# The Crop Calculators – from Simulation Models to Usable Decision-Support Tools

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## EXTENDED ABSTRACT

Crop & Food Research has developed a set of simulation-based Crop Calculators as precision management tools for optimising nitrogen (N) and water management of wheat, potato and maize crops. Their main purpose is to provide best practice N-fertiliser and irrigation management schedules for user-specified crops, or to predict the likely consequences of management decisions. Both economic returns and environmental impact (N-leaching) are taken into account. The Calculators have also been very useful in identifying production constraints. In some cases these have been able to be overcome, or in others inputs have been reduced to avoid environmental impacts and unnecessary costs. They provide a rapid method for assessing the effects of changes in management on production, soil resources and profitability.

The Calculators are based on daily time-step simulation models. Each Calculator has a unique crop model simulating plant growth and development, with responses to variable water and N conditions, but all interact with a common soil model. The system model has CROP, SOIL, WEATHER and MANAGEMENT modules (Figure 1 ). During each daily time-step, CROP grows to a new state according to current soil state, weather and management conditions; and SOIL changes to a new state according to current crop state, weather and management conditions. MANAGEMENT has details of irrigation and N fertiliser application schedules, which may be specified by users to affect soil conditions in one way, or be generated by the system according to soil state and management rules to advise user for decision support in another way.

Plant growth potential and the effects of water and N limitations were simulated. The levels of drought and N-deficit were quantified by simulating the changes in plant available water (balance between rainfall and irrigation versus evapotranspiration and drainage) and mineral N (balance of organic N mineralisation and N fertilisation versus plant N uptake, N leaching and emission) in soil profiles. Crop N demand was calculated as the sum of the N demand for various plant tissue categories. Crop N uptake was driven by the demand, but limited by soil mineral N availability. Effects of drought and N-deficit on crop growth were quantified by reducing leaf area expansion, accelerating leaf senescence, and reducing radiation use efficiency.

The Calculators were validated against field-grown crops. Their prediction on crop growth and yield matched measurements from the crops well under various irrigation and N fertiliser applications and across a wide range of weather and soil conditions. Their effectiveness as management tools was demonstrated through significant reductions in fertiliser applications without reducing yield, especially for potato and maize.

The features of the systems include: keeping it simple; appropriate compromise between accuracy and convenience; the use of real system constraints together with simulation results for suggesting management.

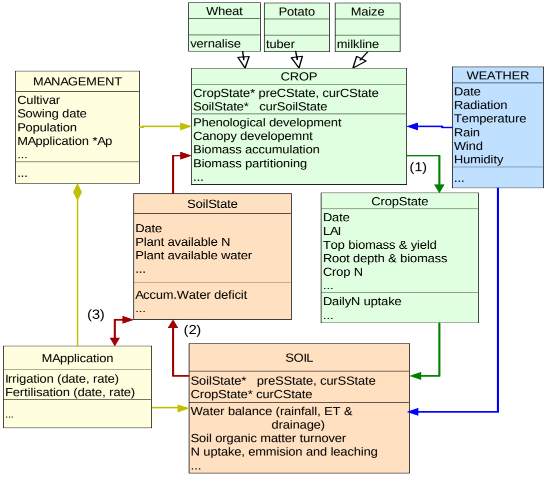

**Figure 1**. Simplified system architecture of the crop calculators, showing how (1) CROP and (2) SOIL changes to a new state during a daily time-step, and (3) how irrigation and N fertiliser application schedules affect to, or are generated from soil state.

## 1. INTRODUCITON

The crop calculators are precision crop management tools for optimising nitrogen (N) and water management of crops. Currently, the set includes the Sirius Wheat Calculator (Jamieson *et al.* 1998; Jamieson & Semenev 2000; Armour *et al.* 2002), the Potato Calculator (Jamieson *et al.* 2003; Jamieson *et al.* 2006) and the AmaizeN Calculator (Li *et al.* 2006a; Li *et al.* 2007a). More tools are in the chain to be added for crops such as forage brassicas (Wilson *et al.* 2004) and peas (Li *et al.* 2006b). Each crop calculator has been developed as a standalone system, and has a unique crop model simulating plant growth and development under variable water and N conditions, but all the crop models interact with a common soil model. The calculators have similar user interfaces and system architecture, and use the same method in dealing with weather conditions and crop management.

In this paper we briefly describe the functionality and operation of the crop calculators, present the merged system architecture that can be used to develop new tools for other crops. The tools may also be deployed in one system for modelling crop rotation and intercropping (Zyskowski *et al.* 2007a). Description of the underlying crop-soil interaction models is given, with emphasis on how simulated water and N limitations affect crop growth and yield. Finally, we provide the methods and principals we used to convert the simulation models into usable decision support tools.

## 2. SYSTEM FUNCTIONALITY

The operation of the crop calculators needs cultivar specific parameters, soil description, and weather data. These data are deployed as a database (files) with the system, and new data can be added easily if they do not exist. Cultivar specification requires numeric growth and development parameters, such as thermal time or photoperiod responses that determine when a cultivar reaches a particular phenological stage. Soil description includes organic N content, water-holding capacity and permeability. Weather inputs are daily solar radiation, rainfall, and maximum and minimum temperature, and optionally wind and humidity.

The system is arranged so that a user may select a cultivar, soil type and weather station by name. They must specify sowing date and population, and provide values of initial mineral N contents and moisture deficit in soil profile. The cost of crop management (irrigation and fertiliser applications) and the price of crop products also may be input for financial analysis.

There are several ways that the crop calculators may be used. At the beginning of the season they may be used to select combinations of cultivar and sowing date, and for planning irrigation and N-fertiliser application regimes. During the crop season irrigation and N-fertiliser schedules may be updated using up-to-date weather, soil and crop conditions. They may recommend the irrigation and N-fertiliser application schedule for best yield based on the site-specific conditions, and assess the likely financial and environmental impact. They may be used to answer “what-if” questions, by calculating the likely consequences of any user-specified management decisions, so can also be used as a rapid method for assessing the effects of changes in management on production, soil resources and profitability. They may also be used as a diagnostic aid in identifying production constraints by comparing crop performance with prediction. In some cases these can be overcome, or in others inputs can be reduced to avoid environmental impacts and unnecessary costs.

The outputs of the calculators include a series of tables and graphs showing crop phenological development, canopy expansion, biomass and harvest yield accumulation, and soil N and moisture dynamics to inform users’ decisions..

## 3. SYSTEM ARCHITECTURE AND CROP MODELS

The engines of the crop calculators are daily time step crop-soil interaction simulation models. Figure 1 is a simplified system architecture diagram, showing the main processes of crop-soil interaction during a daily time-step. Under the control of WEATHER conditions and MANAGEMENT interventions, CROP grows to a new state (daily growth) depending on the SOIL state, and SOIL proceeds to a new state (daily change) depending on the crop state. MANAGEMENT applications (irrigation and fertiliser application rate and date) affects or modifies soil state. Alternatively, soil state and plant demand are used to generate irrigation or nitrogen applications in concert with management rules.

### 3.1. Crop models

Each crop calculator contains a unique crop model simulating plant growth and development. Currently , the models are Sirius wheat (Jamieson *et al.* 1998), Sirius potato (Jamieson *et al.* 2003) and Amaize (Li *et al.* 2006a). The crop models all use a similar approach to phenological and canopy development, biomass accumulation and partitioning (Figure 1), and share similar mechanisms for quantifying crop response to water and N limitation. Potential growth and yield is defined according to the product of intercepted solar radiation and radiation use efficiency (RUE), the latter is species specific and responds to temperature. Drought stress and N deficit are quantified by simulating the changes in supply – soil profile plant available water and mineral N (Jamieson *et al.* 1998), compared with crop demand. Crop N demand is calculated as the sum of the N demand for various plant tissue categories (Sinclair & Amir 1992; Muchow & Sinclair 1994; Jamieson & Semenov 2000; Jamieson *et al.* 2003). Crop N uptake is driven by demand, but limited by soil mineral N availability. The water and N budgets of the crop system are assessed daily, together with budget of plant assimilates, and the responses quantified via green leaf area index (LAI) and RUE (Figure 2).

(1) *Water budget:* Percolation and redistribution of soil water is calculated from using the cascade model of Addiscott and Whitmore (1991). Within any soil layer, water exists in up to three states – unavailable (below the lower limit of extraction), available immobile (between the lower limit of extraction and the drained upper limit) and mobile (between the drained upper limit and saturation). Available water holding capacity per layer $PAW_{max}$) is defined as the capacity of the available immobile phase. Water deficit factors are handled slightly differently in the different models. In the wheat and maize models, a water deficit factor ($W_{df}$) is defined from the ratio of actual PAW ($PAW_{act}$) to the root zone $PAW_{max}$, with a maximum value of 1. If $W_{df} < 1$, daily leaf expansion is reduced and leaf senescence accelerated, resulting in a smaller-than-potential daily leaf area increment (noted as ΔLAIw in Figure2). Daily RUE and transpiration rate are also reduced. In the potato model, the maximum uptake rate for water is set at 10% (Dardanelli *et al.*, 2004) of the available water in the rootzone (sum of actual contents of mobile and immobile available water). $W_{df}$ is then calculated as the ratio of maximum supply rate to potential transpiration,

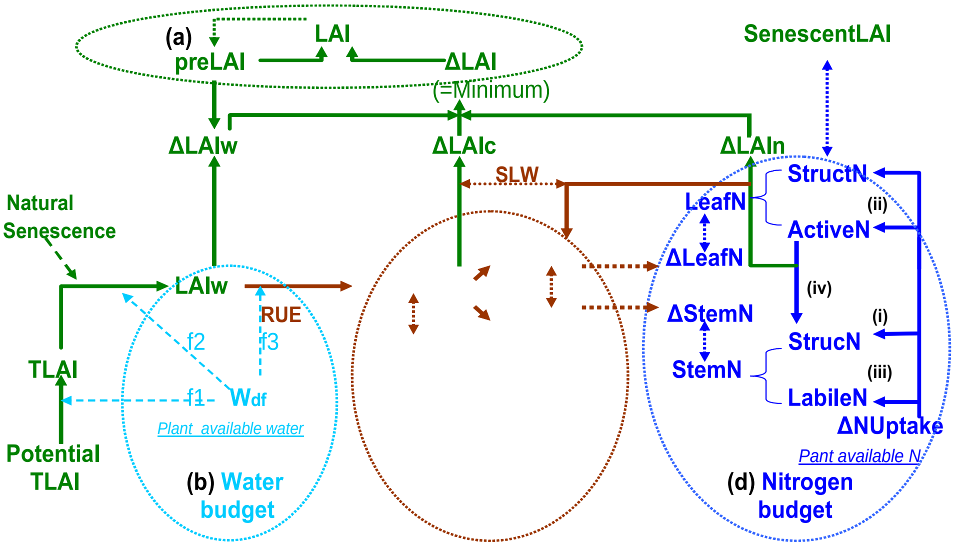

**Figure 2.** Daily plant growth in a model crop during the vegetative growth period, showing the effects of water and nitrogen limitation and other factors reducing carbon assimilation. The four elipses:

(a) Plant leaf area on a given day (LAI) is the sum of the LAI on the previous day (preLAI) and the daily increment (ΔLAI). ΔLAI depends on plant LAI growth potential and the effects of the water, carbon and N budgets.

(b) Water budget: if plant available water is insufficient, the deficit factor ($W_{df}$) will reduce leaf area expansion ($f_1$), accelerate leaf senescence ($f_2$), and reduce radiation use efficiency ($f_3$).

(c) Carbon budget: if daily biomass increment (ΔBiomass) is less than required by leaf expansion (ΔLAIw), then ΔLAIw will be reduced to that which ΔBiomass can support (ΔLAIc ).

(d) Nitrogen budget: Plant N uptake (ΔNUptake) is distributed to N pools in a priority order: (i) structural N, (ii) active N in green leaves, and (iii) labile N in storage. Under N deficit, labile N will be remobilised to the other two pools, and (iv) active N may also be remobilised to structural N, resulting in LAI reduction (from ΔLAIc to ΔLAIn).

upper limit unity, and applied as above.

(2) *Carbon budget*: A constant specific leaf weight (SLW) is used in budgeting the biomass among plant tissues. During the vegetative growth, part (SLW*ΔLAIw) of the daily biomass increment (ΔBiomass) is partitioned into leaf and rest into storage tissues (stems or tubers). If ΔBiomass is insufficient to support ΔLAIw, then ΔLAIw adjusted down to what ΔBiomass could support (i.e., ΔLAIc = ΔBiomass/SLW in Figure 2). During the grain-filling period, all the biomass accumulated is assigned to the pool for partitioning to grain, such that carbohydrate is transferred from vegetative organs to grains (Sinclair & Amir 1992; Muchow *et al* 1990) or to tubers (Jamieson *et al.* 2003).

(3) *Nitrogen budget*: N is allocated into four pools: structural N in shoots and roots, active N in green leaves, labile N in storage, and sink N (grain or tuber), within the crop (Sinclair & Amir 1992; Muchow & Sinclair 1994; Jamieson & Semenov 2000; Jamieson *et al.* 2003; Li *et al.* 2006b). The model also includes root biomass, estimated from above-ground biomass accumulation and root/shoot partitioning ratios based on AFRCWHREAT2 (Porter *et al.* 1993) for wheat, and Miller *et al.* (1989) for maize. As yet no specific fibrous root biomass is simulated for potato. A small amount of N taken up by plants was allocated to root for structural growth. Plant N uptake is allocated first to meet the needs of structural growth (root, stem, leaf), then the active N in leaves, and then labile N in store. Under N limitation, active N in green leaf is remobilised and re-allocated for structural growth of stems and roots, resulting in a reduction of ΔLAI (Noted as ΔLAIn in Figure 2) and associated biomass accumulation. During the grain-filling period of wheat and maize, N movement depends on the supply of remobilisable N from tissue, and the thermal time available to move it. A priority hierarchy means that remobilisable N is taken first from labile storage, second from any available soil sources, and lastly through premature senescence of green area. Therefore, under N limitation, leaf senescence is accelerated to release more N for grain growth when the labile N is exhausted and soil N uptake is insufficient, decreasing LAI.

## 3.2. Soil model

The soil is modelled as a cascade of 5cm layers. Plant available water and N at a given day are calculated using the same method (Jamieson *et al.* 1998) for all the crops. Briefly, the amount of soil moisture in root zone was the result of the balance between water input (precipitation and irrigation) and output (evapotranspiration and drainage), with availability to plants as described above. The dynamics of soil mineral N balances N supply from mineralisation of soil organic N, fertiliser N with losses to N emission and leaching (Addiscott *et al.* 1977) and crop N uptake. Plant available N PAN) is the fraction of soil mineral N dissolved in PAW in the crop root zone. Under severe N limitation, up to 10% of PAN may be taken up in a day (Li *et al.* 2007b), similar to the rules for water uptake (Dardanelli *et al.* 2004).

## 3.3 Weather

Weather files are available for weather to date. Beyond the end of the current weather file, future weather scenarios are used to drive the simulation. The future weather scenarios may be the average weather of multiple years at a site, or any scenario that user specifies, such as a scenario with 75% rainfall of the average.

## 3.4 Crop Management

The MANAGEMENT module holds the information on crop cultivars/hybrids, planting/sowing date and population, plus the irrigation and N-fertiliser application schedule (rate and time). Management applications affect the crop growth mainly through modifying soil moisture and N conditions (Figure 1). They may be specified and entered directly by users to reflect what they actually did or what they will do, or may be generated according to a set of management rules that take account of simulated soil moisture and N status, and user input information of the size or frequency of irrigation inputs and fertiliser applications. Example rules include “to apply 20 mm irrigation when soil moisture deficit (in root zone) reaches 25mm”, or “apply the required N fertiliser as three splits”. The MANAGEMENT module also contains user input information on the cost of inputs and value of outputs to allow cost-return analysis of various management scenarios.

## 4. SYSTEM VALIDITY AND EFFECTIVENESS

A wide range of field-grown crops were used to validate and calibrate these three crop calculators, for example, for Sirius Wheat Calculator (Armour *et al.* 2002, 2004), the Potato Calculator (Jamieson *et al.* 2003, 2006; Zyskowski *et al.* 2007b) , and the AmaizeN Calculator (Li *et al.* 2006a, 2007a). The results showed these calculators were good predictors of crop growth and yield under various irrigation and N fertiliser regimes across a wide range of weather and soil conditions. They are also reasonable accurate predictors of aspects of product quality (e.g., wheat grain protein content and maize silage crude protein content) and phenological development stages (e.g., flowering in wheat and maize and maize silage harvest dates).

The effectiveness of the calculators as management aids was demonstrated best by the fact that they led to significantly reduced fertiliser application without reducing crop yield. For example, across sites and seasons, the Potato Calculator guided management gave yields equals to conventional management, but applied, on average, 129 kg N/ha less N fertiliser than conventional management. This also resulted in a significant reduction in post-harvest soil mineral N residues (Jamieson *et al.* 2006). The maize crops managed using the AmaizeN Calculator across 11 farmers' properties also enabled a reduction of 82 kg N/ha in N fertiliser application in comparison with farmers conventional practice, and resulted in no significant yield reduction (Li *et al.* 2007a).

## 5. SYSTEM USEFULNESS

The user interface and functionalities of Crop Calculators have been evolved during their development and application. To turn a simulation model into a model-driven decision support system, accurate simulation of the soil dynamics and crop growth is only one aspect. Other aspects vital for success of such a crop management tool includes the incorporation of domain knowledge (e.g. irrigation system capacity), a user-friendly interface, appropriate compromise between accuracy and convenience, and provision of services when needed.

### 5.1. Keep it simple, but flexible

Some users like to get fertilisation and irrigation recommendations directly from the crop calculators so that they may follow it immediately. Therefore, the crop calculators were designed to recommend irrigation and N fertiliser application schedules from user inputs such as sowing date, population. Some users also like to use the tools to answer to their what-if questions – "what if I delay sowing? – what if I delay or miss an irrigation? What if I delay or advance fertiliser application by a couple of weeks?". All this is possible with user-editable dates, time and application sizes.

### 5.2 Usability

A crop calculators needs to cope with the real circumstances of the crop management of end users. For example, irrigation scheduling needs to account for irrigation methods and the availability of irrigation facilities. Irrigation equipment and flexibility is highly variable. Ability to deliver water may vary from large applications occasionally, to small applications every day or few days. The management rules must be sufficiently flexible to account for that. Possible rules might be 'apply an irrigation when the soil moisture deficit reaches x mm', or 'apply x mm of irrigation daily', or 'apply 5 irrigations every 7 days'. The Potato Calculator was developed reflecting irrigation management in New Zealand, where applications are usually separated by at least a week and application amounts may 20 mm or more. However, in South Australia and Idaho, USA, small irrigations are applied on a daily or near-daily basis. The irrigation scheduler and its interface were modified to allow for such systems, some of which include fertigation. Acceptability also requires that outputs are in units familiar to users – hence for US use, output is in bushels or tons per acre, irrigation in inch, and depths in feet etc.

### 5.3 Balancing accuracy with convenience

Accuracy of simulation depends to a large extent on the accuracy of the information provided. This in turn would lead to the most accurate management recommendations. However, often obtaining or measuring accurate input information is inconvenient or expensive. Minimising required inputs from users is important, even at the cost of some accuracy in recommendations. For example, accurate simulation of changes in soil profile mineral N for scheduling irrigation and N fertiliser applications requires knowledge of initial conditions to a depth that represents the potential root zone. However, partial (to limited depth) or qualitative (dry, medium or wet soil) information may be sufficient for scheduling, given there are other unquantifiable uncertainties in the system. Another example is maize hybrid information. This includes thermal duration of phenophases and some information on the potential size of leaves. However, maize hybrids turnover is fast, and often the best information is that hybrid x is similar to hybrid y, or a few days earlier or later. Information such as published CMR values must be usable.

### 5.4 Models suggest consequences, domain knowledge suggests management

The engines of the crop calculators are simulation models. However, also embedded in the system is domain knowledge in crop management.

For example, simulation output suggests that more frequent small irrigations and N fertiliser applications is more effective than less-frequent larger applications as a means of raising water and

N-use efficiency and avoid the risk of drainage and N-leaching. However, domain knowledge may show that such an approach is impractical. For instance, in maize crops, machine application of N-fertiliser must be made before the V8 stage (8 leaves) because later than that the height of the crop causes difficulties and will lead to crop damage. Hence, the recommendation is modified so that all the N fertiliser required by the crop should be applied by the V8 stage, even though there is an increased risk of N-leaching if heavy rain occurs soon after application.

### 5.3 Database and services

Backup services are important after deployment to ensure appropriate use. This includes help in system installation, initial site description, provision of weather updates and better soil information, and "help-desk" facilities.

## 6. CONCLUSION

The Crop calculators were developed to assist growers to schedule irrigation and N fertiliser applications for precise management of wheat, potato and maize crops. They have proved their ability to predict crop growth and yield, soil moisture and mineral N dynamics and N-leaching risks. They are useful in economic analysis of management scenarios. Their effectiveness has been demonstrated through reduction of N fertiliser applications without a yield penalty, thus improving the cost-effectiveness of management. Management recommendation are informed both by simulation and domain knowledge, and appropriate compromises between accuracy and simplicity / convenient use have been tested.

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## 8. REFERENCES

Addiscott, T.M. (1977), A simple computer model for leaching in structured soil, *Journal of soil Science,* 28, 554-563.

Addiscott, T.M. and A.P. Whitmore, (1991), Simulation of solute leaching in soils of differing permeabilities, *Soil Use and Management* 7, 94-102.

Armour, T., P.D. Jamieson, R.F. Zyskkowski (2002), Testing the Sirius wheat calculator, *Proceedings Agronomy Society of New Zealand,* 32, 1-6.

Armour, T., P.D. Jamieson, R.F. Zyskowski, (2004), Using the Sirius calculator to manage wheat quality – the Canterbury experience, *Agronomy New Zealand,* 34, 171-176.

Dardanelli, J.L., J.T. Ritchie, M. Calmon, J.M. Andriani, D.J., Collino, (2004), An empirical model for root water uptake, *Field Crops Research,* 87, 59-71.

Jamieson, P.D., M.A. Semenov, I.R. Brooking, G.S. Francis, (1998), Sirius: a mechanistic model of wheat response to environmental variation. *European Journal of Agronomy,* 8, 161-179.

Jamieson, P.D. and M.A. Semenov, (2000), Modelling nitrogen uptake and redistribution in wheat, *Field Crops Research,* 68, 21-29.

Jamieson, P.D., P.J. Stone, R.F. Zyskowski, S. Sinton, (2003), Implementation and testing of the Potato Calculator, a decision support system for nitrogen and irrigation management. In: Decision support systems in potato production: bringing models to practice, (eds) Haverkort A.J. and D.K.L. Mackerron, 85-99pp., Netherlands, Wageningen Academic Publishers.

Jamieson, P.D., R.F. Zyskowski, S.M. Sinton, H.E. Brown, R.C. Butler, (2006), The potato calculator: a tool for scheduling nitrogen fertiliser applications. *Agronomy New Zealand,* 36,49-53.

Li, F.Y., D.R. Wilson, P.D. Jamieson, (2006a), Modeling the population dependence of canopy development and biomass accumulation of field peas (*Pisum sativum* L.). Proceedings of the 13th Australian Agronomy Conference, September 11-14, Perth, WA.

Li, F.Y., P.D. Jamieson, A.J. Pearson, (2006b), AmaizeN: developing a decision support tool to optimise nitrogen management of maize, *Agronomy New Zealand*, 36, 61-70.

Li, F.Y., P.D. Jamieson, A.J. Pearson, P.R. Johnstone, H.E. Brown, R.F. Zyskowski, (2007a), Managing maize precisely: testing a decision support tool for managing crops for silage production. Proceedings of Australasian Dairy Science Symposium, Melbourne, South Australia, September 18-21.

Li, F.Y., P.D. Jamieson, A.J. Pearson and N. Arnold, (2007b), Simulating soil mineral N dynamics during maize cropping under variable nitrogen management. In: Designing Sustainable Farms: Critical Aspects of Soil and Water Management, (eds) Currie L.D. and L.J. Yates, 448-458pp., Massey University, New Zealand.

Miller M.H., G.K. Walker, M. Tollenaar and K.G. Alexander, (1989), Growth and yield of maize (*Zea mays* L.) grown ourdoors hydroponically and in soil, *Canadian Journal of Soil Science*, 69, 295-302.

Muchow, R.C., and T.R. Sinclair, (1994), Nitrogen response of leaf photosynthesis and canopy radiation use efficiency in field-grown maize and sorghum, *Crop Science*, 34, 721-727.

Porter, J.R. (1993), AFRCWHEAT2: A model of the growth and development of wheat incorporating responses to water and nitrogen, *European Journal of Agronomy*, 2, 69-82.

Sinclair, T.R. and J. Amir, (1992), A model to assess nitrogen limitations on the growth and yield of spring wheat, *Field Crops research*, 30, 63-78.

Sinclair, T.R., and R.C. Muchow, (1995), Effects of nitrogen supply on maize yield.I. Modelling phiological responses. *Agronomy Journal,* 87, 632-641.

Wilson, D.R., R.F. Zyskowski, S. Maley, A.J. Pearson, (2004), A potential yield model for forage brassicas, Proceedings of the 4th International Crop Science Congress. Brisbane, Australia.

Zyskowski R.F., P.D. Jamieson, and F.Y. Li, (2007a), LUCI – from single season crops to continuous sequences. Proceedings of MODSIM 2007 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2007, xx-xxpp., Christchurch, New Zealand.

Zyskowski, R.F., P.D. Jamieson, S. Thomas, S. Sinton and G. Francis, (2007b), testing LUCI: Predictions and measurements of nitrate leaching and risk, In: Designing Sustainable Farms: Critical Aspects of Soil and Water Management, (eds) Currie L.D. and L.J. Yates, 151-157pp., Massey University, New Zealand.