Precision Management of Nitrogen and Water in Potato Production through Monitoring and Modelling

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Abstract

Nitrogen and water application rates and timing depend on the final yield a grower expects the potato crop to achieve. Therefore precise measurements of 1) the nitrogen status of the crop and 2) the water status of the soil are needed. A crop growth model LINTUL-Potato calculates yields and the associated resource requirements based on the temperature dependent length of the growing season, the amount of solar radiation (potential yield) and on the soil moisture availability (achievable yields). Irrigation has to take place before a critical soil moisture level is reached and monitoring soil moisture may be done with several devices. Soil fluxes such as capillary rise, drainage and rainfall need not be monitored as they are accounted for by monitoring the soil for moisture depletion. Timing and amount of irrigation follow from the depletion rate, which depends on the proportion of the ground covered by green foliage and on the forecasted evapotranspiration rate by weather services of green foliage. To support decisions on supplemental nitrogen dressing knowledge is required on how much nitrogen is present in the soil at planting. Experimental data incorporated in the crop growth model have shown how much nitrogen a potato crop needs to contain before the end of a crucial time window to achieve the desired yield level. Several sampling techniques showing the crop nitrogen content presently exist. A nitrogen and water decision support system based on model and sensing techniques is nearing completion and already partly ready for world wide web application. Its usefulness for field specific application increases for each individual field, as more reinforcing data become available and are used in the decision process. Such a self-learning system becomes more powerful when more growers join the scheme for more years.

INTRODUCTION

Potential yields of potato crops depend on the cumulative amount of radiation intercepted over the length of the growing season as determined by the frost and heat free period within a year. Within such periods the temperature and daylength in interaction with cultivar characteristics determine the development of the crop. Temperatures determine the foliar expansion rate, and dry matter distribution between foliage and tubers. The photoperiod determines the moment of tuber initiation and the subsequent partitioning of dry matter to haulms and tubers. The earlier tubers are formed, the earlier the tubers start acting as the virtually exclusive sink and the earlier the crop is senesced. Optimising potato crop yields consists of balancing dry matter allocation to the foliage such as to maximise the amount of solar radiation intercepted by the green canopy on the one hand and allocation to the tubers such as to manage crop earliness by maximising the harvest index on the other hand (Kooman et al., 1996).

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Besides the yield defining factors solar radiation, temperature, daylength and cultivar, potato yields are mainly determined by two major yield limiting factors: nitrogen and water. This while assuming that other nutrients, notably phosphorus and potassium are applied at required rates before planting. Water and nitrogen are highly mobile in the soil and are subject to import to and export out of the root zone which makes it necessary to adjust their presence by crop management throughout the growing season (Haverkort and MacKerron, 2000).

This paper focuses on the development of decision support systems in western agriculture where most progressed has been made in the latest decade. Potato production in temperate climates has stabilised and so have yields in North America and in the European Union. Here presently the quality of the crop consumed as crisps and chips is a major subject of research and development, the more so because an increasing proportion of potatoes is processed. Management of water and nitrogen plays an important role to steer dry matter concentration and uniformity of the harvested produce. In Central and East Europe yields still offer considerable scope for increase when adequate amounts of water and chemicals are applied. Potato area and yields are still increasing in many tropical parts of the world where the crop expands rapidly. This expansion is enhanced by the increased availability of water through irrigation schemes. When water is at short supply potato is preferred as the crop much more efficiently uses water to produce useful dry matter than cereals, especially rice. This advantage can only be exploited to the fullest where adequate storage facilities are available as potato is a more perishable commodity.

Besides the objectives of quality and yield optimisation, the efficient use of resources (amount of potato produced per amount of resource applied) and reduced emission of nutrients to the environment are requirements demanded by the general public and consumers. More efficient use of water will reduce the need for energy for pumping and will preserve natural water. A more efficient use of nitrogen will lead to a reduction of residual nitrogen left in the soil at harvest serving two purposes: less energy consumption as nitrogen fixation is an expensive process in terms of energy and less emission of nitrate to groundwater and surface waters.

Improved quality and resource use efficiency increasingly demands precision management of jointly nitrogen and water. These two production factors strongly interact. Shortage of water reduces the efficient use of nitrogen and vice versa. Precision management requires the use of state of the art knowledge on crop-environment interactions as expressed in crop growth simulation models. It also requires adequate sensing techniques of water and nitrogen status of crop and soil to validate and adjust the model outcome at any given time during crop growth. The decision support systems developed so far mainly deal with total fresh matter production. It is clear, however, that water and nitrogen also strongly affect timing of tuberization and tuber number (and this tuber size distribution) and dry matter concentration. Such factors are not yet included in crop growth models to the extend that they can be used in decision support systems.

The objective of this paper is to show what scientific insights have led to the development of tools to measure the nitrogen and water status of soils and potato crops grown in temperate climates and how they can be used in model based decision support systems. The paper shows examples of experiments used to validate models upon which decision support systems are based. These experiments are from different sets of conditions (different years and sites). Perspectives and future developments are also discussed.

NITROGEN

Nitrogen Sources and Uptake

Sources of nitrogen for the potato crop are numerous. The amount of residual nitrogen left over from the previous cropping season as far as not leached during winter may vary between a few and many tens of kilograms per hectare in the top 60 cm soil. Atmospheric deposition with nitrogen from sources as lightning, industry and animal production may be a considerable source depending on where the crops are located and may add up to 20-60 kg per hectare per year. The soil organic matter mineralises during the growing season at increased rates when temperatures increase and water is available for soil microbes to be active. Depending on amount and quality of soil organic matter, including amendments such as compost or manure, this source of nitrogen may also vary between a few to up to over 100 kg per hectare per year. In organic farming these two sources of nitrogen are almost the only ones besides nitrogen fixating bacteria that may add a modest amount of nitrogen to the soil system (i.e. 10-20 kg per ha per year). In current farming systems potato production mainly depends on synthetic nitrogen fertilisers, especially nitrate and to a lesser extent ammonia. Fig. 1 gives an example of a dose response curve of potato yield versus nitrogen fertiliser rate, measured at a site in the Netherlands. At zero nitrogen applied this crop yielded over 25 t per ha of fresh potato tubers from residual nitrogen and mineralised nitrogen. Increased amounts of chemical nitrogen applied increased yields but less than proportionally leading to excess nitrogen. The fate of excessive nitrogen that is not taken up by the crop may be threefold. First, and most importantly N can be leached to the subsoil by rain or by irrigation in excess of the water holding capacity of the root zone. Secondly nitrate can be subjected to microbial denitrification whereby gaseous N_2 and some N_2O are produced. Thirdly, volatilisation of ammonia could occur from surface applied manure or from ammonia fertilizers that are not worked into the soil with high pH. .

Fig. 1 shows that potato crops respond favourably to increasing amounts of nitrogen applied at planting. From about 200 kg N per ha tuber yields do not increase further although the crop still takes up increased amounts of nitrogen. This excessive amount of nitrogen is used by the crop to form foliage and leads primarily to higher nitrogen concentrations in the dry matter of tuber and haulm and secondly to a decline in harvest index (Vos, 1997). Increased nitrogen rates further lead to a reduced proportion of all nitrogen taken up by the crop leaving the remainder subject to leaching.

Fig. 2 shows data from another experiment in the Netherlands where varying amounts of nitrogen were applied at varying times after planting. The crops in all treatments took up nitrogen until about 70 days after emergence. Thereafter the total crop nitrogen content in the foliage and tubers did not further increase. The amount of nitrogen present in the tubers, however, continued to increase until 140 days after emergence. This shows that transfer of nitrogen takes place from the foliage to the tubers, beside littering and leaching of leaves. Timing and amount of nitrogen fertilisation apparently has to take place in the first half of the growing season.

The amount of nitrogen applied at the beginning of the growing season determines the abundance of foliage expressed as leaf area index (LAI). More nitrogen applied leads to increased amounts of nitrogen taken up by the foliage of the crop, which is linearly associated with higher leaf area indices up to an LAI of about 6 (Fig. 3).

Higher leaf area indices take longer to build up and longer to be reduced through dry matter transfer from foliage to tubers than low LAI values. So high values are associated with longer leaf area duration (e.g. Fig. 4). In conclusion: the length of the productive season as set by the environment and the length of the growth cycle of the crop can be made to match by the amount of nitrogen applied within the first two months after emergence. This finding is of crucial importance for the development of adequate nitrogen decision support systems.

Nitrogen Decision Support

Nitrogen application to potato crops requires strategic, tactical and operational decisions. Strategic decisions deal with e.g. organic versus conventional farming or turning grass land into arable land. Tactical decisions are made just prior to planting such as which variety to plant, the application of manure or compost, single or supplemental dressings of chemical fertiliser and when to harvest e.g. main crop, early or seed potatoes. During crop growth operational decisions are made on supplemental nitrogen dressings such as timing and amounts. Fig. 5 summarises the tactical and operational decisions that need to be made in a nitrogen decision support system. The most crucial one being the expected yield of the crop following from cumulative radiation incident over the length of the growth cycle as determined by the length of the frost free growing season and the quantity of water available throughout the season.

When conceiving decision support systems for nitrogen two major findings have to be taken into account. First, the dose-response (Fig. 1 and 3) and the proportion of nitrogen not taken up (Fig. 1). Secondly, the time window when supplemental dressings still effectively increase the total nitrogen content of the crop (Fig. 2). It follows from these two phenomena that in supplemental nitrogen dressing schemes part of all nitrogen requirement has to be applied at planting and part has to be applied during the first half of the growing season. Applying nitrogen too early potentially leads to emission and too late may lead to reduced yields: a proper nitrogen decision support system therefore contains three elements: a) how much nitrogen in total needs the crop to take up in order to achieve the desired yield level?. b) depending on uptake and soil fluxes how much N should we apply early in the season and how much should we apply later on?, and c) what is the appropriate time slot to apply?. Decision support is needed to know how much should be applied. Several methods exist. The amount of inorganic nitrogen present in the soil can be assessed and verified whether there is enough for the remainder foliar growth requirement. The method is cumbersome and costly and due to soil heterogeneity not very accurate. Other methods in use are the invasive assessment of petiole sap nitrate concentration or a non-invasive measurement of the leaf chlorophyll concentration (SPAD) (Fig. 6). These methods require a calibration line with desired levels of nitrate or chlorophyll declining with time. If the readings fall below the line at any given time nitrogen needs to be applied. These methods have the inconvenience in common that the total and final amount the crop needs are not taken into consideration in the decision procedure, whereas the supplementary amounts of N needed to increase petiole sap and chlorophyll readings and safeguard yield need to be learned from experience. Nor do these methods take into account the requirement that ideally all nitrogen should be taken up in the first half of the growing season as in the second half mainly transfer of nitrogen to the tubers from the foliage takes place.

Two methods overcoming these disadvantages have been developed in the Netherlands and are presently exploited commercially. They have in common the assumption that total yield depends on total crop nitrogen content at the date at which the first half of the growing season ends. It is clear that e.g. the physiological age of the seed as influenced by agronomic conditions influences the length of the growth cycle. By assuming a certain length of the growing season this should be taken into account by the grower when making decisions. At the latest about 20 days prior to this date the crop nitrogen content needs to be determined and if insufficient the lacking amount needs to be applied. The total crop nitrogen content is determined by invasive sampling of a number of whole plants in a field and assessing their nitrogen concentration. A more elegant non-invasive way is through the measurement of reflectance at red and green wavelengths with a scanning device whereby a curvi-linear relationship exists between foliage reflectance, crop standing biomass and nitrogen content (Fig. 7).

WATER

Water Sources and Uptake

Crop yield is commonly a linear function of seasonal evapotranspiration, ET, with slope and intercept of the relation depending on climate and crop species but not on the degree of water limitation. For instance, sprinkler irrigation experiments in potato in the Netherlands showed increase per mm extra ET of 42 kg ha^{-1} per mm^{-1} for total plant dry matter and 37 kg ha^{-1} mm^{-1} for tuber dry matter (Feddes, 1987). World wide over half of the potato crops are irrigated. In temperate climates with a maritime climate such as in Northwest Europe and Northeast America winter rainfall excesses ET in winter but in summer evapotranspiration is greater than precipitation (Fig. 8). The precipitation deficit during the growing season often reaching several hundreds of millimetres has to be supplied to the crop by water held in the topsoil and or by irrigation. A well-developed canopy with an LAI over 3 fully covers the ground and has an evapotranspiration rate near to that of an open pan. The ET of crops with LAI < 3 is smaller than potential ET, the reduction factor being roughly proportional to the percentage soil cover or fraction light interception. Depending on the amount of nitrogen applied (Fig. 4) the ground cover duration and, hence, the duration of maximum evapotranspiration varies. Management of water and nitrogen thus is about adjusting the amount of nitrogen and biomass to the amount of water available. If water is not a limiting factor yields are mainly determined by the length of the growing season and solar radiation. Fig. 8 shows a crop that received no nitrogen that only covered half the soil area with green foliage. The 50 kg N per hectare treatment just about reached 100 % ground cover equivalent to an LAI of 3 (Haverkort et al., 1990) whereas the 400 kg N treatment still had green foliage at harvest. Where irrigation water and irrigation equipment is available more nitrogen can be given to crops than to rain fed crops as the total amount of foliage produced will be greater. With increasing soil moisture deficit plants need to develop a more negative water potential to extract water from the soil. As soil water is depleted plant water potential drops down to a level when the stomata close (at the critical soil moisture deficit) thus reducing water loss to the atmosphere. The objective of irrigation scheduling (Fig. 9) it is to avoid that soil water deficit falls below the "critical deficit" when partial stomatal closure occurs that would affect growth negatively.

Water Decision Support

When there is not sufficient water available from soil and rainfall to support a full cycle of crop growth that occupies the complete available frost free growing season growers need to manage water through irrigation management and choice of cultivar. Water management in crop production consists of supplying the crop with water such that the length of its growth cycle matches the length of the growing season. If irrigation possibilities exist the full growing season (as determined by climate and cultivar) can be used. If no irrigation possibilities exist two strategies can be followed. Strategy 1 is planting an early maturing crop to avoid dry spells in summer; this strategy is suitable for conditions where water stress is likely to aggravate as the season progresses. The second option is to plant late maturing crops that will suffer somewhat during transient dry spells by shedding leaves but will regrow as soon as rains start falling. That strategy can be adopted when drought is an erratic and transient phenomenon. The major aim in irrigation scheduling is avoiding soil water content to drop below the critical soil moisture level. Lack of water can be diagnosed using invasive methods such as pressure chamber measurements, psychrometry and measurement of relative water contents or with non-invasive methods such as the stem flow technique, porometry and infrared thermometry (De Neve et al., 2000). None of these methods, however, can be used in irrigation scheduling as the soil moisture deficit has already exceeded the critical level when leaf readings indicate stress, in other words the crop responds when it is too late and growth is already affected negatively. Therefore, numerous soil moisture measurement methods and devices have been developed and the readings they provide have been calibrated with a soil water retention curve to be of use in soil moisture deficit calculations. De Neve et al. (2000) compared the following methods for their usefulness in decision support systems: gravimetry, neutron probe, gamma probe, time domain reflectometry, frequency domain reflectometry, gypsum block, psychrometry and tensiometry using a vacuum gauge and a pressure transducer. There is no need to measure soil fluxes such as capillary rise, drainage and rainfall as these are accounted for by monitoring the soil moisture status.

New developments in irrigation decision support systems consist of model assisted risk assessment of irrigation. Fig. 10 shows calculations with a model of crop growth and development of final financial yield when irrigation is applied on a specific day. Real time weather is used to simulate actual yield (or crop financial benefit) until the day on which an irrigation decision has to be taken. Henceforward the model calculates yields with and without irrigation based on the next 5-day weather forecast and long term past weather data. Such information will aid the grower in his/her decision to take the risk to irrigate and the associated costs. Then there may be a chance of over irrigating when it starts to rain after irrigation or take the risk not to irrigate with a chance that a prolonged dry spell will affect yields.

CONCLUSIONS AND PERSPECTIVES

Once a potato crop is planted nitrogen and water are the two main yield and quality determining factors growers can influence. The objective of growing a crop is to make most optimal use of the available length of the growing season by matching it with the length of the growth cycle of the crop. The earliness of cultivar that the grower chooses to plant is directed at this match. And further fine-tuning takes place through a proper scheduling of nitrogen fertilisation and irrigation. These two factors strongly interact whereby irrigation scheduling determines the expected yield upon which subsequently nitrogen dressing is based.

Restrictions in the use of both water and nitrogen for environmental reasons make fine-tuning of processes in crop and soil more needed than before. This provides the incentive to develop decision support systems. Farms, especially in Europe increase in size so sensing and modelling based decision support systems become more cost effective per unit area. Improved knowledge about the soil-crop system obtained from sensing and modelling aided by information and communication technology (ITC - World Wide Web applications) rapidly improve the quality of the decision support that is generated. Finally there is a strong consumer induced tendency that retail chains require that production took place according to “good agricultural practices”. This often means that growers have to use soil and crop data and decision support systems to justify the inputs of resources.

Quantitative approaches such as crop growth models and other numerical methods open options to literally learn from past experiences in a sophisticated way. So-called ‘self-learning systems’ (Fig. 11) make the data collected in the past valuable for improvement of future decisions. Such a system is presently being developed for potato production in the Netherlands. Crop production data derived from generic sources such as weather stations and soil maps are combined with specific data obtained from monitoring and sensing (e.g. nitrogen and water) and actually applied management (e.g. application of nitrogen and water) and accomplished results yields and quality data from the processing industry. The data are stored in a database and used in decision support systems advising on water and nitrogen. Advise such as shown in Fig. 10 is generated accompanied by risk analysis with probability ranges using long term weather and other (e.g. potato prices) data. Data from each field and each year will improve and increase the value of such a self-learning system and the fields upon which it is based.

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Figures

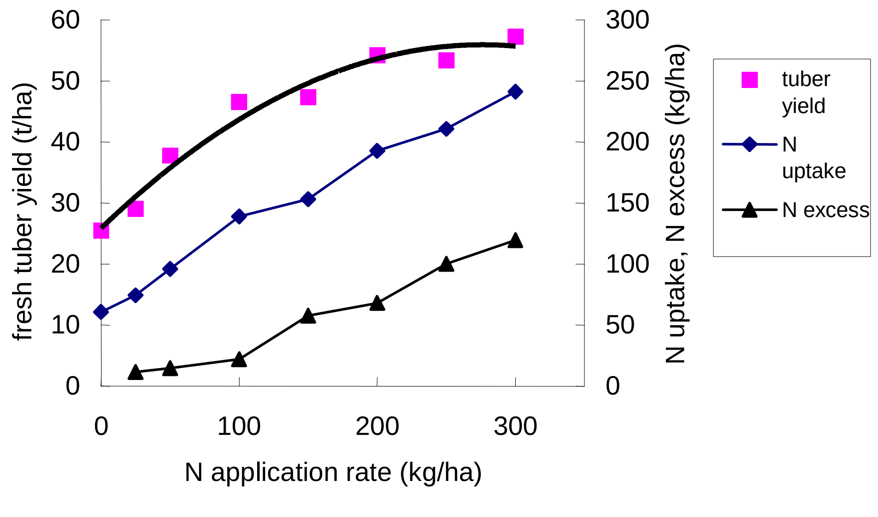

Fig. 1. An example of the response of potato to nitrogen fertiliser application. Left Y-axis: fresh tuber yield (t ha^{-1}), N excess is the difference between N taken up and available from application and soil reserves. Data after Vos (1997).

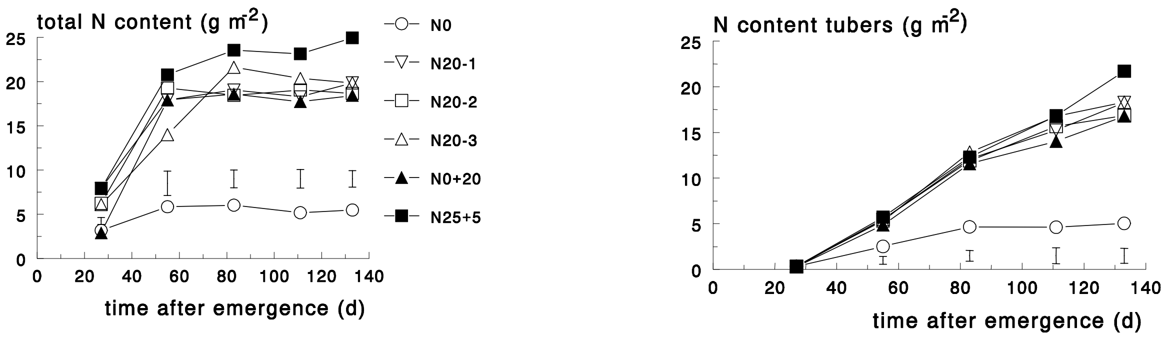

Fig. 2. Changes with time of total crop nitrogen content and tuber nitrogen content at varying rates and timing of nitrogen application (based on data from Vos, 1999).

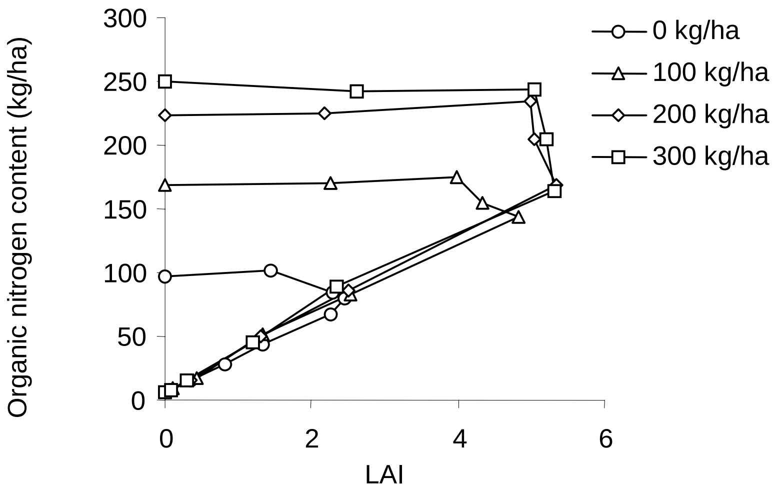

Fig. 3. Development of leaf area (LAI) and nitrogen taken up during crop growth at four N application rates (Booij et al., 2000).

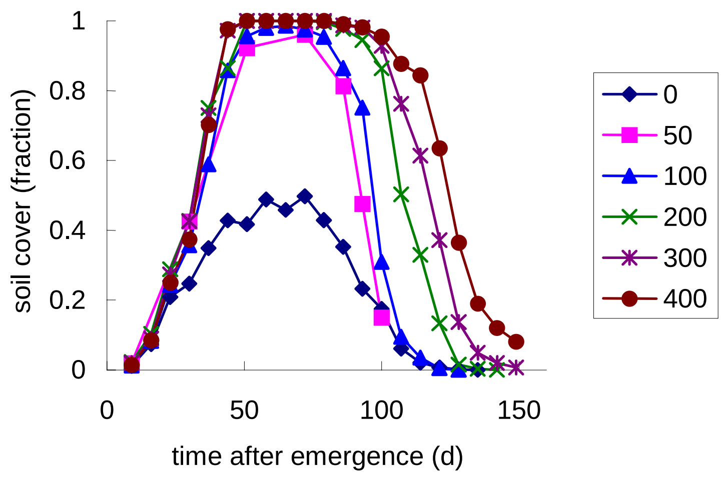

Fig. 4. Change in fractional soil cover with time for potatoes receiving 0, 50, 100, 200, 300 or 400 kg N ha^{-1} (Vos and MacKerron, 2000).

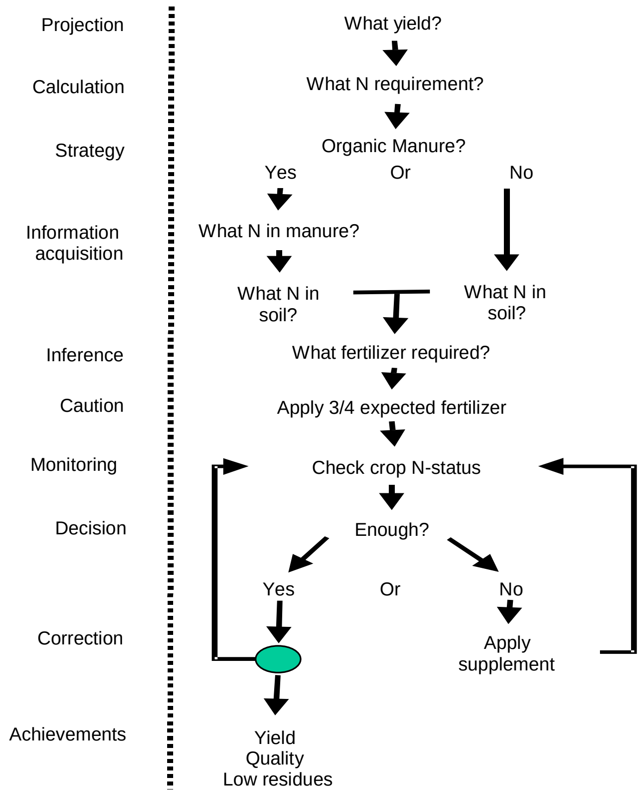

Fig. 5. Diagram showing decision tree for nitrogen application to potato crops (MacKerron, 2000).

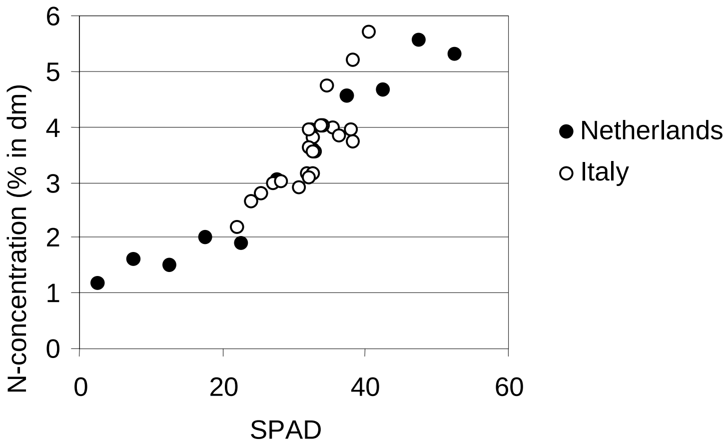

Fig. 6. Relation between SPAD readings and concentration of nitrogen (%) in the dry matter of an individual leaf. (data from Della Vedove and Vos in Booij et al., 2000).

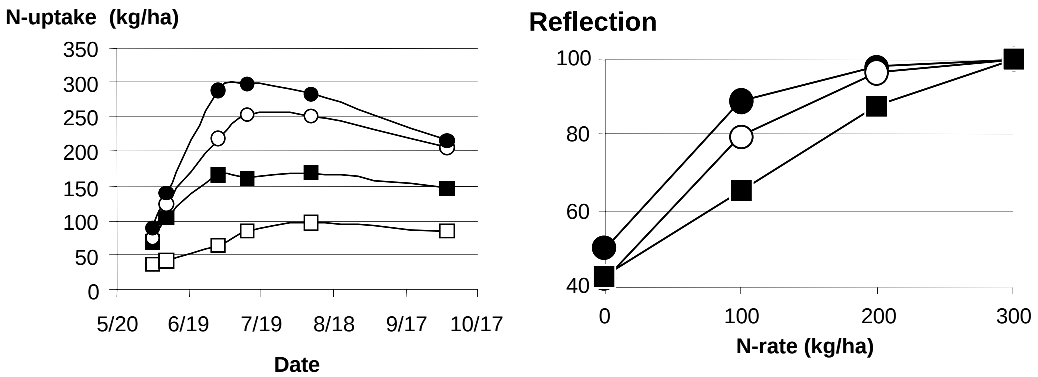

Fig. 7. Left: Changes in total nitrogen crop nitrogen content during crop growth at different levels of nitrogen availability (0 (□); 100 (■); 200 (○) and 300 (●) kg N/ha) during crop growth. Right: Relative crop reflection at different times (25/6 (●); 15/7 (○) and 12/8 (■)) during crop growth at these nitrogen rates Booij et al., 2001.

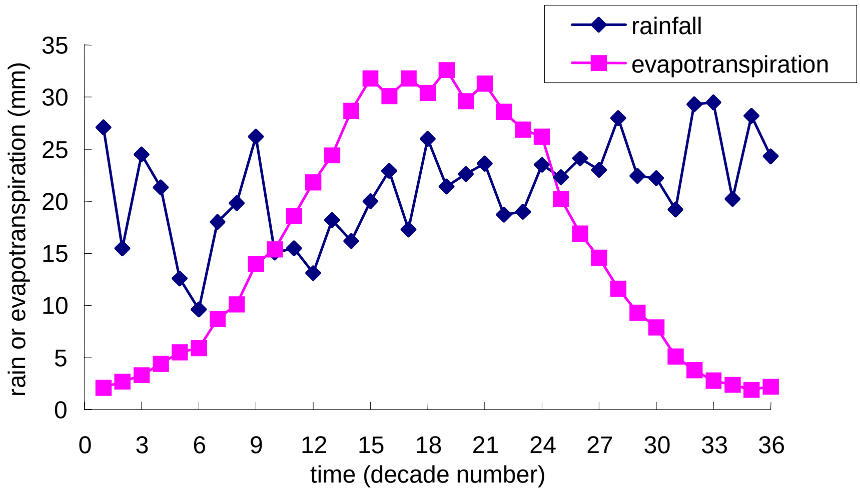

Fig. 8. Precipitation and evapotranspiration averaged over 1961-1990 in the Netherlands.

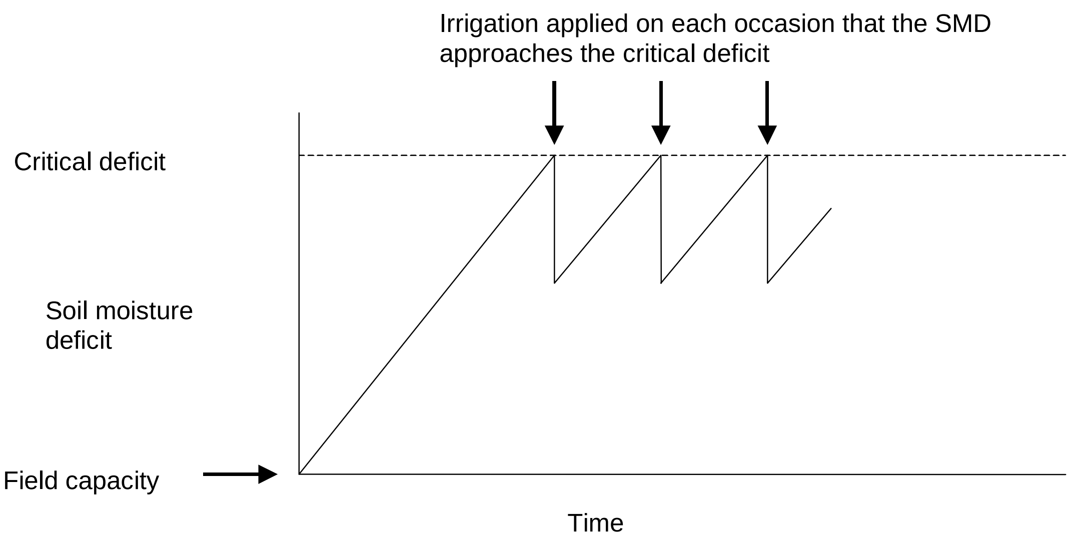

Fig. 9. Diagrammatic representation of irrigation scheduling (Bailey 2000).

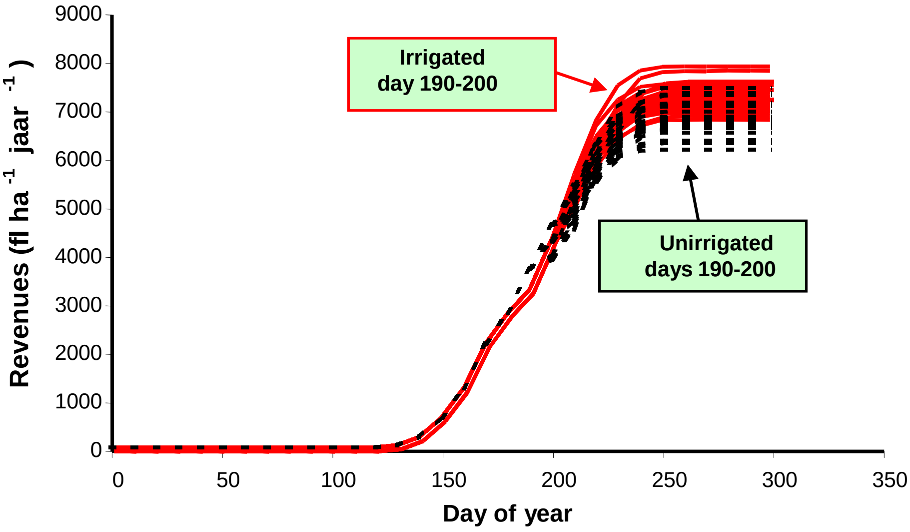

Fig. 10. Irrigation scheduling: results of simulating irrigating according to crop need, either or not on day 195 Source unpublished data HPA/AVEBE/PRI.

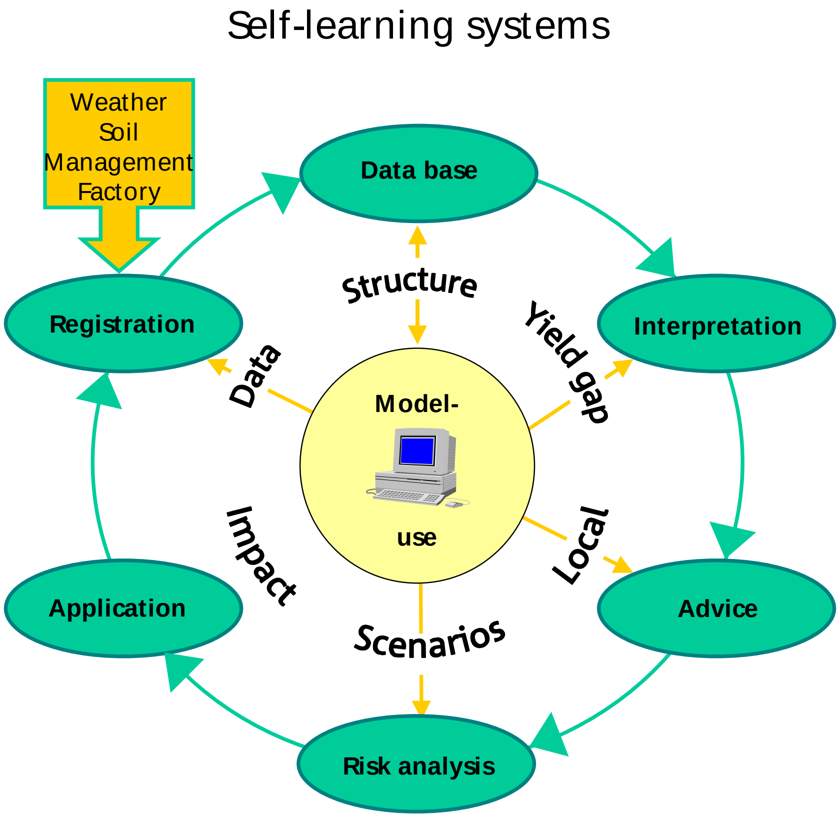

Fig. 11. Schematic representation of a self-learning or self adjusting system making use of automated generation and transfer of knowledge.