.e. the whole plant). Both the curd and leaves were analyzed for fresh weight, dry weight and nitrogen content. Furthermore, leaf soil coverage and specific leaf area index were measured. Additionally, root growth and root length density were extensively analyzed.

Gathered data resulted in a crop growth model for growth estimation of a cauliflower crop and its nitrogen content, depending on its application rate. Parallel with this crop growth model, a soil mineralization-water model has been developed through intensive root growth measurements to provide an accurate projection of the volume of soil where uptake is taking place, influencing soil-N-sequestration and N-mineralization.

The combined model makes it possible to estimate not only crop growth, but also nitrate leaching and soil mineralization during a complete growing season, based on the local average climate or actual climatic data. As such, this model will provide a user friendly tool for farmers to determine their crops needs and overall farmland status, enabling them to make well-informed decisions concerning sustainable present and future cropping.

Keywords: *Sustainable horticulture, crop growth modeling, N-leaching, cauliflower fertilization, plant growth simulation*

1. INTRODUCTION

Present agricultural and horticultural practices make use of huge amounts of inorganic fertilizers, mainly N, P and K, to maintain production capacity and quality. Especially in intensive productions systems, such as open field vegetables, the applied fertilizer rates substantially exceed the basic needs of the crop. The Short Term Goal (2007) for the excess of nitrogen on the soil balance, determined by the MINA-plan 3 (Ministerie van de Vlaamse Gemeenschap, 2003), was based upon a quality standard for potable water (50 mg nitrate/L) and amounts up to a total of only 70 kg N/ha. This Short Term Goal was hardly met in open field horticulture where it is not uncommon to apply mineral N fertilizations in the range of 350 kg/ha annually and where at the same time, large amounts of N are released because of mineralization of soil organic matter and frequent organic fertilization. This implies that technological innovations in the field of N fertilization are necessary to increase the efficiency of the applied N, thus enabling farmers to stay within range of the environmental standards without loss of produce or quality.

On average only a limited amount of the applied dosage is found in the crop (< 50 % for N, < 10% for P and <49% for K). The remainder is being transported by means of leaching, run-off and degradation to the environment. Marine as well as terrestrial environments are very sensitive to an extra input of nutrients (eutrophication) with the possible loss of habitat causing a decrease in biodiversity and an increase in soil, water and air pollution as a consequence. Above all, this overuse of fertilizers represents a substantial cost surplus for the farmer, even more so due to the fines that are imposed as a compensation of the environmental impact. In Figure 1 the Flanders territory can be observed with every dot representing a measurement of nitrate concentrations in the ground water in the spring of 2006. Red dots are places were the threshold of 50 mg nitrate/L was exceeded.

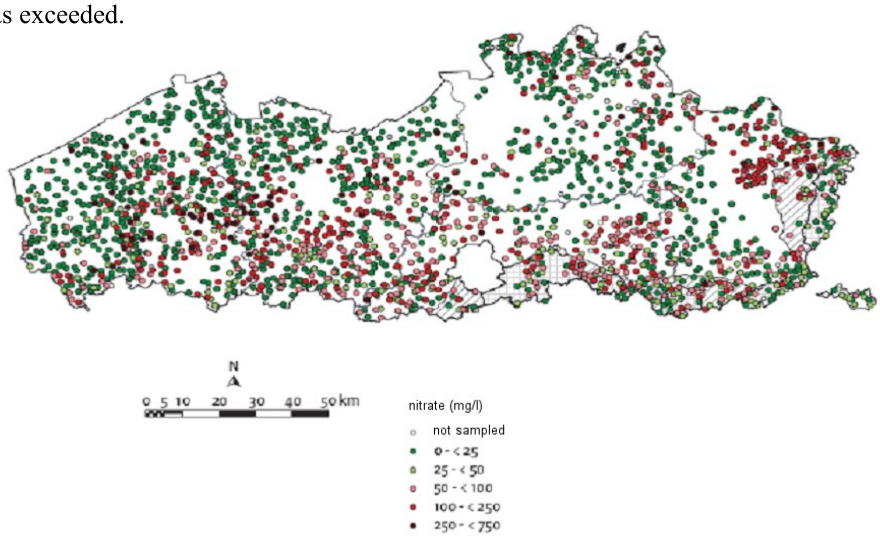


Figure 1. Nitrate concentrations measurements of the phreatic probing net of the Fertilization Action Plan in the spring of 2006 (Vlaamse Milieumaatschappij, 2006)

Substantial improvements were made in the sector through the fractionated application of nitrogen, the use of nitrification inhibitors combined with NH4-fertilizers in row fertilization and the use of one or two analyses of mineral nitrogen content in the root zone, in order to determine the fertilization dose. For this purpose a decision support system (DSS), based on a simple soil N balance calculation during the growing season and accounting for the N-uptake pattern of the specified crop, is used (KNS-system, Lorenz *et al*., 1985). However, this N-fertilization DSS does not allow for a proper estimation of N-leaching or even the mineral N residues in the soil profile after the growing season, which is essential when striving to an optimized return on a long term basis.

The goals of this research study were to optimize the N-fertilization strategies in open field horticulture in terms of the highest possible use efficiency of nutrients and water, approaching it with a model-based 'just-in-time' principle. Through the use of a dynamic model instead of a static balance calculation, a very precise fertilization that is designed according to the needs of the crop will be possible. It will also allow the history of the field to be taken into account and estimate the soil N mineralization and N uptake levels, thus predicting environmental impact while incorporating prevailing precipitation distribution and temperature. On the one hand the model can extend fertilization options and on the other hand enable insight into the problems of overuse of fertilizer with its resulting environmental impact.

2. MATERIALS AND METHODS

To reach these goals the dynamic soil-plant model, with an ability to optimize for a just-in-time N-fertilization is being developed. The research is done over a period of 4 years (2008 – 2012), to gather data on a site of the Experimental Station for Vegetable Production at Sint-Katelijne-Waver (PSKW) in Belgium.

2.1. Experimental set-up

The experiment was set up across 32 plots, each plot being 40 meters long and 1.40 meters wide. Each of these plots has been fitted for 20 meters with an impermeable foil at a depth of 90 cm (further on referred to as 'shell'). In every one of these shells a drainage pipe was placed. In this way the water leaching out of each shell, can be retained in a barrel. As such, the total leached water volume per shell can be measured and frequently analysed for mineral N content.

After a variability study in late 2008 with leeks and identical fertilization treatments to homogenize all the plots, no significant differences existed among the 32 different plots of the experiment. In March 2009 the experiment started. Cauliflower was planted and an annual rotation of cauliflower – leek will be maintained during the entire duration of the project. The experimental field is split up into two blocks of 16 plots. With four different fertilization strategies and four different fertilizer application rates a four by four completely randomized factorial design was set up per block.

Nitrogen was applied twice during the growing season; once at planting and once eight weeks after planting. With every application the amount of fertilization was determined as the difference between the mineral N in the root zone and a reference value. These reference values for the different application rates were based on the KNS-system (Lorenz *et al.*, 1985). The second highest application dosage was set equal to the general recommended reference value of the KNS-system, the other values (one higher and two lower) were chosen at equidistant intervals of this KNS-reference value. This choice was made in such a way to expect production loss at the lowest application rate and luxury consumption at the highest. The values of these rates can be found in Table 1.

Table 1. Target values and fertilizer application in kg N/ha, representing the four different application rates for cauliflower 2009

	Target value on plant data	Fertilizer application on plant date	Target Value Soil N min 7 weeks after planting	Fertilizer application 7 weeks after planting
D1	50	30	100	43
D2	100	80	150	35
D3	150	130	200	25
D4	200	180	250	18

The fertilization treatments were:

- A broadcast fertilization with calcium ammonium nitrate (CAN);
- A row fertilization with ammonium sulfate nitrate (ASN);
- Another row fertilization with ASN and a nitrification-inhibitor 'Entec';
- Fertigation every two weeks with ammonium nitrate.

The cauliflower crop was harvested in May 2009 and the same experimental set-up was repeated for the subsequent leek crops, from June 2009 until November 2009. In 2010 and 2011 the same basic rotational experiment was continued, with the only difference that each year the N application rates were redistributed in such a way that the general reference value of the before mentioned KNS-system still remained very close to application rate 3 and the other rates were stretched a bit further in the hope to see more significant differences in the upgrowth/uptake process. In 2011 the lowest application rate was chosen to be 0.

2.2. Online monitoring

Weather data is gathered on hourly basis. Furthermore, soil moisture content is also measured at two depths on an hourly basis by means of time domain reflectometers or shorter TDR-sensors, and the same counts for soil temperature. At the same time the leaching water is being retained in a barrel and its cumulative volumes measured every 10 minutes. All this data is being wired to a server, ready for analysis.

2.3. Soil sampling

The soil has been sampled four times during the growing season at two different depths, 0-30 cm and 30-60 cm depth. The results were used to determine the supplementary fertilizer applications. To correct for the heterogeneous distribution of the nitrogen in the plot (due to the different fertilization strategies) a systematic sampling scheme was used instead of a classic random one. There is also a soil sample taken before every planting and after every harvest.

To get an idea of the spontaneous soil mineralization, in 2011 the crop was removed from some parts of the plots and soil samples were taken at 3 depths, adding the 60-90 cm region.

2.4. Plant sampling

On a regular basis plant samples were taken and analyzed. We can group them into biomass samples, destructive plant measurements, coverage sampling, non-destructive sampling of soil coverage, and root samples, taken to estimate root growth volume and root length density. Describing how plant samples were taken is not the main issue of this article, so will not be addressed further.

3. MODEL DEVELOPMENT

The combined effort of data gathering on environment, soil and plant material resulted in two modules. The first one consists of a generic crop growth module where the growth of a cauliflower crop can be estimated, together with its nitrogen content, depending on the respective application rate. Parallel to this growth module, a soil mineralization-water module has been constructed, which enables to determine soil water status, N sequestration and N-mineralization. Both modules can run autonomous with the correct input data, but when put together and integrating over actual weather data it provides an easy tool for determining the overall condition of plant and soil, minimizing the overuse of fertilizer and enabling the application of just-in-time fertilization.

At this stage, the output of the crop growth module is being used by the soil module for daily estimation of plant growth with water and N uptake from the soil. At the end of the day every process is integrated and adjusted for the next day.

3.1. Crop growth module

A generic plant model is used to develop the crop growth module. Once the module is initialized with cultivation technical information and plant starting values, growth processes will start running under influence of the prevailing climate. There is a continuous interaction between climate, photosynthesis and plant developmental stage.

Climate

Hourly data is available and fast processes such as photosynthesis, respiration and evapotranspiration are calculated every hour. At the end of every day an evaluation of the biomass increase is made.

Photosynthesis

The Acock formula (1) is being used for the estimation of the net photosynthesis of an entire plant (Acock *et al.,* 1978). As can be seen, this formula shows that the plant photosynthesis is principally influenced (see P_{max}) by the effect of temperature and vapor pressure deficit (VPD), for which correction functions have been developed. Further important influences are leaf senescence and of course the N application rate. To incorporate these, corrective parameters have been calibrated with the data of 2009.

$$P_c = P_{\max}\frac{\tau C}{K}\ln\left[\frac{Q_e K I_0 + (1-m)\tau C}{Q_e K I_0\, e^{-K(LAI)} + (1-m)\tau C}\right] \tag{1}$$

P_c = Crop in mg CO_2/m^2 s; P_{max} = Asymptote of the PS rate in mg CO_2/m^2 s; PS rate=f(Temp and DDD); Q_e = PAR utilisation-efficiency in CO_2/J; C = CO_2 concentration in the air in mg CO_2/m^3; τ = Leaf conductance for CO_2 transfer m/s; K = Extinction coefficient; m = Leaf transmission coefficient; I_0 = PAR above the canopy J/m^2 s; LAI = leaf area index (m^2 Leaf / m^2 soil)

Phenology

The phenological development of a plant is influenced by temperature. In the module a base temperature is chosen, under which no plant growth takes places. With this base temperature the effective temperature can be calculated and the sum of this parameter is used as a timescale for the phenological evolution of the plant. At a certain amount the next phenological phase is induced and the phenological development stage (DVS) of the plant will alter its influence on growth processes, f. e. from vegetative to flowering stage. This threshold point is also derived from the data of 2009.

Partitioning

Last but not least, the combination of photosynthesis, evapotranspiration and respiration calculations results in a total net dry matter growth. This biomass increase is then distributed among the various plant organs, depending on the current DVS of the plant. Calibration of this partitioning is based upon data gathered in 2009. As a result, plant organs will increase size, and leaf growth especially will influence future plant processes directly, resulting in greater soil coverage and changing photosynthetic capacity.

All these plant processes continue to be evaluated on a daily basis until the curd (or fruit) has reached a favorable size and weight, and harvest can be undertaken.

3.2. Soil module

The soil water module is based on a version of the software WAVE 2.0 developed by the Institute for Land and Water Management at the Catholic University of Leuven. The model roughly consists of separate subroutines for water, solutes and nitrogen, where processes such as denitrification and mineralization are worked out (Vanclooster *et al.,* 1994).

The soil water module used in the 'cauliflower' model is basically an adapted version of WAVE, with the crop module being used as the process initiator. Also rooting specifications are treated slightly different, because of the non-uniform rooting of many horticultural crops. The soil module, at this stage is fed with data from the crop module and the climatic data. Water is the driving force for distribution of solutes and N in the soil. Water also makes it possible for the nutrients to be taken up by the plant, which makes up for the loss of water and nutrients in the soil. To enable these calculations, the soil is virtually made up of thin layers, where nutrients move when water is available. According to the relative root distribution, rooting depth and root length, as was given by the crop module, a specific uptake in a rooted layer can be determined. The surplus as well as the content in the non-rooted layers will undergo normal uncultivated soil processes and leach or evaporate. After each day the roots in these layers will change according to the realized growth.

Currently work is being done to fine-tune the root processes and to differentiate the area of uptake according to the different fertilization strategies.

4. RESULTS

This short overview of results shows graphs, for a broadcast fertilization with the lowest and the second highest application rate that have been generated with the model, calibrated on the data of 2009. The results of 2010 are similar and continue to validate the model. Further development and fine-tuning is still necessary, and is being undertaken at present, with the more detailed data gathered this spring.

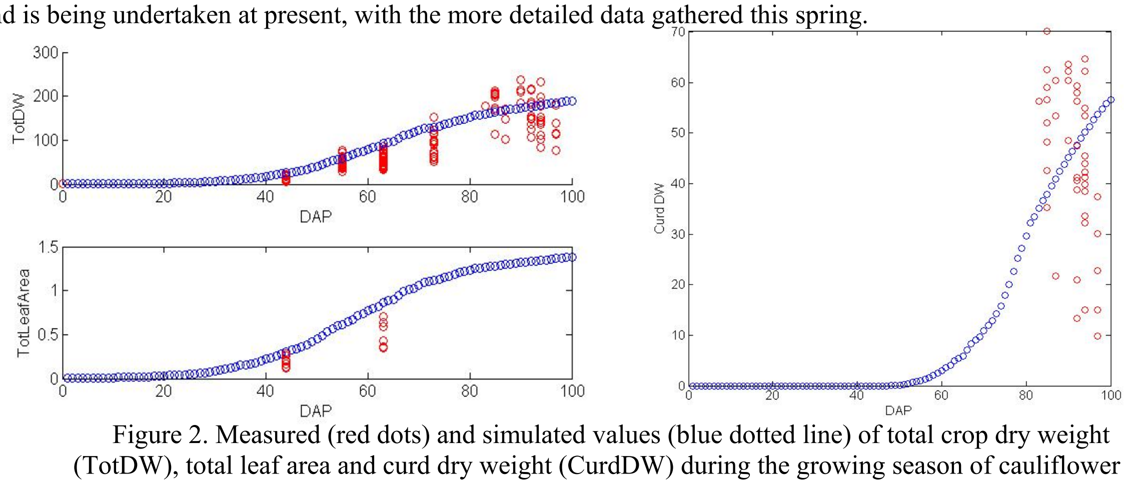


Figure 2. Measured (red dots) and simulated values (blue dotted line) of total crop dry weight (TotDW), total leaf area and curd dry weight (CurdDW) during the growing season of cauliflower of 2009 (DAP, days after planting), for N dosage application 1, broadcast.

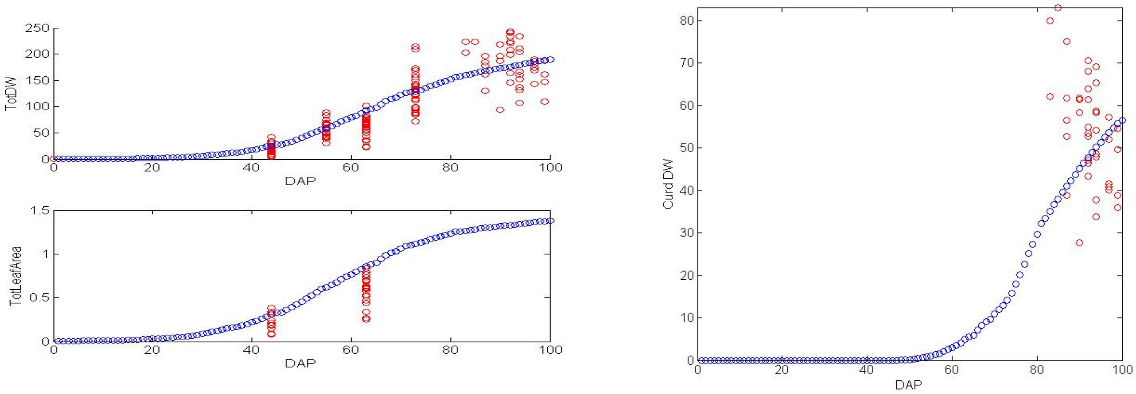
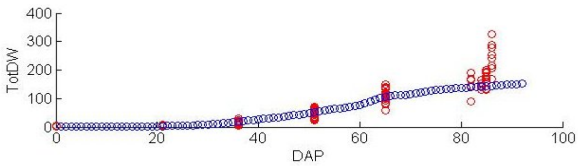


Figure 3. Measured (red dots) and simulated values (blue dotted line) of total crop dry weight (TotDW), total leaf area and curd dry weight (CurdDW) during the growing season of cauliflower of 2009 (DAP, days after planting), for N dosage application 3, broadcast.

As can be seen in figure 2 and 3, the model fits very well with the measured data. The same results were obtained using the data of 2010, available in figure 4.



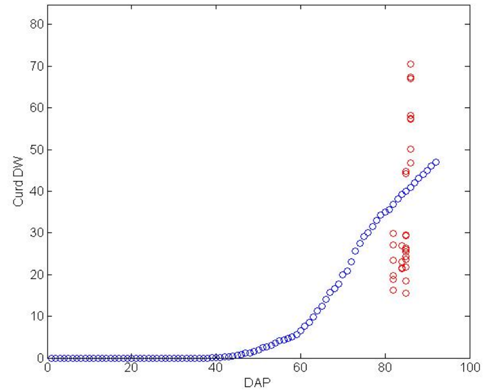


Figure 4. Left: Measured (red dots) and simulated values (blue dotted line) of total crop dry weight (TotDW) (left) and curd dry weight (CurdDW) (right) during the growing season of 2010, for dosage application 3, broadcast.

Figure 5 represents the simulated values of the daily and cumulative N uptake of the plant from the soil. The values of the first graph provide the necessary daily input data for running the soil model (i.e. soil N-uptake); the latter one provides data for making up the nitrogen soil balance at the end of the growth season.

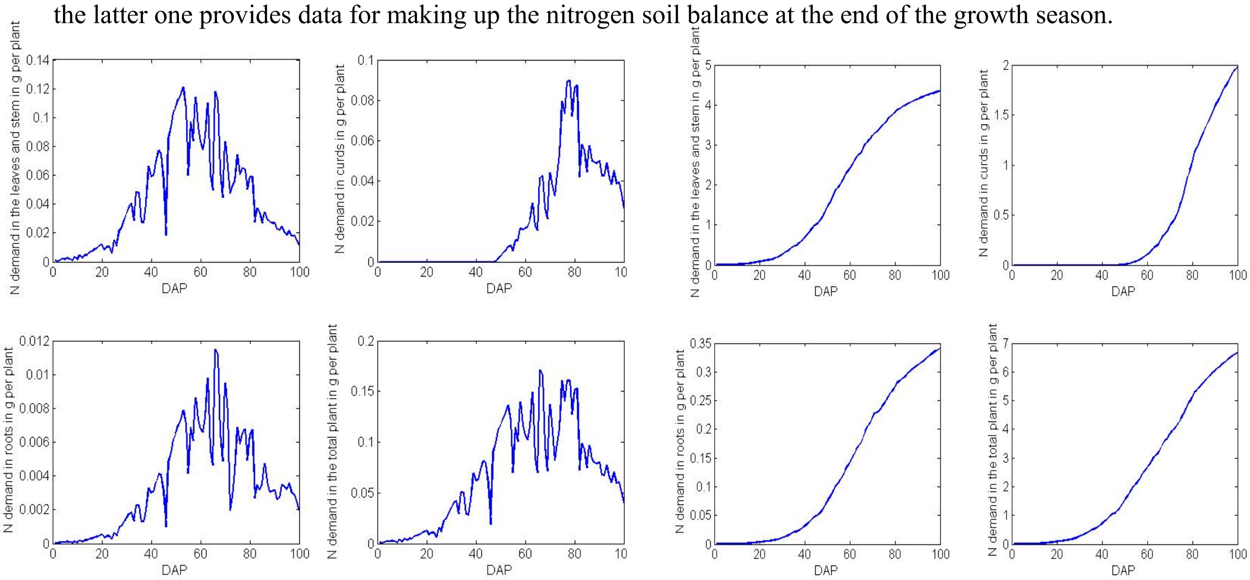


Figure 5. Top, from left to right: Daily N demand in shoot in g per plant, daily N demand in curds in g per plant, cumulative N demand in shoot in g per plant, cumulative N demand in curds in g per plant. Bottom, from left to right: Daily N demand in roots in g per plant, daily total N demand in g per plant, cumulative N demand in roots in g per plant, cumulative total N demand in g per plant. All graphs are simulated values for cauliflower 2009, dosage 3 and broadcast.

The end this overview, figures 6 and 7 show results from the soil water module. One can observe the measured and simulated values of soil N content at two different depths, during the growth season of cauliflower in 2009. Peaks in the blue line are caused due to fertilization application and as expected a lag of these can be found in the 30-60 cm layer. We conclude that the overall calculated estimates coincide strongly with the measurements.

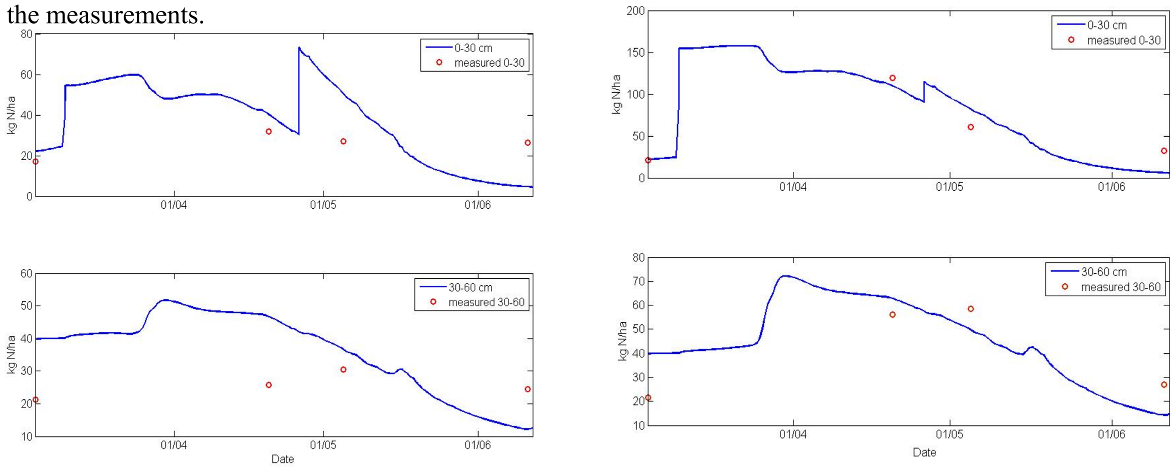


Figure 6. Soil N content in kg N/ha for the 0-30 cm soil layer (top) and 30-60 cm soil layer (bottom) with the simulated (blue line) and measured (red dots) values for the lowest dosage application, broadcast (left) and for the third dosage application rate, broadcast (right).

Combining the last shown results of the crop module (i.e. N-uptake) and the soil water module already fairly accurate soil nitrogen balance, the amount of nitrogen leaching from the soil and the crop N demand can be estimated on a day to day basis, allowing for more accurate 'just-in-time' fertilization treatments in the future.

5. DISCUSSION AND CONCLUSIONS

The presented model is on the way of being further developed, but seeing the preliminary results we can already conclude that the model is quite robust. With the basic outputs of the model, insight can already be gained in the growth processes of cauliflower, influenced by actual weather and application treatments.

Highly significant differences between application strategies have not been found and fine-tuning with the newly gathered data is still necessary to obtain more detailed information. However, as a first indication the results of these simulations can already be helpful to farmers for determining when, how and how much to fertilize, under prevailing climatic conditions and, as a result of the nitrogen balance estimate, how much of the applied nitrogen will eventually leach out of the soil into the ground water.

This first exercise emphasizes the importance of a very close monitoring and follow-up towards environmental impact of highly intensified open field horticulture, a sector very susceptible to overuse of fertilizer because of the lack of sufficiently predictive models in the past, and its significant impact on the environment. It is promising to see the presented model already performs very well, but work needs to be done still to incorporate more detailed data and to fine-tune for different treatments.

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