A spatially referenced water and nitrogen management model (WNMM) for (irrigated) intensive cropping and pasture systems

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Abstract

A spatially-referenced biophysical model, the Water and Nitrogen Management Model (WNMM), has been developed and demonstrated to simulate soil water movement and soil-plant C and N cycling under the given agricultural management, for the purpose of identifying optimal strategies for managing water and fertiliser N under intensive cropping systems (mainly wheat-maize) in China and under perennial pastures in Australia. A uniform data structure, ARC GRID ASCII format, is used both in GIS and WNMM for achieving a close GIS-coupling strategy. The WNMM simulates the key processes of water, C and N dynamics in the surface and subsurface of soils, including evapotranspiration, canopy interception, water movement, groundwater fluctuations, soil temperature, solute transport, crop/pasture growth, C and N cycling in soil-plant system, and agricultural management practices (rotation, irrigation, fertiliser application, grazing, harvest and tillage). It runs at a daily time step at different scales, driven by lumped variables (climatic data and crop biological data) in text data format and spatial variables (soil and agricultural management) in ARC GRID ASCII format data. In particular, the WNMM simulates the transformations of several N species in agricultural fields, including mineralisation of fresh plant residue N and soil organic N, formation of soil organic N, immobilisation in microbial biomass, nitrification, ammonia volatilisation, denitrification, and nitrous oxide emissions from soils. Based on WNMM, a user-friendly agricultural decision support tool (ADST) is developed for optimal water and fertiliser management.

Key Words

WNMM, GIS, simulation, soil water, N transformations, agricultural scenarios

Introduction

Soil N is of particular interest in studies of nutrient cycling in agroecosystems, as a limiting factor to crop growth and a source of N causing environmental problems. Simulation models, which describe in sufficient detail the turnover of N in the atmosphere-soil-crop system, can be of great assistance in understanding the interactions between different processes. Also, they can be used to identify gaps in our knowledge and can help in designing experiments that aim at clarification of poorly understood parts of the system. The integration of mechanistic models for identifying Best Management Practices (BMPs) for agriculture has been significantly improved/refined in recent decades.

Computer models can be categorised as lumped or as spatial parameter models, depending on the kind of parameters required. A lumped model is one in which processes are modelled within a system of discrete spatial objects, and the model solution describes the input and output of each object without attempting to determine the precise spatial distribution of the processes within the object. Lumped models can be represented by ordinary differential equations, that is, by differential equations whose dependent variables are a function of a single variable such as time. In the United States and Europe, there are a number of published and widely used lumped models simulating soil water dynamics, C&N turnovers and crop growth: NLEAP (Shaffer *et al*. 1991), RZWQM (Ahuja *et al*. 2000), CENTURY (Parton *et al*. 1994), GLEAMS (Knisel 1993), NCSOIL (Molina *et al*. 1983), EPIC (Williams 1995), DNDC (Li *et al*. 1992), SOILN (Johnsson *et al*. 1987), and DAISY (Hansen *et al*. 1991). All these models consider the main soil N dynamic processes, namely, fertiliser N application, mineralisation, immobilisation, nitrification, denitrification, and in a few cases N_2O emission, ammonia volatilisation, nitrate (NO_3^-) leaching, and crop N uptake. They have various objectives and simulate components of agroecosystems with varying degrees of complexity. Some modelling concepts are shared by all these models, while others are unique to a particular model. There are also differences in the way that components, such as N transformations, crop growth and water routing, interact. Whilst these models have achieved various degrees of success in application, they all have weaknesses, have failed under certain circumstances, are site-specific, and use lumped parameters.

Spatial models, on the other hand, run over a continuous space in which the solution is determined for each spatial element. The solution is one, two, or three dimensional, depending on how many spatial dimensions are used to describe the model variables. Spatial models are based on partial differential equations, whose dependent variables are a function of two or more variables, such as time and space. There are few published spatial simulation models of agro-ecosystems, namely, SWRRB-WQ (Arnold *et al*. 1990), SWAT (Arnold *et al*. 1993), ANSWERS-2000 (Bouraoui and Dillaha 1996), and ecosys (Grant 2001). Spatial models provide users with analytical tools that allow them to predict runoff, soil erosion, and nutrient transport on the surface and in the subsurface at regional scales. They also allow users to evaluate alternative practices and scenarios that can significantly influence these processes in large agroecosystems. They have limitations when applied, however, including the empirical expressions for soil water dynamics and C&N transformations; the large input data requirements; parameters that are difficult to estimate or to obtain; uncertainty in inputs, and a lack of technical support to understand or interpret the tremendous amount of simulation outputs.

Recently, researchers have successfully integrated mathematical simulation models with spatial-referenced database systems like GIS and expert systems to significantly reduce the time and labour required to run the models, and to graphically visualise the simulation outputs. Several papers provide excellent overviews of the integration of GIS and environmental models (DeVantier *et al*. 1993; Zhang *et al*. 1990; Fedra 1993; Maidment 1996).

In the North China Plain (NCP) which produces 30% total cereals in China, agriculture is facing a huge challenge how to maintain economically acceptable yields but minimise the adverse impact to the environment. One of the main objectives of the large collaborative research project supported by the Australian Centre for International Agricultural Research (ACIAR) was to develop sustainable management practices of irrigation and N fertiliser use for maize-wheat cropping systems in the NCP. The spatially referenced system model was selected as the best approach to provide information and recommendations to increase the efficiency of water and fertiliser N, reduce the potential for contamination of groundwater with NO_3^-, and emissions of the greenhouse gas N_2O for this large region. The model described in this paper is referred as the Water and Nitrogen Management Model (WNMM). Currently it has been extended to simulate pasture growth based on Moore *et al.* (1997) and grazing practice for pastoral systems in Australia.

In this paper, the theoretical description of this spatially-referenced WNMM, its GIS interface (GIS-WNMM), and WNMM-based agricultural decision support tool are briefly illustrated. Also, the sensitivity analysis of WNMM to lumped and spatial parameters and variables as well as its applications at site and regional scales are reported.

Model Description

Process model

WNMM simulated key processes of water and C&N dynamics in the surface and subsurface of soils, including evapotranspiration, canopy interception, water movement, groundwater fluctuations, soil temperature, solute transport, crop growth, comprehensive N transformations in soil-crop system, and agricultural management practices (crop rotation, irrigation, fertiliser application, harvest, and tillage). The hydrology of soil-crop system in WNMM is described in Figure 1. The potential evapotranspiration referenced for 40cm-high alfalfa is estimated using the Penman-Monteith method. Soil evaporation and plant transpiration are predicted separately by considering ground cover, leaf area index and crop root density distribution in soil profile. Dynamic soil water content and flux are calculated by the numeric solution of one-dimensional Richards' equation or a simple tipping-bucket water balance model. A sink term regarding crop root water uptake is considered in both approaches. Nitrate, ammonium and urea transports are governed by the convection-diffusion equation or an empirical solute transport equation adopted in EPIC model (Williams 1995). Soil temperature at depths is estimated using the same approach in EPIC (Williams 1995). A sinusoidal function of Julian day is assumed, with subsurface temperature changes lagging behind those at the soil surface.

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WNMM simulates comprehensive transformations of several N species in the agroecosystems, including mineralisation of fresh crop residue N and soil organic N, formation of soil organic N, immobilisation in biomass, nitrification, ammonia volatilisation, and denitrification as well as N_2O emissions (see Figure 2). It mainly divides soil C into three pools: fresh residue C, microbial biomass C (living and dead), and humus C (active and passive in terms of mineralisation). The flows between the different pools are calculated as first-order processes in terms of C, the corresponding N flows depending on the C:N ratio of the receiving pools. The C:N ratios of the various pools are assumed to be constant in the simulation. Mineralisation or immobilisation is determined as the balance between the release of N during organic C decomposition and immobilisation during microbial synthesis and humification. All the rate constants of first-order reactions for C&N transformations in the soil are modified by factors involving clay content, pH, temperature, and moisture status in soil layers. Urea hydrolysis is calculated as a function of soil urea content, soil water content and soil temperature. Soil pH change is simulated by considering urea hydrolysis, ammonia volatilisation, and nitrate production and reduction in the soil.

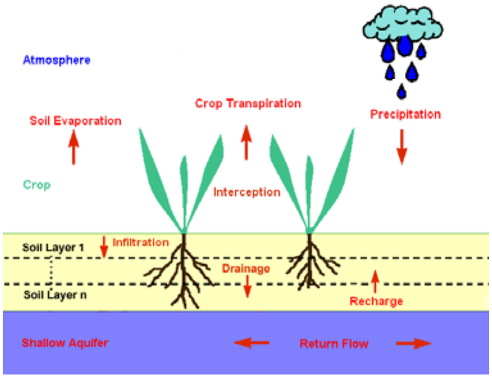

Figure 1. Conceptual diagram of water balance in soil-crop system in WNMM.

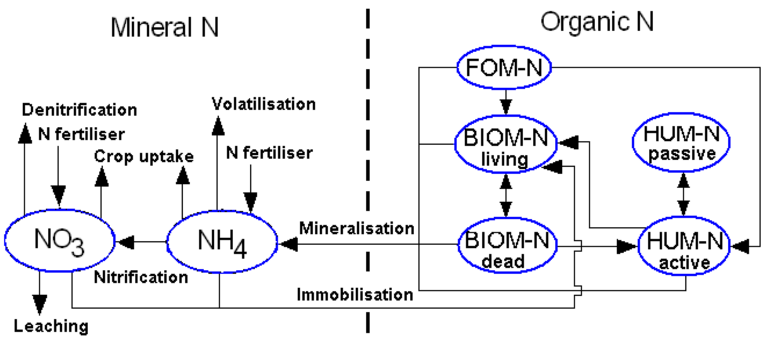

Figure 2. Diagram of nitrogen cycling in soil-crop system in WNMM.

The NO and N_2O leakages from nitrification process are estimated as a function of nitrification rate, soil water filled pore space and soil temperature. As one of the microbially-mediated processes, denitrification simulated in WNMM is a function of soil nitrate content, soil water content and available organic carbon content, and its main products are NO, N_2O and N_2. At present, there are three options of simulating denitrification in WNMM: daily simple first-order reaction (Xu *et al*. 1998), DAYCENT (Parton *et al*. 1996 and Del Grosso *et al*. 2000) approach and DNDC (Li *et al*. 1992) fully-process based approach.

The crop growth module is a simplification of the EPIC crop model, which applies the concepts of phenological crop development based on daily accumulated heat units, harvest index for partitioning grain yield, Monteith's approach for potential biomass, and stress adjustments for water, temperature and nitrogen availability in root zone of the soil profile. It predicts total crop dry matter, leaf area index, root depth and density distribution, harvest index, crop yield, and N uptake. A GRASSGRO-like pasture growth model is extended recently as well as grazing practice for Australian conditions in WNMM. The crop/pasture N utilisation is estimated using a supply and demand approach. The actual N uptake is composed of uptake due to convection (mass flow of N to the roots) and uptake as a result of N movement to roots by diffusion as well as N_2 fixation if leguminous pastures are present.

WNMM also simulates the agricultural management practices including crop rotation, tillage and stubble return, irrigation, and N fertiliser applications.

Data required by WNMM are categorised as GIS layer information (soil type, land cover, and village administrative boundary); database-formatted source data (soil physical and chemical properties, land use types, and agricultural management survey based on village units); referenced data (climatic reference data and crop biological data); and control data (starting date, period of simulation, initial land surface and soil conditions, agricultural management scenarios). The first two data categories are converted to ARC GRID ASCII format from other formats and sources in the GIS environment.

GIS-WNMM interface
Because the model is proposed for being deployed at the regional scale and its key parameter inputs, including soil physical, chemical and biological properties, precipitation and agricultural practices, are spatially heterogeneous due to the nature of the environment and human artificial influences, WNMM is regarded as a large scale simulation model and needs GIS coupling for managing spatially-referenced data. The strategy of coupling GIS with WNMM is by using a uniform data structure, ARC GRID ASCII format, which can be fully operated both in GIS environment and in this process model.

ArcGIS 8.x (ESRI 2001) and ArcView 3.x (with Spatial Analyst) (ESRI 1996a) for Windows are chosen as the basic platforms for geodatabase processing. The script language ‘Avenue’ (ESRI 1996b) built in ArcView GIS 3.2 is used to develop the GIS-WNMM interface. In order to make it as a professional GIS application and easily deployed to users, the interface is developed as an ArcView extension, which may be just added in by a mouse click to largely extend ArcView functionality for WNMM simulation (Figure 3).

This interface has the capability to produce all the GIS-related input ARC GRID ASCII files for WNMM simulations, which are clearly shown under the menu item of ‘GIS-WNMM’ in Figure 3, and also directly display the spatial outputs of WNMM simulations for further interpretation and documentary editing without any file exchange.

GIS-based ADST
Based on WNMM, a user-friendly agricultural decision support tool (ADST, see Figure 4) is developed for optimal water and fertiliser management. This involves simulating a large number of management scenarios using WNMM, assessing Best Management Practices (BMPs) from selected criteria and using ESRI MapObjects GIS component to manage the relevant spatial databases. The ADST is a GIS-based map display tool with a number of search/query functions for seeking site-specific BMPs.

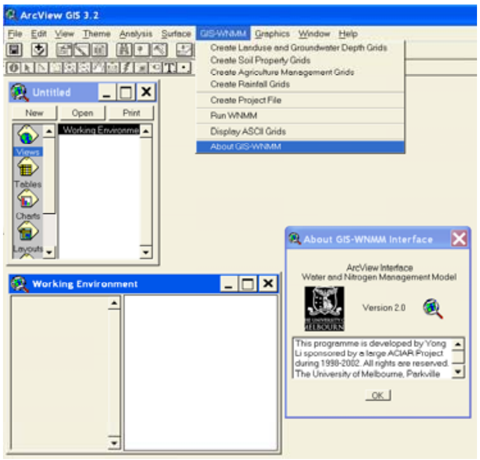

Figure 3. ArcView interface for WNMM.

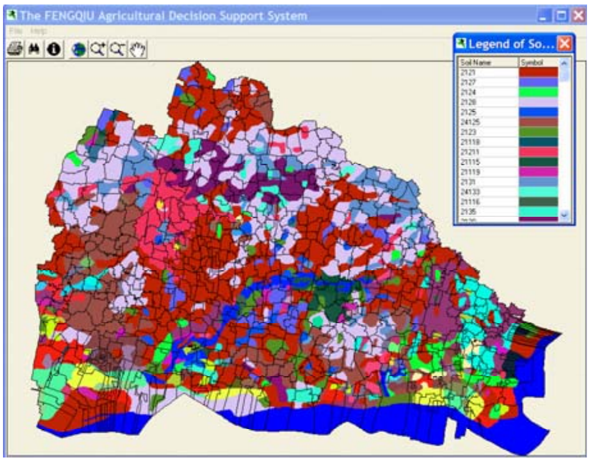

Figure 4. An example of ADST.

Sensitivity analysis
The sensitivity analysis of all input parameters and variables over their potential range and complexity is not practical. Therefore, in this paper, a more pragmatic and constrained approach to model sensitivity analysis is taken, in which an a priori set of key input variables to which the model is most sensitive were identified from an understanding of model structure and the underlying physics and physiology of the natural system. This section presents such an analysis and discussion of the behaviour of WNMM to perturbation of a selected set of input parameters and variables. Using a one-year dataset of 1999-2000 from Fengqiu County in the NCP, the sensitivity analysis was carried out by running WNMM with the value of a single selected parameter or variable altered by plus and minus 10%, holding all other selected parameters or variables constant.

In terms of parameter and variable selection, the lumped input variables include some of meteorological variables and crop biological parameters, while the input spatial variables were considered as soil properties (initial conditions and hydraulic parameters), land use, and agricultural management (N fertiliser application and irrigation). The affected output variables in WNMM were total actual soil evaporation (TASE), total actual crop transpiration (TACT), total actual evapotranspiration (TAE), net deep drainage beneath 1.7m (NDD), final soil water storage of 1.7m soil profile (FSWS), total dry matter (TDM), grain yield (GY), the predicted maximum value of LAI (LAI_{pm}), total N leaching beneath 1.7m (TNL), total crop N uptake (TCNU), total N volatilisation (TNV), total N denitrification (TND), and total N_2O emission (TNE).

The results indicated that air temperature (average, minimum and maximum) and relative humidity have the most effect on all the outputs. NDD is the most sensitive output variable to all five climatic variables, particularly to relative humidity, solar radiation and wind speed, and consequently, TNL is the second most sensitive output. Among crop biological parameters, the energy use efficiency strongly affects TDM, GY, and TCNU, and to some degree, it also influences TND and TNE. The crop maximum stomatal conductance impacted significantly only on NDD, with TASE, TACT, TNL and TNV being affected slightly. As expected, the crop N concentrations strongly affected TCNU, and to some extent, TND and TNE.

For the spatial parameters and variables, the altered saturated soil water content and *n* for van Genuchten retention equation have strong effects on all the output variables, particularly TND and TNE, while the changes of α for van Genuchten retention equation and saturated hydraulic conductivity have slight effects on all the outputs variables. Among the output variables, TND and TNE are very sensitive to the changes of saturated soil water content and *n*. Under the no crop-growing scenario, TASE increases by 190% and TNL increases by 296% relative to under the crop growing scenario. TAE decreases by 66% due to the absence of crop transpiration, which normally accounts for most of the evapotranspiration in the soil-crop system in the NCP. Both changes of fertiliser N amount and application method do not influence the hydrological output variables or crop growth variables, not even TCNU, and have very slight effects on TNL. However, as expected of more N applied in the soil, the change of fertiliser N amount significantly affects TNV, TND, and TNE by over 5%. Changing the application method strongly affects TNV, but the effects on TND and TNE are limited. Within WNMM, irrigation operation is characterised by two variables (irrigation amount and timing). Irrigation amount was selected as the only testing input variable in this paper. As the result, the perturbation of irrigation amount strongly affects NDD, TNL, TND, and TNE, and has no or very little influence on TASE, TACT, TAE, TDM, GY, TCNU, and TNV.

Model applications

WNMM has been used for winter wheat – summer maize cropping simulations of two-year (1998-1999 and 1999-2000) studies at site scale, and one-year studies at county scale, respectively, in the NCP. At site scale, the first year (1998-1999) simulation was used to calibrate WNMM against the extensive measurements of soil water and N dynamics as well as crop growth carried out in two one-hectare experimental plots (OHEP) of Fengqiu and Luancheng Agricultural Experimental Stations in the NCP, while the second year (1999-2000) simulation verified the performance of WNMM. Since there is only one village-based field survey conducted in the fall of 1999 in whole counties of Fengqiu and Luancheng, covering information of agricultural management practices and crop yields for year 1998-1999, respectively, the WNMM simulations ran for only one year at county scale.

In this paper, we present some results simulated by WNMM against the field observed data at the site scale in Fengqiu County and at the county scale in Luancheng County. At the county scale, crop grain yield is the only observation available to compare with the WNMM prediction because of lack of other measured information.

Site scale

The OHEP site in Fengqiu County is located 100 m southwest of Fengqiu Agricultural Experimental Station, 10 km North of Yellow River, Henan Province, China. Basically on this site, the top 40 cm soil is sandy loam to silt clay loam with bulk density of 1.45 g cm^{-3}, pH of 8.5, soil organic matter of 9.1 g kg^{-1} soil, and CEC of 7.6 cmol kg^{-1} soil. Usually, farmers sow winter wheat and summer maize in October and June, respectively, and harvest them in June and September, respectively. In winter wheat growing season, N fertilisers are applied twice (before sowing and in the early spring) at rates of 150 and 100 kg N ha^{-1}, respectively, and irrigations are operated three times (October, March and May) with ~100mm water each, respectively. For summer maize, N fertilisers are applied twice (in the middle of July and the early

August) at rates of 150 and 80 kg N ha^{-1}, respectively, and irrigations are operated twice (timing coinciding with N fertiliser applications) with ~100mm water each, respectively. The WNMM simulations were carried out from 1 October 1998 to 30 September 2000 (see Figure 5), including two-round winter wheat and summer maize growing seasons, and were quite close compared with the field *in-situ* measurements of soil water, NH_4-N and NO_3-N contents at depths, evapotranspiration, leaf area index, ammonia volatilisation, soil N_2O emissions and crop grain yields.

WNMM was also applied for a pasture system in Ellinbank, Victoria. Figure 6 shows the good prediction of the aboveground green dry matter production, comparing with the field measurement.

County scale

At the county scale, WNMM was applied in Luancheng County, Hebei Province, China from 1 October 1998 to 30 September 1999. The soil spatial information was derived from the soil map and soil survey report produced in the second national soil survey of China in the early 1980s. The hydraulic properties of soil types, such as saturated water content, shape parameters of van Genuchten retention equation and saturated water conductivity, were estimated by the locally developed pedo-transfer functions. The spatial crop distribution was based on the latest land use map. A comprehensive field survey was carried out in the fall of 1999, covering all the information of agricultural practices of the 1998-1999 rotation year in 162 individual villages. In this case, weather variables including precipitation were all treated as uniform in the county. The measurements of the initial layered soil water and N species in the OHEP site of Luancheng County were scaled to the whole county for simulation. The regional bottom boundary conditions were always a flux condition, free drainage, as groundwater table in the county is far deep from soil surface (> 35 m). The surveyed crop yields in 162 villages were used to assess the performance of the WNMM simulation at the county scale (Figure 7). The result indicates that the spatial variations of predicted crop grain yields by WNMM were parallel to the region where crop grain yields were surveyed. As the predicted crop grain yields were village-averaged and compared with the surveyed crop grain yields, a significant determining coefficient R^2 of a linear regression was achieved as 0.43.

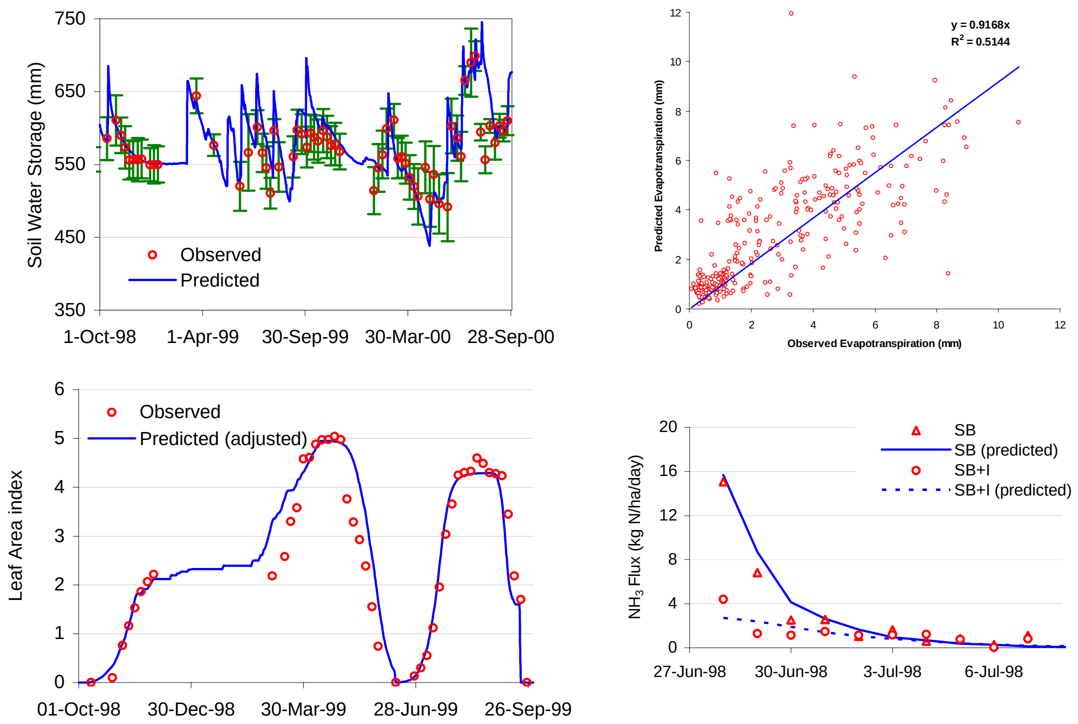

Figure 5. The WNMM predictions versus the observed data of 170cm soil water storage, actual evapotranspiration, crop leaf index, and ammonia volatilisation in the OHEP of Fengqiu County, Henan Province, China. Bars represent ±1 standard deviations. In terms of N fertiliser application, SB denotes surface broadcasting method, and SB+I for surface broadcasting immediately followed by irrigation.

Conclusions

A GIS-based water and nitrogen management model has been developed to simulate dynamic soil water movement and soil-crop C&N cycling under given agricultural management. It simulates key processes of water and C&N dynamics in the surface and subsurface of soils, including evapotranspiration, canopy interception, soil water movement, soil temperature, solute transport, crop growth, C&N cycling in agroecosystems, and agricultural management practices (crop rotation, irrigation, fertiliser N application, harvest, and tillage). It runs at a daily time step at the site, field or county scale, and is fed with lumped parameters (climatic data and crop biological data) in text format, and spatial parameters (soil and agricultural management) in ARC GRID ASCII format.

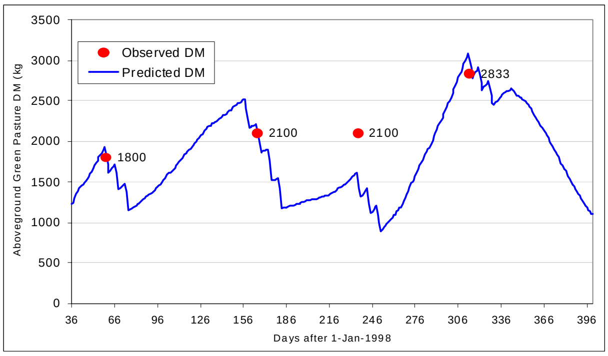

Figure 6. The WNMM predictions versus the observed data of aboveground green dry matter of a pasture system in Ellinbank, Victoria for 1998-1999.

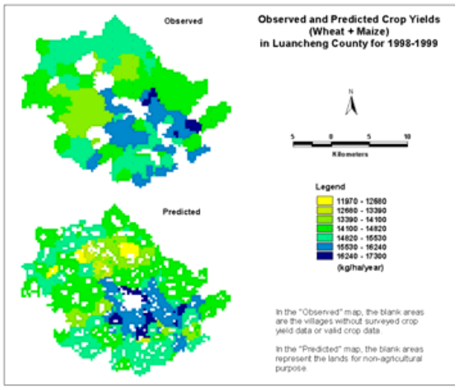

Figure 7. The WNMM predictions versus the observed grain yields in Luancheng County, Hebei Province, China for the 1998-1999 rotation year.

The sensitivity analysis of the model for lumped and spatial parameters and variables was also carried out in this study, and indicated that WNMM is sensitive to the parameters and variables of climate, soil hydraulic properties, and land use management in crop production and soil N transformations. It implies that it has the capability for users to identify optimal management practices of water and fertiliser in intensive cropping systems for enhancing farm profitability and environmental integrity.

WNMM was successfully applied in Fengqiu County, Henan Province and Luancheng County, Hebei Province, China at site and regional scales, respectively. Through various aspects of WNMM components, WNMM was intensively calibrated and verified against comprehensive field observations of soil water, evapotranspiration, crop growth and yield, ammonia volatilisation, denitrification and N_2O emissions, and NO_3-N concentrations. At site scale, WNMM demonstrated excellent performance in simulating soil water content, crop growth and yield, ammonia volatilisation and NO_3-N concentration. At county scale, the WNMM application was also successful. In Luancheng County 43% observed crop yield variations were captured by the WNMM simulation. This result was fairly acceptable because other controlling factors like soil salinity and other element deficiencies may play roles in constraining crop yield at county scale.

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