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Final report

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1 Acknowledgments

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2 Executive summary

Wheat and maize are important crops in China's western provinces which are a high priority for Australian assistance. Crop production is limited by the availability of water and nitrogen (N), yet where irrigation and N fertiliser are applied they are used wastefully. The low efficiency of water and N use in irrigated cropping results in lowered incomes for farmers and impaired water quality. Inefficient use of N fertiliser and excessive irrigation directly leads to emission of the greenhouse gas (GHG) nitrous oxide (N_2O). Volatilisation of ammonia (NH_3) is often the major pathway of N loss and contributes indirectly, after NH_3 returns to the soil, to N_2O emissions. Excess soil nitrate (NO_3^-) is leached to groundwater, resulting in the alarmingly high concentrations of NO_3^- in groundwater accessed by community bores, and contributes to eutrophication in most rivers and lakes in China.

The overall objective of the project is to improve the management of water and N fertiliser to increase farm incomes, improve environmental quality and reduce N_2O emissions from agriculture. The systems studied are irrigated maize and wheat cropping and intensive vegetable farms in the western Yellow River basin of northern China, and intensive irrigated pasture, irrigated maize and rain-fed wheat systems in Australia. The project has two specific objectives: (I) to introduce best management practices for water and N management that take into account social and economic aspects, N_2O emission and climate variability and (II) to develop policy options that lead to more efficient use of water and N fertilisers, and to the reduction of N_2O emissions.

The project is a mix of detailed experimental measurement, the collection of relevant resource data, development of a socio-economic sub-model, calibration and modification (where necessary) of the existing WNMM model, and the development of a GIS-based Agricultural Decision Support Tool (ADST) for use at appropriate scales. The project comprised a number of specific activities to meet each of the two objectives that were carried out at three sites in Shanxi, dissemination sites with an AusAid project in the Inner Mongolia Autonomous Region (IMAR), and three sites in Australia.

The main focus for the Australian component is on modelling and the ADST development with data from complementary research projects funded by the CRC Greenhouse Accounting, AGO and GRDC. The team of the University of Melbourne is one of the core partners of these projects and aims to develop new open path (laser and FTIR)-micrometeorological technology for measuring the emission of greenhouse gases (GHG).

It is a complex project with strong focus on in-depth research in both cutting edge measurement techniques and pioneering modelling to integrate bio-physical science, economics and policy. The project has successfully carried out and achieved the proposed objectives and outputs, in many cases exceeding what was originally expected. The significant outcomes of the project are summarised as follows:

The project contributed to the establishment of the open path (laser and FTIR) micro-meteorological technique for quantifying GHG emissions at large scale from intensive agricultural systems.

The project established the first automatic chamber system for continuous measurements of greenhouse gases (GHG - N_2O, CO_2, CH_4) and NOx, and provides for the first time long-term continuous baseline data for calculating the emission factors, the validation of process models, as well as assisting with the identification of better fertiliser and irrigation management practices. The project also developed a digital camera technique to estimate the soil N supply capacity for wheat (Li et al, 2010).

The project further developed a world acclaimed spatially referenced and process based decision support system based on the Water and Nitrogen Management Model (WNMM), for improved irrigation and fertilizer management for agricultural productivity and environmental quality. The WNMM model and decision support system have been adopted by the scientists in the US (Stanford University), Korea, and Italy as well as in Australia and China.

The bio-physical model has been successfully integrated with a socio-economic model, based on the Driving force–Pressure–State–Impact–Response approach. This integrated model framework was used to assess the effects of policies options for improving decision making for water and nitrogen management. Integration of economic modelling with WNMM has demonstrated that there is little impact on Australian farmers' N fertiliser decision making by including N_2O emissions in the carbon emissions trading scheme (Farquharson et al, 2010).

Using a combination of the continuous auto-chamber method and a process based model, we were able to revise Australian N_2O emission factors for rain-fed wheat to 0.1% and for pasture to 0.4%, rather than the IPCC default value of 1% of applied N. Simulation of the total N_2O emissions in the WA wheat belt using WNMM has shown that IPCC overestimates N_2O emission by a factor of 3.

At irrigated agricultural areas (oases) in the Gobi desert in IMAR, using a combination of field measurement, modelling and ^{15}N tracer techniques, we found that 25 to 40% of irrigation water and 186 to 255 kg N ha^{-1} of nitrate (50 to 90% of applied N fertiliser) was leached below the root zone. We developed best management practices (BMPs) that resulted in fertiliser use efficiency increasing by threefold. BMPs with improved irrigation water use efficiency have been recommended to the local government and farmers, with estimated savings of 4.2×10^6 m^3 of water and 118.2 tonnes of N fertilizer per year compared with the traditional practice in the Chahantan oasis.

Significant amounts of N fertiliser, 30 to 40 kg N/ha (at Yongji), 110 to 150 kg N/ha (Yuci) and 140 to 280 Kg N/ha (Hongtong), and irrigation water, 10 to 25%, can be saved without reducing the crop yield in Shanxi. Considerable numbers of farmers have already adopted the optimised management practices used in the experimental field. The net financial saving is $25 to $200/ha. The financial saving associated with the irrigation water saving is modest under current water charging conditions. The potential economic benefit of the saved water was not calculated.

The project demonstrated that 'efficiency enhanced fertilizers' (controlled release, urease and nitrification inhibitors) effectively reduced N losses and greenhouse gas (N_2O) emissions. Using the nitrification inhibitor DMPP, N_2O emissions can be reduced by up to 65% (Chen et al, 2010) and NH_3 losses by 80% (Turner et al, 2010). Economic impacts of Sulfur Coated Urea (SCU) were very significant, as it allowed the use of 42% less N but produced 8% higher maize yield, and 72% less N_2O emissions.

Significant scientific impacts were achieved, with more than 40 SCI papers published, mostly in the top-tier international journals of the field. . More than 30 presentations were given in national and international workshops and conferences.

3 Background

The production of sufficient food for the huge population (in excess of 1.3 billion) has always been a priority of the Chinese government. Because of the limited arable land per capita, the best option to meet this demand is by increasing crop yields, usually by increasing fertiliser inputs, particularly N, and irrigation. However, many farmers in intensively farmed areas of China use too much N fertiliser. The China Council for International Cooperation on Environment and Development (CCICED) estimated that the over-use of N fertilisers on grain and vegetable crops leads to a loss of about 1.74 million tonnes of N each year (Norse and Zhu, 2004).

Excessive use of N increases NO_3^- accessions to groundwater and emissions of reactive N (NH_3 and NOx) and greenhouse gas (N_2O) to the atmosphere. In the preceding ACIAR project (LWR1/1996/164) in the North China Plain (NCP) it was shown that after accounting for all N losses from the soil that as much as 120 kg/ha more N was applied each year than was required for optimum crop yield. The value of this excess N was estimated to be worth about $1.3 billion. Field measurements and modelling showed that up to 30% of the irrigation water was lost through deep drainage because of inappropriate irrigation practices (Chen *et al*., 2002). Overall, the results indicated that 25% of N fertiliser and 30% of irrigation water could be saved without reducing the yields of either wheat or maize, and the leaching of NO_3^- and emission of N_2O would be substantially decreased. Knowledge-based optimum N fertilization rates indicate applications with 30–60% N savings compared with current agricultural N practices of 550–600 kg of N per hectare fertilizer annually that do not significantly increase crop yields but do lead to about 2 times larger N losses to the environment (Ju et al, 2009).

In Shanxi Province agriculture supports about 20 million people, or 60% of the population. This province is said to be the driest in China in that it has about 0.5% of all China's water resources to support about 2.5% of the total population. On average each person employed in agriculture farms only 100 m^2. Of the 4.4 million ha of arable land, approximately 1.3 million ha are irrigated. The main crops are wheat and maize, with total grain production from irrigated cropping of about 10 million tonnes per year. Irrigated crops receive about 240 kg N/ha as chemical fertiliser, principally as urea. This is equivalent to just over 650,000 tonnes of urea, at a value of around $200 million (based on 1800 RMB/tonne urea and 1A$ = 6 RMB). Nitrogen use efficiency has been estimated to be about 30%, so there is potential for substantial savings. There is evidence of over-irrigation and substantial NO_3^- leaching. However, there are no measurements or model estimates of N losses and N_2O emissions from irrigated cropping systems.

The most western part of IMAR includes degraded sandy soils of the Gobi desert. AusAID established the Alxa League Environmental Rehabilitation and Management Project ($18 million) to contribute to environmental improvement through sustainable resource use, whilst addressing causes of poverty. The development of irrigated agricultural areas (oases) to resettle households from impoverished pastoral areas has been an important element in an overall strategy to halt land degradation. The project had a component on community development that introduced improved cropping practices, particularly for maize and spring wheat, which comprise 80% of the cropped area. All cropping, about 20,000 ha, is based on groundwater extraction in 10 major oases which support about 33,400 people. The irrigation amounts range from 1000 mm to 1700 mm per crop per year, typically as flood irrigation. Over-extraction of water has lowered the watertable and increased the pumping cost of electricity to 120-230 RMB/mu ($360-690/ha). The lowering of the hydrostatic head will also shorten the useful life of many bores and increase both the cost of new bores and the cost of deepening existing ones. Local AusAID irrigation experts estimated over-irrigation to be about 30%. Typical N fertiliser application rates are about 250 kg N/ha. Due to the light texture of the soils, the excessive irrigation and fertiliser applications result in substantial water loss through deep drainage and alarmingly high concentrations of NO_3^- (200 mg/L) and NO_2^- (50 mg/L) in groundwater accessed by community bores.

The problem of boosting food production while minimising the environmental impact of high-input agriculture concerns government officials and scientists in China. This project "*Improving the management of water and nitrogen fertiliser for agricultural profitability, water quality and reduced nitrous oxide emissions in China and Australia",* is consistent with research priorities in both countries and also consistent with the priorities under the Australia-China Joint Declaration on Bilateral Cooperation on Climate Change. The project was also envisaged to have significant poverty reduction potential because the costs of fertiliser and irrigation (pumping cost) account for more than 50% of total farming inputs, and agriculture is an important source of income for farmers in the western part of China.

The efficient use of water and nutrients in agriculture is also of crucial importance in Australia, both for the profitability of farmers and the protection of land and water resources. In Australia, the rate of use of N fertiliser has been growing exponentially, with increases particularly on irrigated crops, horticulture and pastures, which have led to accelerated rates of soil acidification, increased N_2O emissions, NO_3^- contamination of water, and eutrophication of water bodies. These problems have been recognised by several R&D organisations as areas of high priority, such as the CRC for Greenhouse Accounting, the Australian Greenhouse Office (AGO) and the Grains Research and Development Corporation (GRDC), Dairy Australia. These organisations are supporting studies that focus on water and nutrient dynamics in irrigated pastures in the Goulburn Valley, wheat cropping in northeast Victoria (Rutherglen) and Western Australia (Cunderdin), and on irrigated maize (Griffith) and cotton (Narrabri). The team at the University of Melbourne plays a significant role in all these projects. In Australia, extension of the capability and functions of the WNMM model (developed in the previous ACIAR project for irrigated wheat and maize in the NCP), and its testing against data from intensively monitored experimental sites, could facilitate the development of BMPs applicable to a range of crops and irrigated pasture. Application of the BMPs will enable farmers to make more efficient use of water and N fertiliser, and contribute to the cropping and dairy industries' ability to meet environmental targets for NO_3^- releases to receiving waters and N_2O emissions.

From the previous LWR1/1996/164 project it was demonstrated that 25% of N fertiliser and 30% of irrigation water could be saved without reducing the yields of wheat and maize on the NCP. The main reasons for the excessive use of N fertiliser and irrigation water were as follows.

(a) Farmers lack conviction that high yields can be obtained with less N fertiliser. These farmers lack site-specific quantitative advice on application rates and appropriate methods of application.

(b) The cheap price of fertiliser and irrigation water, resulting in little incentive for saving fertiliser or water.

(c) Little awareness of the environmental consequences of excessive fertiliser and water use by local governments and farmers.

The spatially-referenced and process-based model WNMM, developed in ACIAR project LWR1/1996/164 for the NCP, provides a biophysical basis for evaluating a range of current or recommended management practices for irrigated wheat and maize in the focus areas of the Yellow River Basin (Chen et al., 2004). The model takes into account agricultural management practices such as crop rotation, irrigation, fertiliser application, harvest and tillage. It has been closely coupled with standard geographic information systems (GIS). The current project was to add a module for simulating the economic outcomes, and possible social consequences, of changed management practices for water and N. The output will be a GIS-based Agricultural Decision Support Tool (ADST) for water and N management for irrigated agriculture that offers users, at a range of scales and for various weather scenarios, choices for balancing production outcomes against environmental outcomes. The ADST was to be delivered in a user-friendly and graphically-based computer model using the GIS MapObject technique, primarily for the desktop PC, but also to develop a version for handheld pocket computer.

In this project there is also significant capacity building and the introduction of new technologies. The project was to assist the establishment of large auto-chambers with real-time, continuous measurement of N_2O, CO_2 and CH_4 concentrations in China and introduce new state-of-the-art greenhouse gas (GHG) detection techniques such as open path laser and Fourier Transform Infrared spectroscopy (FTIR), combined with micrometeorological techniques in Australia. The open path system/micrometeorological technique measures GHG fluxes over hundreds of metres across fields, thus integrating spatial variation of emissions.

The research teams in Australia and China have extensive experience and expertise in studying soil N dynamics and GHG emissions in agriculture. The proposal was aimed to deliver tangible outcomes in terms of the cost-effective use of water and N fertiliser on-farm through innovative modelling, especially by the combination of biophysical and economic factors. The outcomes will have benefits for farm profitability, but in addition advisers and policy makers will have more reliable estimates of the impact of intensive farming practices on water quality and N_2O emissions from agriculture. However, a large part of the project involves applied and adaptive research that is needed to ensure the accuracy of predicted outcomes under a range of biophysical, management and economic regimes.

The project is consistent with the research priorities and expertise of all the collaborating teams. The large number of relevant projects contributes towards the success of the project.

4 Objectives

The overall objective of the project is to improve the management of water and N fertiliser to increase farm incomes, improve environmental quality and reduce N_2O emissions from agriculture. The systems to be studied are irrigated maize and wheat cropping systems and intensive vegetable farms in the western Yellow River basin of northern China, and intensive irrigated pasture and maize, and rain-fed wheat systems in Australia. The project has two specific objectives.

Objective 1: To introduce best management practices for water and N management that take into account social and economic aspects, N_2O emission and climate variability.

The activities to achieve this are:

Activity 1: Adapt and calibrate the WNMM model to incorporate social and economic aspects affecting the choice of water and N management practices by farmers for irrigated crops in the focus areas in Shanxi, and apply the model to dissemination areas in IMAR and Hebei.

Activity 2: Develop sustainable management practices to minimise N_2O emissions by more reliable measurement techniques and improved modelling.

Activity 3: Evaluate BMPs on-farm in the focus areas.

Activity 4: Develop practical tools to deliver tested BMPs.

Activity 5: Further develop WNMM to account for the impacts of climate variability and its performance in Australian conditions.

Objective 2: To develop policy options that lead to more efficient use of water and N fertilisers, and the reduction of N_2O emissions.

The activities to achieve this are:

Activity 6: Survey farmers to determine the sensitivity of farmers to changes of the price of water and N fertiliser.

Activity 7: Use the spatially-referenced decision support tool to develop the policy options and test these with farmers and regulators.

An additional activity (*Activity 8*) will involve activities synthesising all the components of the project, including a final workshop.

5 Methodology

The project is a mix of detailed experimental measurement, collection of relevant resource data, development of a socio-economic sub-model, calibration and modification (where necessary) of the existing WNMM model, and the development of a GIS-based ADST for use at appropriate scales. The project comprised a number of specific activities for each of two objectives, as identified in Table 1, carried out at three sites in Shanxi, dissemination sites with AusAid projects in IMAR, and three sites in Australia. There were leaders in the focus areas in China and a leader in Australia, and a scientific leader for each theme, under the overall coordination of the Project Manager/leader.

For Alxa League we used data on soil, land use and climate at one of the groundwater oases from the AusAID project to calculate ‘safe-bet’ BMPs for early implementation to act as both demonstration and calibration plots.

The main focus for the Australian component was on modelling and the ADST development with data from the complementary research projects funded by CRC Greenhouse Accounting, AGO and GRDC, in which the team of the University of Melbourne is one of the core partners.

Three sites in Shanxi were selected on the basis of irrigated cropping, contrasting soil and climate conditions, and local government support. Yuci county, situated in the middle part of the province, 40 km from Taiyuan; central south Hongtong county (Linfen basin), and the far south county of Yongji, which is close to the border of Henan province and the Yellow river, and with similar soil and climate to the North China Plain. The studies with irrigated wheat and maize in Yuci county were associated with the “948” project ‘Optimum use of water and fertilizer nitrogen for intensive cropping systems’ commissioned by the Institute of Hydraulic Resources of Shanxi with funding from the Chinese Ministry of Water Resources. The site in IMAR is situated in south-eastern Alxa League. The locations of these sites are shown in Fig. 1.

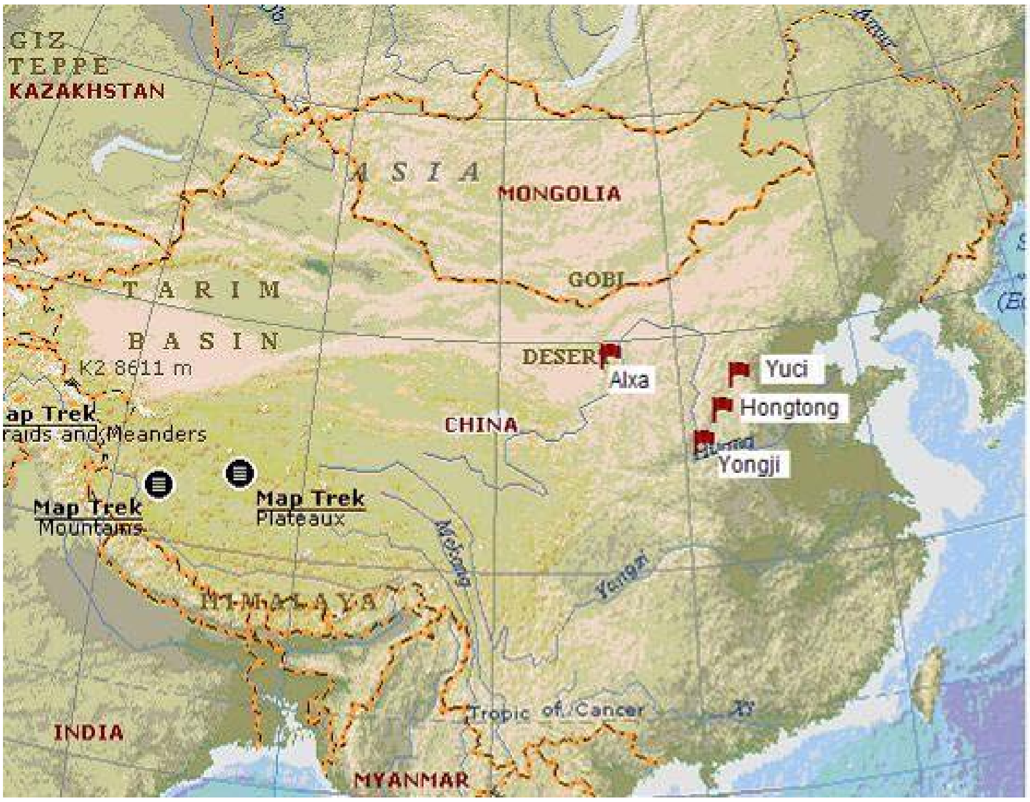


Fig. 1. The locations of the experimental sites (marked with a flag) in China.

Three sites in Shanxi: Yuci County in the north: rainfall 418-483 mm p.a., mean annual temperature of 9.8^0 C; Hongtong County: rainfall 528 mm p.a. and mean annual temperature of 12^0 C; Youngji county in the Yuncheng basin:, rainfall 505 mm p.a. and mean annual temperature of 13.5°C. The soils ranged from sandy loam, loam to clay loam, with soil organic matter between 10 to 14 g/kg, total N of ~0.6 to 1.4 g/kg. All soil are alkaline with pH >8.3.

A number of specific actions for each activity were designed to achieve each of the two main objectives (Table 1).

Table 1. Main activities and actions

Objective 1. To introduce best management practices for water and N management that take into account social and economic aspects, N_2O emission and climate variability	
Activities	**Actions**
1. Adapt and calibrate the WNMM model to incorporate social and economic aspects affecting the choice of water and N management practices by farmers for irrigated crops in the focus areas in Shanxi, and apply the model to dissemination areas in IMAR and Hebei	1.1 Appointment of personnel, site selection, experimental design, and equipment purchase 1.2 Collect and digitise soil, climate and land use information of the focus areas (three counties Shanxi) 1.3 Analysis of the N and water cycles and practices of irrigation and fertilizer application, and to collect economic field data on agricultural practices and financial viability of rural households in the focus areas. 1.4 Conduct field experiments to obtain the essential data of soil water and nutrients dynamics and crop production for adaptation and validation of the model. 1.5 Build a socio-economic component of the model. 1.6 Test, modify and calibrate the WNMM for the local conditions with existing data available in the area and new experimental data. 1.7 Test various management, policy and climate scenarios with the newly calibrated WNMM to simulate water and N dynamics and crop performance, and to develop a farmer-oriented agricultural decision support tool (GIS-based ADST) for the focus areas. 1.8 Develop a range of potential management practices by varying the amount, time and methods of irrigation and fertiliser application in consultation with local collaborators. 1.9 Train Chinese scientists in water and N modelling.
2. Develop sustainable management practices to minimise N_2O emissions by more reliable measurement techniques and improved modelling	2.1 Conduct long term (12 to 24 months) and continuous measurement of N_2O emission using automated chambers. 2.2 Develop the best methods and measuring techniques for delivering accurate and reliable data for on-farm N_2O emissions by comparing conventional chamber techniques with open-path systems (laser and FTIR)/micrometeorological techniques. 2.3 Conduct laboratory and field studies examining factors that influence the partitioning of the denitrification products N_2O and N_2, and separating the contribution of N_2O emission between denitrification and nitrification. The experiments will also quantify the impact of agronomic practices on N_2O emission 2.4 Modify WNMM to improve the modelling of N_2O emissions
3. Evaluate BMPs on-farm in the focus areas.	3.1 Test and refine calculated best management practices at field experimental and demonstration sites. 3.2 Produce tested best management practices for irrigation and fertiliser use on the major soil types in the region, which increase the profitability of grain production, minimise environmental impacts, and reduce N_2O emissions, in a GIS-database and distributed as CD ROM and as printed material.
4. Develop practical tools to deliver tested BMPs.	4.1 Develop printed materials for BMPs which can be used by individual farmers, local agricultural extension officers, local agricultural decision-makers, and researchers. 4.2 Develop GIS-based ADST for desktop PC using MapObjects which can be used by local agricultural extension officers, local agricultural decision-makers, and researchers.

	4.3 Handheld PC-based ADST which is mainly for local agricultural extension officers and agricultural decision-makers.
5. Further develop WNMM to account for the impacts of climate variability and in Australian conditions.	5.1 Incorporate weather variability into WNMM and ADST for different climate scenarios. 5.2 Simulate phosphorus (P) cycling in specified agro-ecosystems 5.3 Simulate pasture growth and grazing practice for Australian conditions with WNMM 5.4 Upgrade GIS-WNMM interface
Objective 2: To develop policy options that lead to more efficient use of water and N fertilisers, and to a reduction of N_2O emissions	
6. Survey farmers to determine the sensitivity of farmers to changes in the price of water and N fertiliser	6.1 Using WNMM, identify farmers and regions with a high potential to pollute (NO_3^- leaching and N_2O emission) and where there is potential to improve the efficiency of irrigation and fertiliser. 6.2 Test farmers' willingness to modify their behaviour in response to a pollution tax, increased irrigation water price or removal of subsidies, or an increased grain price. 6.3 Select feasible policy options.
7. Use the spatially-referenced decision support tool to develop the policy options and test these with farmers and regulators.	7.1 Run simulations of selected policy options with WNMM and ADST to develop new BMPs. 7.2 Test the policy options and the new BMPs developed with farmers and policy makers for the three counties in Shanxi and two AusAid project sites, at Alxa in IMAR and Wanquan in Hebei. 7.3 Prepare briefing materials for government.
8. Synthesising Activities	8.1 Conduct a workshop on improving the management of water and fertiliser for agricultural profitability, water quality and reduced nitrous oxide emissions in China and Australia 8.2 Analysis of impacts in terms of adoption and likely effect on farm incomes and environmental quality 8.3 Preparation of final report

(I). Methodology for building the economic modelling component.

In the economic modelling component, N outflows need to be allocated to the places where they originate in the study area. They can then be translated into economic outputs at a microeconomic (farm) level, using a gross margins analysis, developed from field surveys. This assessment needs to incorporate the methods employed by farmers to irrigate and fertilise their crops. The model was fully integrated with the WNMM model to minimise the effort involved in analysing multiple allocation scenarios. An assessment of the water and N productivity of the study areas can then be carried out, and a conceptual model developed in consultation with stakeholders. Fengqiu County in Henan province, one of the previous project sites, was the first case study site for the development of the socio-economic component of WNMM, as some advantage could be taken of the availability of existing biophysical data.. With continuing support from the CAS the adoption of improved management practices around and beyond Fengqiu County can be enhanced.

(II). Methodologies for developing sustainable management practices to minimise N_2O emissions, with more reliable measurement techniques and improved modelling in Activity 2.

- Continuous (12 to 24 months) measurements of N_2O emission using automated chambers with real time measurement of N_2O and CO_2 and CH_4 during the whole wheat-maize growing season at Yuci and Yongjie sites were undertaken. Minimum of six chambers at each site.

- N_2O emissions are notoriously variable in time and space so that the representativeness of the chamber measurements needed to be established. This will be done by comparison with field-scale micrometeorological techniques over periods of 10 to 14 days after irrigation and N fertiliser application. In addition to the auto-chambers, a large number (~100) of mini-chambers (15cm diameter) were used to apply geostatistics and a backward Lagrangian stochastic (BLS) dispersion model to study the spatial variability and footprints of N_2O emission (Turner et al., 2004). Annual or biennial field expeditions were conducted to evaluate the performance of the chambers over a range of cropping phases and soil moisture conditions.
- Open path laser and Fourier Transform Infrared (FTIR) spectroscopy/micrometeorological techniques were to beused to measure $N_2O/CH_4/CO_2$ emissions and NH_3 volatilisation.
- Examining factors that influence the partitioning of the denitrification products N_2O and N_2, and separating the contribution of N_2O emission between denitrification and nitrification, and the effects of nitrification inhibitors and alternative nitrogen fertilizers on N_2O emissions.
- Improving the N_2O emission sub-model in WNMM using measured parameters and improved algorithms by reviewing and comparing N_2O components of other models, such as DNDC, DAYCENT and Ecosys.

(III). Methodologies for developing practical tools to deliver BMPs in Activities 3 and 4.

The delivery of WNMM-derived BMPs to different audiences in China and Australia requires effective distribution tools. We propose three levels for delivering the BMPs - text-format booklet, desktop PC stand-alone software, and handheld-based ADST.

- Booklets are suitable for all audiences, including individual farmers, local agricultural extension officers, local agricultural decision-makers and researchers.

The region-specific BMPs from Activity 3 will be printed in a small booklet, with a simple classification and query system which allows users to easily look up items in the booklet. For a selected region, the BMPs will be printed in map format and superimposed over a soil map, land use map and village boundary map. Alternatively, this information can be compiled in simple dial cards containing the location, crops and BMPs.

- PC stand-alone software is suitable for most of the audiences, including educated individual farmers, local agricultural extension officers, local agricultural decision-makers and researchers.

The main aim of this kind of ADST is to allow users to graphically allocate the BMPs to a specific soil type in the soil map of a specific region on a Desktop PC platform.

Basically, this system is an explorer of proposed agricultural scenarios, specific to the soil characteristics, in terms of N fertiliser use and irrigation for wheat-maize cropping systems. It consists of three source databases: (a) attributes of soil types, (b) proposed agricultural scenarios and evaluation indices of the proposed agricultural scenarios produced by WNMM, and (c) the strategy evaluation program, consisting of two spatial databases in ESRI shape file format: (i) soil type, and (ii) village administration, and a GIS display interface that uses ESRI MapObjects technology (*http://www.esri.com/software/mapobjects/mo-index.html*).

The distinguishing feature of this system compared with other ADSS, e.g. DSSAT (*http://www.icasa.net/dssat/index.html*), is that it does not have WNMM simulations built inside because these are too complicated for agricultural decision-making. The decision-makers need to focus on the outputs of the proposed agricultural scenarios under the WNMM simulations. The complexity of the possible agricultural scenarios involving N fertiliser application and irrigation was fully considered through consultation with farmers and local extension officers.

- Handheld-based ADST (HADST) is optional and primarily only suitable for some of the educated farmers in Australia, most local agricultural extension officers and most local agricultural decision-makers.

There are two levels to carry out this HADST application. Site-specifically, with the expected HADST farmers and extension officers or decision-makers are able to electronically input soil and crop data, to retrieve in-situ meteorological data through the internet, to run and calibrate WNMM, and to make practical decisions in the field, in terms of pursuing the site-specific BMPs. At regional level, the Desktop PC-based ADST with the evaluated BMPs, characterised by soil types, will be syncretised into the Microsoft Mobile Windows®-based handheld-devices for applications. It will extend farmers and decision-makers' capability to adopt or to try the latest innovative agricultural research outcomes. In addition, user knowledge and model calibrations will be accumulated in HADST to improve farmer decision-making in the future.

The HADST developed here will include a handheld computer (e.g. HP iPAQ 4/5000 series Pocket PC) a number of handheld, synchronized softwares. Software includes a HADST manager, which manages the soil and crop database, site meteorological dataset through the internet, model simulation, post-processing of simulation (graphing and reporting), and model upgrading through the internet, and WNMM for advising agricultural practices of irrigation and N fertiliser application as well as crop rotation. In addition, the handheld-syncretised ADST (GIS-based) is also included for directly advising on the evaluated BMPs simulated by WNMM. Meanwhile, a central server is needed to provide a number of services to the HADST users, e.g. WNMM upgrade patches, online documentation and related stakeholder news as well as users' enquiries.

(IV). Methodologies for further developing WNMM to account for the impact of weather variability on agricultural sustainability, and to develop practical tools simulating pasture growth and grazing management in Australia (Activity 5).

- Identifying specific BMPs under different weather scenarios to ensure the sustainable development of agriculture

WNMM is driven by a daily weather dataset for simulating numerous components in agroecosystems, and has the capability to assess the response of hydrological and natural resources to climate change. A long-term measured weather dataset is often insufficient to carry out such impact studies because it only provides one realisation out of a spectrum of possible climate scenarios. When long-term weather datasets are not available, a number of stochastic daily weather generators will be used, such as CLImate GENerator, CLIGEN (Nicks *et al*., 1995).

- Simulate pasture growth and grazing practice for Australian conditions

The components to simulate pasture growth and grazing practice are required to apply WNMM in Australia. In Australia, GRASSGRO (Moore et al., 1997) developed by CSIRO and GRASP (McKeon et al., 1982) developed by Queensland DPI, are often used to simulate pasture systems. Considering the availability of model source code and algorithm transparency in the public domain, one of these two models will be incorporated into WNMM as a pasture-grazing component to simulate grass growth, pasture species competition for light, water and nutrients, animal grazing, and animal waste input (organic C and nutrients in dung and urine). Using data collected at Ellinbank and Kyabram in VIC and Wagga Wagga in NSW, as part of complementary projects, WNMM will be calibrated and adapted for application to these systems.

- Simulate phosphorus (P) cycling in agroecosystems

In many Australian agricultural systems, P has been applied intensively and is often the only fertiliser used. P is not only an important element required for plant growth, but also has the potential to pollute ecosystems if not properly managed. It is essential to be included in the simulation model, particularly for Australia, as P pollution may be a more important aspect of sustainable agriculture than N for some systems. In systems in which P is limiting plant productivity, the availability of P also affects plant uptake of N. The simple approach (adopted in EPIC, SWAT and ANSWER models, originating from the CREAMS/GLEAMS models) and the comprehensive approach (adopted in the ANIMO model (Schoumans and Groenendijk, 2000)) will be considered to extend WNMM to P cycling simulation in agroecosystems. The P cycling component will have parallel pathways to the N cycling component, except for volatilisation and some of the soil transformations, and will focus on P adsorption/desorption in the soil as well as transport in runoff and on eroded soil particles. To validate the P component of the model, we will use data collected from a complementary project at Dookie. The experiment at Dookie is designed to measure P dynamics in a flood irrigated dairy system receiving P from a range of sources (superphosphate, DAP and partially acidulated rock phosphate).

- Upgrade GIS-WNMM interface for ArcGIS® 9 platform

The GIS-WNMM interface for ArcView® GIS 3.x developed in the previous ACIAR project will be translated for the ArcGIS® 9 platform for the consideration of system operational consistency. Consequently, the WNMM CMS (see below) will be part of this GIS-WNMM interface for ArcGIS® 9. The programming computer language for developing this interface will be the same for WNMM as for the BMPs delivery tools, MS Visual Basic.NET®, which is very powerful in handling relational database and internet applications.

(V). Methodologies for developing policy options that lead to more efficient use of water and N fertilisers (Activities 6 and 7).

The sources of NO_3^- pollution will be identified using the WNMM model. This will lay the foundation for targeting farmers who need to reduce NO_3^- leaching. Their responsiveness to economic policy measures will be assessed, along with an evaluation of their farming practices. The focus is on identifying those who have the potential to pollute the most and getting them to modify their behaviour. For example, the crude method of taxing all farmers for fertiliser use can be refined to target the polluters. In addition, it may be possible to investigate a Coasian approach to trading the right to pollute between those that do and those that are affected. Because water is the conduit by which pollution is transmitted, the prices and practices of irrigation also need to be investigated. Reducing the subsidies paid on water may reduce the degree of pollution transfer. Regardless of whether this will occur or not, water management that reduces the amount of water applied will reduce NO_3^- leaching. Finally, as the price of grain is artificially low, freeing its price and letting it rise may change farm practices. This will have an impact on the rate of pollution, and as such will also need to be investigated.

Information dissemination and capacity building

Capacity building involved a range of skills and targeted at different groups.

(a) A number of collaborators in China with a background in modelling and/or GIS will be trained to be ‘super-users’ of WNMM and the ADST, which will involve visits to

China by Australian team members and Chinese collaborators visiting Melbourne. Super-users will guide other Chinese users of WNMM and the ADST. There will be two super-users in Shanxi, one at CAU in Beijing, and two at the University of Melbourne. These people will develop a thorough understanding of WNMM and the ADST logic and algorithms, and work closely with Dr Li Yong in Melbourne on any model modification and further development. In addition, training workshops on the use of WNMM and the ADST will be conducted, in groups, for up to 40 other scientists so that they can use WNMM and the ADST to full capability, and test scenarios of particular relevance to their areas (based on the CD ROM package).

(b) Chinese scientists in Shanxi will be trained to conduct laboratory and field experiments associated with N_2O emissions in chambers. Scientists from CAS experienced in chamber measurements will be trained in open-path laser, FTIR and micrometeorology measurements of NH_3 volatilisation and N_2O emission, and will gain experience in making these measurements in association with scientists from the University of Melbourne.

(c) At least one workshop each year will be held for County and Provincial extension personnel to raise their awareness of, and experience in the use of the ADST, which will be provided on CD-ROM with supporting documentation. Advice and guidance for running the ADST will also be provided through email support and web-based instructions, demonstrations and downloads. The CD with supporting documentation will also be posted to key County and Provincial extension and policy makers.

(d) Dissemination will involve (a) to (c) as well as through demonstration sites on farmers' fields to show the benefits of improved practices. Site visits will be arranged for farmers and extension officers, with the practices explained and feedback sought about further improvement and any barriers to adoption. The visits will be publicized in local popular media (newspapers and television). On-site sign boards will explain the practices and outcomes, and printed hand-outs will be provided. Information on new management practices and environmental impacts will be incorporated into the extension effort by AusAID project in Alxa League and Hebei, and that of the Soil and Fertiliser Institute in Shanxi. Soil and land use maps and technical notes explaining best practices, as well as what the ADST does, will be provided. Results and recommendations will also be communicated to a committee of Shanxi Provincial and County officials, and officials of CAS and the Ministry of Agriculture.

At the Alxa League in IMAR and Wanquan in Hebei sites, government personnel will be informed of research outcomes and impacts on agricultural policy in a specific report through the AusAID projects. The report will also be presented to the focus county and provincial governments in Shanxi, and forwarded to interested parties through the advisory committee, such as leaders of the CCICED who provide advice directly to the State Council in China.

6 Achievements against activities and outputs/milestones

Most of the milestones outlined in the project proposal have been achieved and are summarized in the Table 2, given its complexity and slippage of the delivery and installation of key equipment (second generation FTIR; CAS – automated open-top chambers at Yongji site).

Table 2. Methodology flow chart (PC = partner developing country, A = Australia)

Activity	**Outputs/milestones**	**completion date**	**comments**
1. Objective 1: To introduce best management practices for water and N management that take into account social and economic aspects, N_2O emission and climate variability.			
1.1 Appointment of personnel, site selection, experimental design, equipment purchasing (PC).	Appointment of personnel. Developed protocols of experiments, data collection and modelling.	Yr 1, m1 to m6	
1.2 Collect and digitise spatial information (soil, land use, management practices and climate) (PC)	Spatial database for three counties	Yr 2, m6	
1.3 Analysis of the N and water cycles and practices of irrigation and fertiliser application, and to collect economic field data on agricultural practices and financial viability of rural households in the focus areas (PC)	Description of agronomic practices Analysis of household economics	Yr 2, m6	Confined at Fengqiu site
1.4 Conduct field experiments to obtain the essential data of soil water and nutrients dynamics and crop production for adaptation and validation of the model (PC)	Essential data of soil water and nutrients dynamics and crop production collected for running the model.	Yr 1, 2, 3 at Yuci and Yr3, Y4 at Hongtong and yr3,4, 5 at Yongji	N_2O measurement at Yongji started in yr3 due to late commencement of CAS funding for Auto-chambers
1.5 Build an economic component of the model (PC)	Framework of economic sub-model for WNMM	Yr 2, m12	
1.6 Test, modify and calibrate the WNMM for the local conditions with existing data available in the area and new experimental data (PC)	Validated biophysical components of WNMM for Shanxi and Alxa and conditions, integrate	Yr2, m3 for Yuci, yr3 m12 for Hongtong and yr5 for Yongji, Yr3 m6	

	economic sub-model.	for Alxa	
1.7 Test various management, policy and climate scenarios with the newly calibrated WNMM to simulate water and N dynamics and crop performance, and to develop a farmer-oriented agricultural decision support tool (GIS-based ADST) for the focus areas (PC)	Credible simulations of realistic policy and climate scenarios ADST framework developed and functioning	Yr 3, m6, Yr4, m6 for Hongtong m6, Yr3 m6 for Alxa yr4 m12 for Yongji	
1.8 Develop a range of potential management practices by varying the amount, time and methods of irrigation and fertiliser application in consultation with local collaborators (PC)	Derived BMPs for irrigation and fertiliser management including socio-economic and improved N_2O emission sub-models and simple climate scenarios	Yr 3, m12 for Alxa, Yr3, m12 for Yuci and Yr4 m6 for Hongtong, Yr4, m3 for Yongji	
1.9 Train Chinese scientists in water and N modeling (PC)	'Super-users' identified and trained. Training workshops for model users completed (two training workshops in China and two in Australia, more 40 people attended)	Yr 2, m9 (3 super-users in Chin, Sun Bo, Hu Kelin and Liu Yuntong); Yr4 m6 (4 super-users in Australia, Prakash Dixit Dixit, Manuele Roitero, Jessie Liu, Humaira Sultana)	
2.1 Conduct long term, continuous measurement of N_2O emission using automated chambers (PC and A).	Baseline of N_2O emissions for irrigated wheat and maize, and intensive vegetables.	Yr2, m12 in A and Yr3,4,5 in PC	Only on maize, wheat and cotton in China, wheat, pasture in Australia, not conducted in intensive vegetables.
2.2 Develop the best methods and measuring techniques for delivering accurate and reliable data for on-farm N_2O emissions by comparing conventional chamber techniques with open-path systems (laser and FTIR)/micrometeorological techniques. (PC)	Determination of best methods and measuring techniques for delivering accurate and reliable data for on-farm N_2O emissions	Yr2, m9	
2.3 Conduct laboratory and field studies examining factors that influence the partitioning of the denitrification products N_2O and N_2, and separating the contribution	Understanding how soil and environmental variables influencing the N_2O/N_2 ratio in denitrification, and	Y3 m6	

of N_2O emission between denitrification and nitrification. The experiments will also quantify the impact of agronomic practices on N_2O emission (PC and A)	contributing processes. Parameterized the N_2O sub-model of WNMM.		
2.4 Modify WNMM to improve modeling of N_2O emissions (PC)	Validated N_2O component of model	Yr 3, m12	
3.1 Test and refine calculated best management practices at field experimental and demonstration sites (PC).	Validation of recommended BMPs in selected sites.	Yr 3,4 in Yuci and Hongtong, Alxa, yr4,5 in Yongji	
3.2 Produce tested best management practices for irrigation and fertiliser use on the major soil types in the region, that increase the profitability of grain production, minimise environmental impacts, and reduces N_2O emission, in a GIS-database which can be easily accessed via the Internet or as printed material (PC)	Publication of BMPs	Yr 2, m12 in Alxa, Yr 3 m12 in Yuci Hongtong	Only at the intensively instrumented sites
4.1 Develop printed materials for BMPs which can be used by individual farmers, local agricultural extension officers, local agricultural decision-makers, and researchers (PC)	Publication of BMPs for extension	Yr 4, m 6 to Yr 4 m6	websites of Shanxi Agricultural Academy, Department of Agriculture of Shanxi Province and Hongtong County, AusAid publications for Alxa
4.2 Develop GIS-based ADST for desktop PC using MapObjects which can be used by local agricultural extension officers, local agricultural decision-makers, and researchers (PC)	New GIS based decision support tool (ADST) in text, maps and CD/Handheld PC for distribution	. Yr 4, m6	
4.3 Handheld PC-based ADST which is mainly for local agricultural extension officers and agricultural decision-makers (PC)	New GIS based decision support tool (ADST) for Handheld PC for distribution	. Yr 4, m12	
5.1 Incorporate climate variability into WNMM and ADST for different climate scenarios (A)	Tested WNMM for rainfed, irrigated pastures and maize in Australia and Incorporated climate variability sub-model into WNMM.	Yr 2, m12	

5.2 Simulate P cycling in agroecosystems (A)	Incorporated and tested P component in WNMM	Yr2, m6	
5.3 Simulate pasture growth and grazing practice for Australian conditions with WNMM (A)	Pasture and grazing model available		Yr 3, m3
5.4 Upgrade GIS-WNMM interface (A)	Convert GIS-WNMM interface for ArcView® 3.x to ArcGIS® 9.	Yr 1, m12	
Objective 2: To develop policy options that lead to more efficient use of water and N fertilisers, and of reduction of N_2O emissions**.**			
6.1 Using WNMM, identify farmers and regions with a high potential to pollute (NO_3^- leaching and N_2O emission) and where there is potential to improve the efficiency of irrigation and fertiliser (PC)	Practices and regions identified.	Yr 3, m12	
6.2 Test farmers' willingness to modify their behaviour in response to a pollution tax, increased irrigation water price or removal of subsidies, or an increased grain price (PC)	Understanding the farmers' willingness to modify their behaviour in response to a range policy options and select the feasible policy options.	Yr2, m12	Fengqiu, Alxa and Yuci
6.3 Select feasible policy options (PC)	Policy options identified.	Yr 2, m12	Fengqiu and Alxa
7.1 Run simulations of selected policy options with WNMM and ADST to develop new BMPs (PC)	Developed new BMPs with selected policy options.	Yr3, m12	Fengqiu and Alxa
7.2 Test the policy options and the new BMPs developed with farmers and policy makers (PC)	Identified the acceptable policy option with balanced economical and environmental interest.	Yr3, m9	Fengqiuand Alxa
7.3 Prepare briefing materials for government (PC)	Delivery of briefing materials	Yr4, m9	Via Prof Chen Mingchang, Shanxi Agricultural Academy, CAS, and AusAid
8.1 Conduct a workshop on improving the management of water and fertiliser (PC and A)	Workshop conducted Proceedings published	Yr 4, m12	In conjunction with Aust-China water

			Centre
8.2 Analysis of impacts in terms of adoption, and likely effect on farm incomes and environmental quality (PC and A)	Impact analysis completed	Yr 5, m9	Fengqiu, Alxa, Hongtong sites
8.3 Preparation of final report/Review (PC and A)	Report delivered to ACIAR	Yr 5, m12	

7 Key results and discussion

1. Water and N fluxes, efficiencies of irrigation water and fertiliser N, crop yields derived from the field experiments under various management practices and agricultural systems.

1.1 Irrigated maize at the oasis.

Alxa is in the western part of the Inner Mongolia Autonomous Region (IMAR). Using a combination of field measurements, modelling and the ^{15}N trace technique we found that 160-322 mm (25-40%) of irrigation water and 186-255 kg N ha^{-1} of nitrate was leached below the 1.7m root zone. 50-90% of applied N fertiliser was lost in the microplot experiment in which ^{15}N labelled urea was used as a tracer.

1.2 Irrigated maize and wheat at Yongji site.

The yields of wheat (8.8~8.5 t/ha) and maize (8.8~9.2 t/ha) were similar in the traditional farmers' and optimised practices. However, the N application rates in optimised practices,180 kg N/ha, were 47 and to 61% less than that in farmers' traditional practices, 340 and 462 kg N/ha for maize and wheat, respectively.

At the Yongji site, similar yields of wheat (4.6~4.7t/ha) and maize (8.0~8.6t/ha) were achieved in the optimised treatments with 18% less (40kg N/ha) N fertiliser and 12% less (50mm) irrigation compared to the traditional farmers’ practices (Table 3).

Table 3. Wheat, maize and cotton yields (tonnes/ha) in 2006/2007 at the Yongji site in Shanxi.

Treatment	N Application (kgN/ha)	Irrigation (mm)	Yield (tonnes/ha)	Fertilizer cost saving (RMB/ha)
Traditional Farmer Practice				
Wheat	220	386	4.8±0.4	
Maize	210	198	8.0±0.9	
Cotton	110	120	3.51	
Optimised				
Wheat	180	339	4.6±0.4	160
Maize	180	90	8.6±0.4	120
Cotton	135	130	3.81	

Based on the apparent N budget, the total plant N recoveries were 22% in the farmers’ traditional treatment and 35% in the optimal treatment, indicating substantial N losses (Table 4). There was also substantial mineral N surplus in the soils at harvest, 110 and 127 kgN/ha in the optimum and traditional farmer practices treatments, respectively, indicating a large potential for further reductions of N application rate and improvement of N efficiency.

Table 4. Apparent N balance in the wheat-maize rotation at the Yongji site (kgN/ha)

Treatment	Control (no N applied-OPT)	OPT	FP
(A) N input			
N rate	0	360	430
N (mineral) before sowing in (0-90cm)	15	15	15
Total input	15	375	445
(B) N output			
Plant N uptake	156	283	252
N (mineral) after harvest in (0-90cm)	31	110	127
Apparent N recovery (%)		35	22

The nitrate concentrations in groundwater fluctuated considerably throughout the year, and ranged from 3ppm to 25ppm. The peak nitrate concentrations were two and half times that of the drinking water standard (10ppm) (Fig 1).

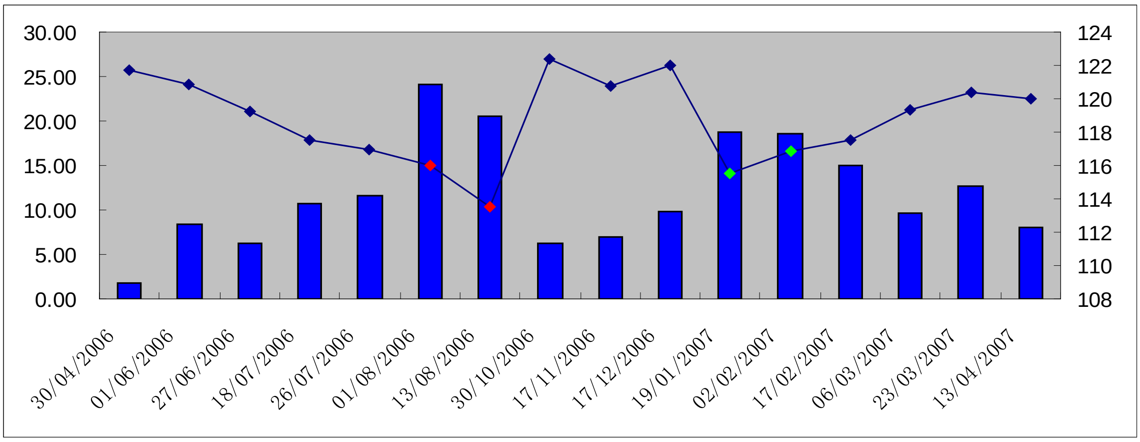


Fig.2. Nitrate concentration, Nitrate-N (μg/ml), left Y axis, and ground water table depth (cm), right Y axis.

The results in 2007/2008 were similar: 14% higher wheat yield was achieved in the optimised treatment with 18% less N fertiliser application (40 kgN/ha) compared to the traditional farmers' practices. The optimised treatment of split applications of a total of 180 kg N/ha urea resulted in a wheat yield of 5.0 t/ha whereas the traditional farmers' practices of a single basal application of 220 kg N/ha resulted in a wheat yield of 4.3 t/ha. There was substantial mineral N in the soils at harvest (about 30% of applied N), indicating potential for further reductions of the N application rate.

Similar maize yields (8.9~9.1 t/ha) were achieved in the optimised treatments but with 14% less N fertiliser (30 kgN/ha) than the farmers' practice.

In contrast, and similar to the last year's results, the farmers' practices of N application and irrigation on cotton were almost as efficient as the optimised practices, suggesting little potential for improvement under cotton.

1.3 Irrigated maize and wheat at Hongtong site.

At Hongtong site, the yields of wheat (8.9~9.1t/ha) and maize (8.0~8.2t/ha) were also similar in the two treatments (Table 3), but farmers traditionally applied far more N, 462 and 340 kgN/ha for wheat and maize, respectively, compared to 180 kg N/ha in the optimised treatment. The irrigation in the optimized treatment was about 20 mm less. The fertiliser cost saving alone ranged from 120 to 160 RMB/ha in Yongji and 640 to 1128 RMB/ha at Hongtong (1A$ equals 5RMB). The slightly higher N and irrigation were applied in cotton in the optimized treatment, with slightly higher cotton yields.

The similar wheat and maize yields with significantly less input of N fertilisers, particularly in Hongtong, has had a significant impact on the local framers practices already. In 2008 many farmers near the experimental sites applied similar amounts of N as in the optimized treatment.

Table 5. Wheat, maize and cotton yields (tonnes/ha) in 2006/2007 at the Hongtong site in Shanxi.

Treatment	N application (kg N/ha)	Irrigation (mm)	Yield (tonnes/ha)	Fertilizer cost saving (RMB/ha)
Farmer Practice				
Wheat	462	321	8.9±0.44	
Maize	340	319	8.0±0.9	
Optimised				
Wheat	180	294	9.18±0.43	1128
Maize	180	297	8.21±0.38	640

The results in 2007/2008 were similar: The yields of wheat (8.8~8.5 t/ha) and maize (8.8~9.2 t/ha) were similar in the traditional farmers' and optimised practices. However, the N application rates in optimised practices,180 kg N/ha, were 47 and to 61% less than that in farmers' traditional practices, 340 and 462 kg N/ha for maize and wheat, respectively.

The fertiliser cost saving ranged from $25 to $30/ha in Yongji and $120 to $211 in Hongtong. The consecutive and consistent two years' results of lower input of N fertiliser without yield losses (particularly in Hongtong) has had a significant impact on farmers' practices already. More than 60% of farmers near the experimental site applied similar amounts of N as in the optimised treatment developed by our project.

2. Greenhouse gases (GHG) emissions

For the first time in China emissions of the greenhouse gases of N_2O, NOx, methane (CH_4) and CO_2 were measured continuously by automatic chambers in the ACIAR project by the team of Chinese Academy of Agricultural Sciences (CAAS) at Yuci and team from Chinese Academy of Sciences (CAS) at the Yongji. Both CAS and CAAS provided substantial co-funding ($500,000) to establish such sophisticated systems.

2.1 Yuci site

Excellent datasets of N_2O emissions were derived from the continuous automatic chamber system developed by the CAAS team at the Yuci site, with high temporal resolution (Fig.3). The results show that the optimized treatment (using 33% less N) emitted 46-53% less N_2O while achieving similar yield comparing to the traditional practice (Table 6). Although the nitrification inhibitor (NI) treatment applied 45% less N, it resulted in 42% less N_2O emissions and the maize yield also dropped by almost 10%. The same amount of N in the Sulfur Coated Urea (SCU) treatment achieved 72% reduction of N_2O emissions but also had 8% higher maize yield (Table 6).

Fig. 3. The automated sampling system at Yuci site

Table 6. The results of the experiment from 2007 to 2009 at Yuci

Year	Treatment	N applied (kgN/ha)	N_2O emission (kg $N\cdot ha^{-1}$)	p<0.05	Yield ($kg\cdot ha^{-1}$)	p<0.05
2007	T	330	1.46±0.16	a	11900±500	b
	O	220	0.78±0.15	d	12000±350	b

2008	T	330	1.4±0.13	a	12100±800	b
	TT	330	1.45±0.21	a	12300±600	b
	O	220	0.71±0.11	d	12250±550	b
	OT	220	0.73±0.13	d	12200±750	b
2009	T	330	1.55±0.28	a	12200±520	b
	O	220	0.73±0.10	d	12300±830	b
	U	180	1.20±0.05	b	10700±170	c
	NI	180	0.90±0.03	c	11160±290	b
	SCU	180	0.44±0.07	e	13270±130	a
	CK	0	0.21±0.12	f	9329±300	d

Note T: traditional treatment, O:optimized treatment; TT: tradition fertilization and irrigation; OT: optimized fertilizer and tradition irrigation; U: urea treatment; NI: nitrification inhibitor (DCD) and Urea; SCU: Sulfur Coated Urea; CK: no fertilizer.

2.2 Yongji site

Professor Xunhau Zheng, a world leading scientist in GHG research from agriculture, at the Institute of Atmospheric Physics, Chinese Academy of Sciences (CAS) (Beijing), established the state of the art of automatic and continuous chambers system for wheat, maize and cotton (Fig. 4), with $500,000 cash support from CAS. The system is capable of measuring all three GHG gases, N_2O, CO_2 and CH_4 as well as NOx. The system has been successfully operating for more than 24 months. The system has achieved very high precision and is capable of measuring very small GHG fluxes in the winter time. The auto chamber system is capable of detecting as little as 3-9 µg N_2O-N/m^2/h emission fluxes and 0.6-1.8 µg NO-N/m^2/h emission fluxes.

In contrast to Yuci site, there were only small differences in N_2O emissions at the Yongji site between the optimised and traditional practices. The N_2O emissions accounted for 1.4 to 2% of applied N, higher than to IPCC default value of 1% and much higher than Australian wheat system of less than 0.2%.

Fig. 4. Automatic chamber system at the Yongji Site, developed by Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP-CAS).

3. Measurement of ammonia losses

The low efficiency of water and N use in irrigated cropping results in lower incomes for farmers, and impaired water quality. Volatilisation of ammonia (NH_3) is often the major pathway of N loss and contributes indirectly, after NH_3 returns to the soil, to N_2O emissions. Urea is the N fertiliser of choice in the County, and volatilisation losses of NH_3 from surface application of urea have been shown to be large. Best management practices in which the fertiliser is placed deep in the soil have been developed for Shanxi Province. We focused on developing methods for measuring the success of the practice. Some results of our work in this area are given in another section of the report. Here, we describe the methodology employed. We have used arrays of passive samplers, a newly developed chemiluminescsence analyser, and open-path lasers to measure both point and line-averaged concentrations of NH_3, and have inferred the emissions of NH_3 using mass-balance or backward Lagrangian stochastic (bLs) dispersion techniques.

Passive samplers

A study was conducted at Yongi, Shanxi Province, China in July 2006 to determine the loss of ammonia from an application of urea to an irrigated maize crop. Urea (200 kg N / ha) was applied to a 50 m x 50 m square plot of maize using farmers' local practice of deep point placement, and the area was irrigated with overhead sprinklers for 3 hours. Ammonia loss was determined using samplers (Leuning et al., 1985), pictured at left, and a mass balance micrometeorological method. As seen in the illustration, the samplers are vane-mounted so that they always point into the wind. They allow air to pass through them at a rate directly proportional to the wind speed and a chemical absorber in the sampler absorbs all the NH_3 in the air stream.

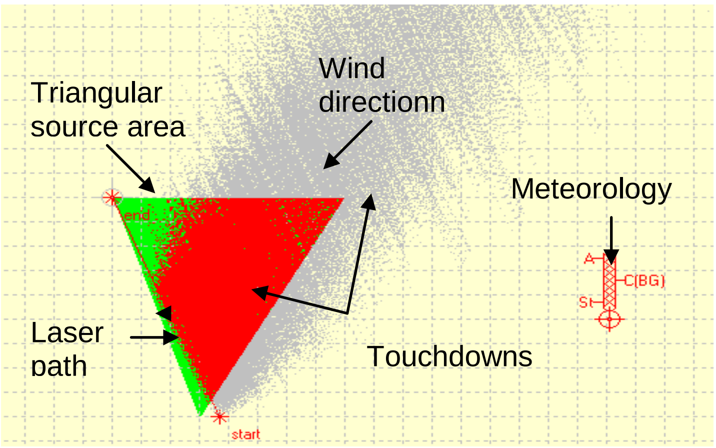
The absorbed NH_3 is subsequently washed out from the sampler and its mass determined. This provides a direct measurement of the rate at which NH_3 has been transported by the wind at the height of the sampler. By mounting samplers at different heights within the boundary layer at the centre of the treated plots and integrating over the depth of the boundary layer (Leuning et al. 1985), the total rate of loss of NH_3 from the plot can be calculated. Rates of ammonia loss from the treated area ranged from 0.2 to 4.2 µg N / m^2 / s and the cumulative ammonia loss was 2.7 kg N / ha (~1.4% of applied N). Ammonia loss from this site was much lower than that measured by Zhang et al. (1992) and Cai et al. (2002a, b) for maize at other sites on the North China Plain. They found that NH_3 loss varied from 11 to 48% of the N applied depending on method of fertilizer application and environmental conditions. The small loss at the Yongi site was probably due to the deep placement of fertilizer and the overhead irrigation which would have moved the fertilizer deeper into the soil.

Open-path lasers

Open-path lasers (at left) have been developed for CO_2, NH_3 and CH_4. They measure line-averaged gas concentrations over distances up to 1 km. The units are portable and can be battery powered. Two NEO NH_3 laser units, at left, were purchased for ACIAR work and were taken to the field site at Yongji in 2006 and 2008.

In practice, a reflector at the end of the path reflects the laser beam back to the transmitter, illustrated at left.

The bLs technique



The technique uses a Lagrangian dispersion model to trace air parcels backwards from the sensor to the source and background areas in simulations of their trajectories. It counts the number of touchdowns of the parcels inside and outside the source area and uses this information to partition the measured concentration and the gas flux between contributions from source and background.

The model is implemented through an interactive software package called WindTrax.

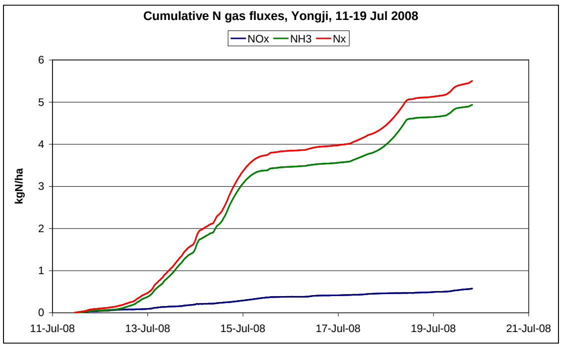
Required inputs to implement the model:

- wind speed
- wind direction
- surface roughness, z_0
- turbulence, u_*
- atmospheric stability, L
- exact geometry of source
- height and location of sensor
- length of measuring path
- number of trajectories, usually 50,000

The cumulative loss determined by the combination of passive samplers and the bLs technique at Yongji in 2006 was 2.1% of the N applied, still very much less than that measured for maize at other sites on the North China Plain.

Chemiluminescence gas analyser

A field-mounted chemiluminescence gas analyser was used to measure NH_3 and NO_x concentrations at Yongji in 2008 in a similar study of NH_3 loss to those in 2006. The analyser has a very high precision of < 1ppb. It provides a point measurement rather than a line average, but uses the same bLs approach to calculate the gas losses. The final cumulative loss of NH_3 was estimated to be 6.6 kg N/ha and that of NO_x 1.2 kgN/ha. The results confirm the results of our previous studies in showing that the deep placement of fertiliser is effective in reducing NH_3 losses, but that even though the fertilizer is placed below the soil surface a small amount of NH_3 (and NO_x) can still be lost to the atmosphere.

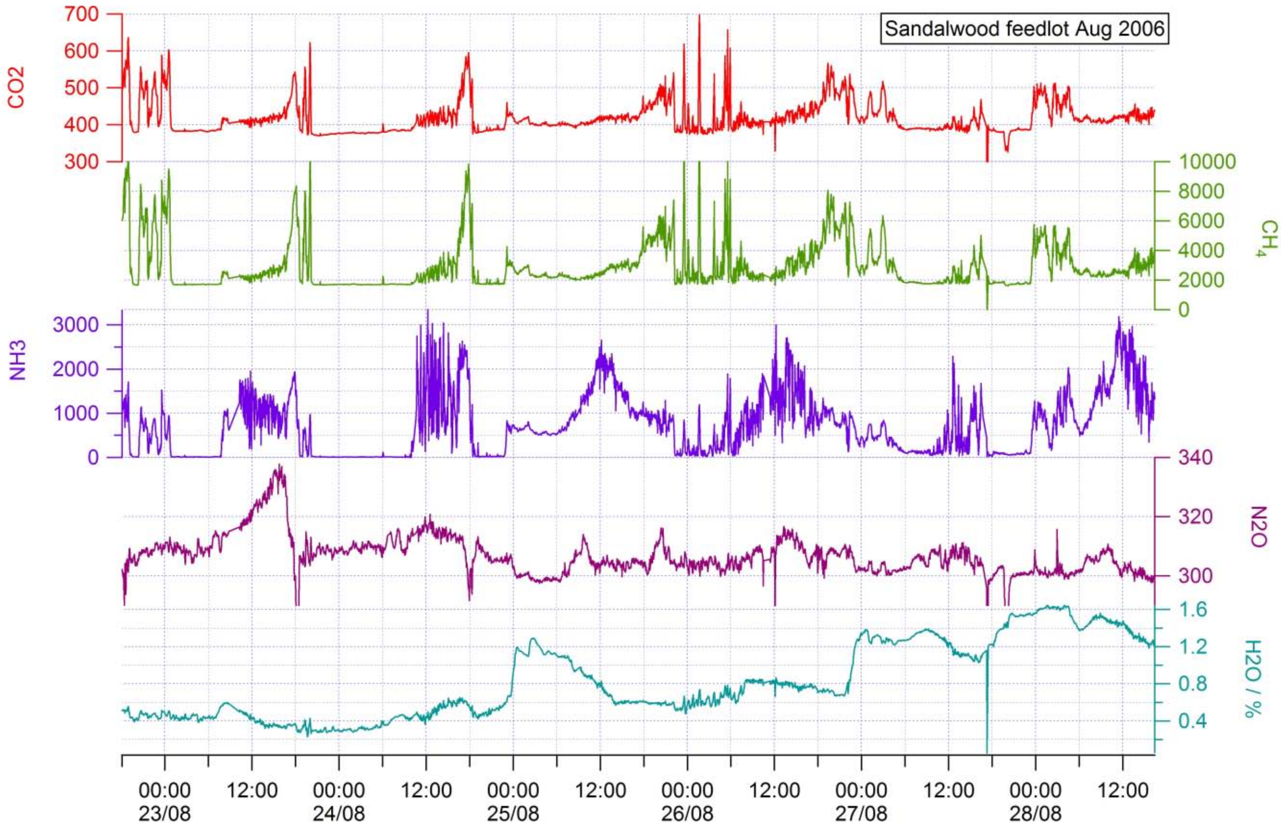


<u>Open–path Fourier Transform Infrared (FTIR) Spectroscopy</u>

FTIR

- identifies and quantifies concentrations of infrared absorbing gases
- examines transmission spectra from a broad-band infrared source and matches spectra against a database of spectral line parameters
- relative precision (1sd) of measurements typically ~ 0.1%
- can measure the concentrations of all the infrared gases of interest simultaneously
- gases from agricultural sources: NH_3, N_2O, CO_2, CH_4
- can be used in both closed- and open-path systems
- detection limit for NH_3 is < 3ppbv
- a virtue is that it can be used to measure N_2O emissions from agricultural operations, the focus of Activity 2 of the project

FTIR spectrometer built by the University of Wollongong. It is portable, tripod mounted, but presently requires 240V AC power. Unlike previous versions, it requires no cooling by liquid N. Its most effective path length is ~120 m. **One of these instruments has been purchased with ACIAR funds and it is proposed to use it for training operators from Asian countries in measuring greenhouse gas emissions**



Continuous open-path FTIR measurements downwind of a cattle feedlot. These measurements are combined with turbulence data to calculate rates of gas emission via the backward Lagrangian stochastic dispersion model.

4. Spatial modelling and decision support system

4.1 Integration of the WNMM model with an economic module.

This updated version of WNMM has been successfully tested on data obtained from the Fengqiu site (site extensively studied in the predecessor project) and the Alxa League site. The development of a theoretically sound economic evaluation framework underpinning the economic module in WNMM is seen as a major advance, allowing for the future quantification of the public good costs and benefits of public and private investment into agricultural GHG emission reductions.

4.2 Calibrated WNMM for Shanxi region.

WNMM has been calibrated for the Shanxi sites to simulate soil water, N and N_2O emissions. WNMM well captured the dynamics of soil temperature, soil water content and ultimately N_2O fluxes during the crop growing season. The Figure 5 is for Yuci site. Similar calibrations to WNMM were carried out in Hongtong and Yongji counties.

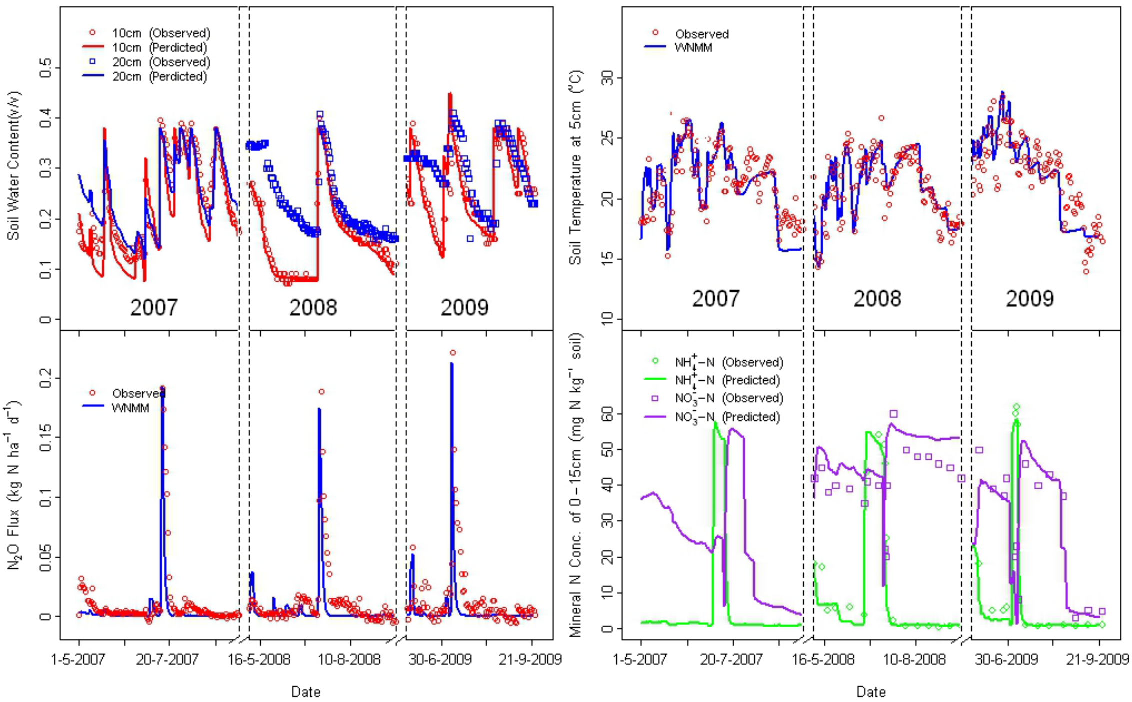


Fig. 5 . The observed and WNMM-predicted soil water content, temperature, mineral N and N_2O emissions in Yuci site.

4.3 Scaling up WNMM for the Shanxi region.

The site-calibrated WNMM was further calibrated at the county scale to correct or improve the accuracy of the soil attribute properties which were based on the 1980s national soil survey before they were used by WNMM for identifying best management practices (BMP) for each specific soil type in this county. As required by WNMM and considering the temporal stability of soil pH, clay content and CEC, only soil SOM, total N, total P and hydraulic properties were considered.

In Yuci county with the soil properties updated according to the field survey, the performance of WNMM in predicting maize yields was significantly improved (Fig. 6).

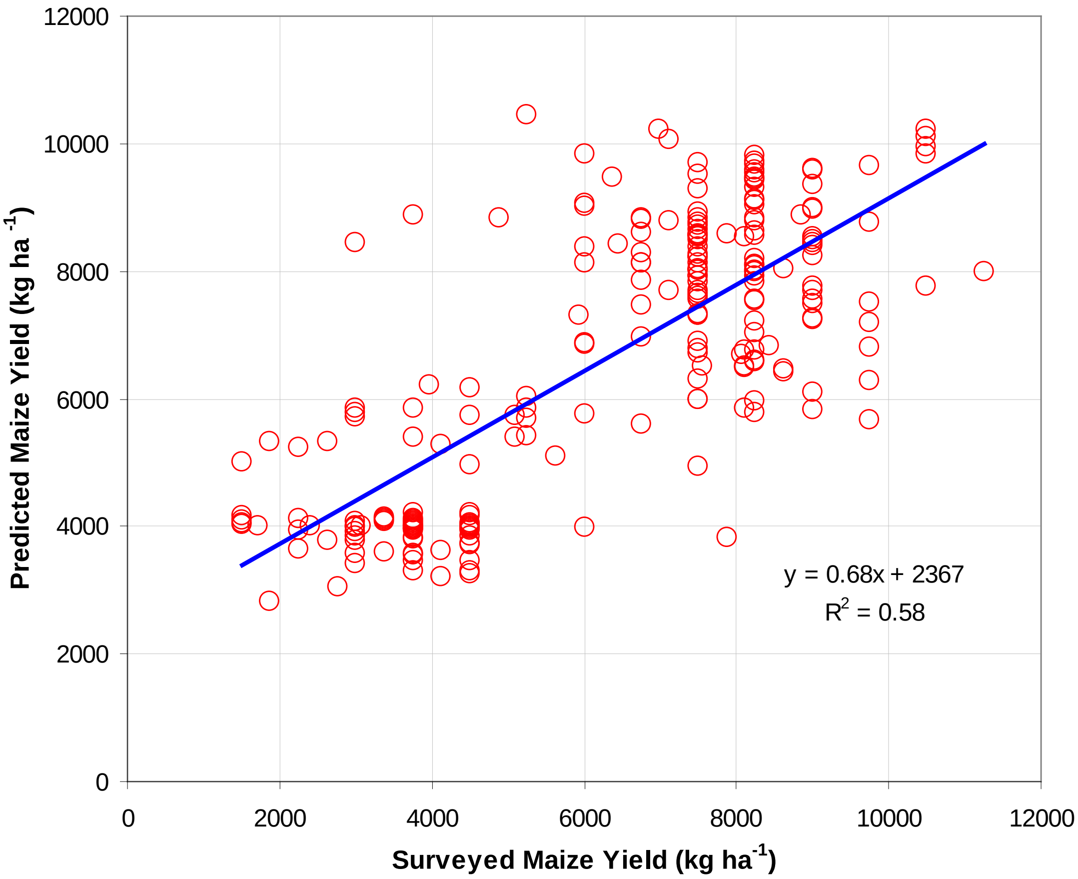


Fig. 6. Surveyed maize yield vs. WNMM-predicted maize yield in Yuci County for 2006 by using (A). default soil hydraulic properties and (B). modified soil hydraulic properties, respectively.

In Hongtong County, once the soil hydraulic properties were calibrated using satellite images, the WNMM prediction of wheat yields was substantially improved (Fig. 7).

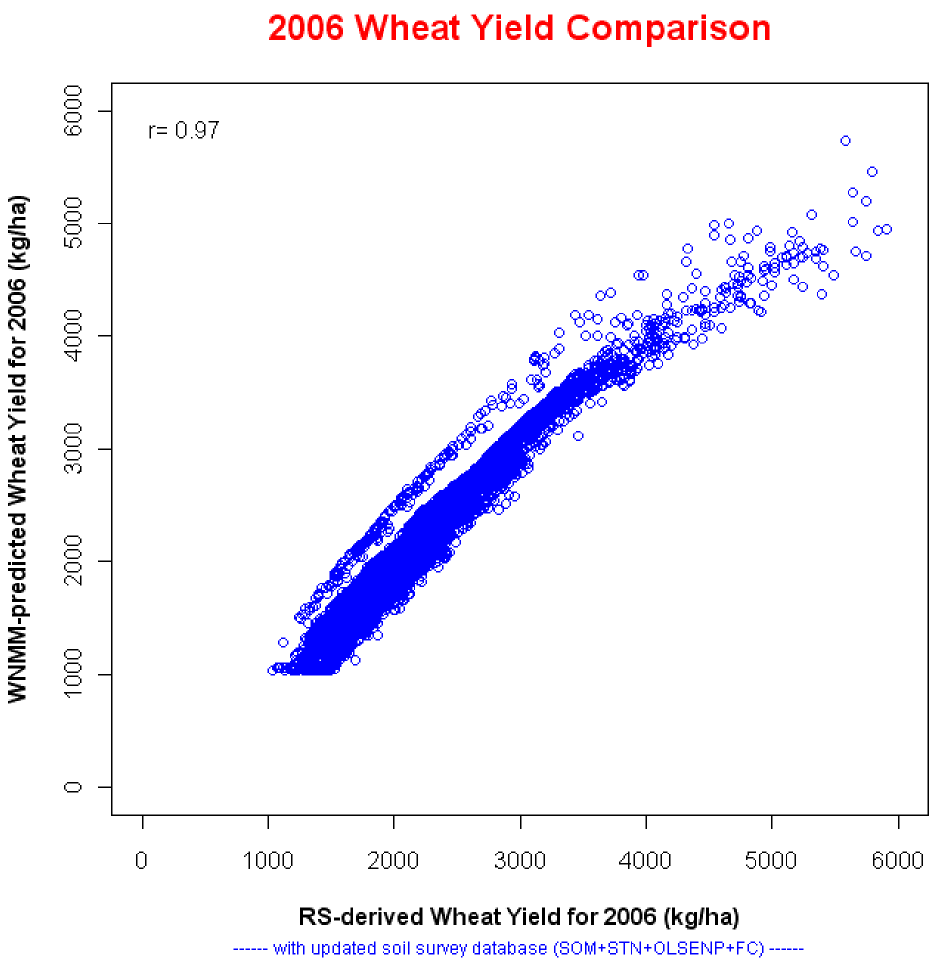


Fig. 7. Comparison of RS-derived wheat yield and WNMM-predicted wheat yield for 2006 by using updated soil information of soil organic matter, total N, Olsen P and field capacity.

4.4 Development of best management practices

According to the field surveys by the local agricultural department and us, there are only one cropping system (mono maize) in Yuci County, two cropping systems (rainfed mono wheat and irrigated wheat-maize) in Hongtong County, and two cropping systems (irrigated wheat-maize and cotton) in Yongji County. The practice scenarios regarding the differences in the practices of fertilization and irrigation for these cropping systems were established. The historic long-term historic daily weather data were also collected from the county weather stations and drove WNMM. Using the soil information for each county, thousands of agricultural practice scenarios were simulated for each soil type using WNMM from 1960s to 2007 and evaluated using the following BMPs assessment system (Table 7).

Table 7. Evaluation indices and weights (in bracket) of the BMPs assessment system for Hongtong County

Group	Subgroup	Index*
Crop production $((1-\alpha)\cdot\frac{\beta}{1+\beta})$		Yield (0.6)
		Success probability (0.4)
Environment (α)	Resources use efficiency (0.5)	FNUE (0.5)
		WUE (0.5)
	Environmental pollution (0.5)	1 - Nleached (0.4)
		1 - NH_3 (0.2)
		1 - N_2O (0.4)
Economic benefit $((1-\alpha)\cdot\frac{1}{1+\beta})$		Profit (1.0)

Note: α is the awareness of environmental issues (0-1), default 0.5 (normal), and β is the importance of agricultural crop production compared to agricultural economic benefit (0.5-2.0), default 1.0 (equal).

The soil, agricultural practice scenarios, WNMM simulations and BMPs evaluations were then assembled into the new framework for the Agricultural Decision Support System for desktop computers (Figs. 8, 9).

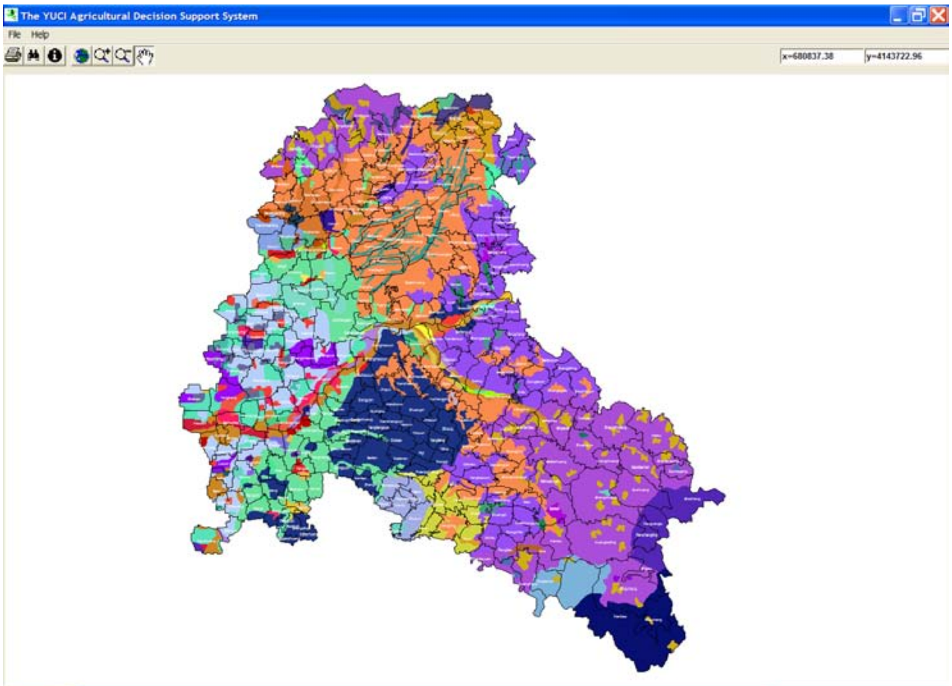


Figure 8. The interface of agricultural decision support system for Yuci County.

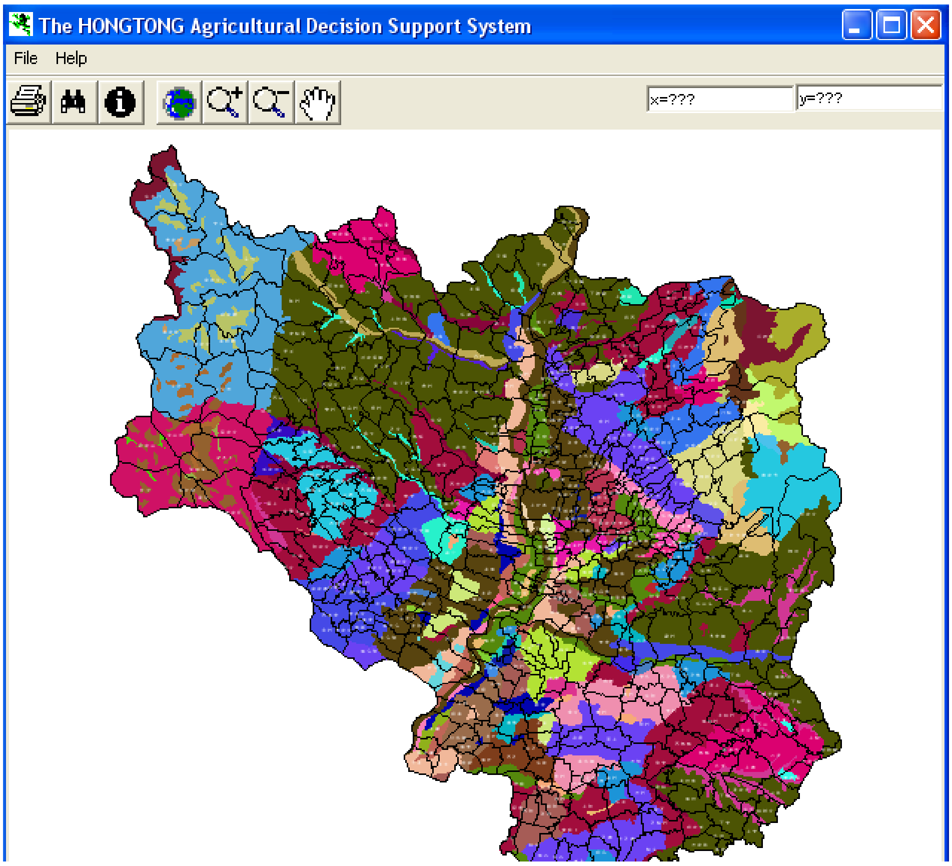
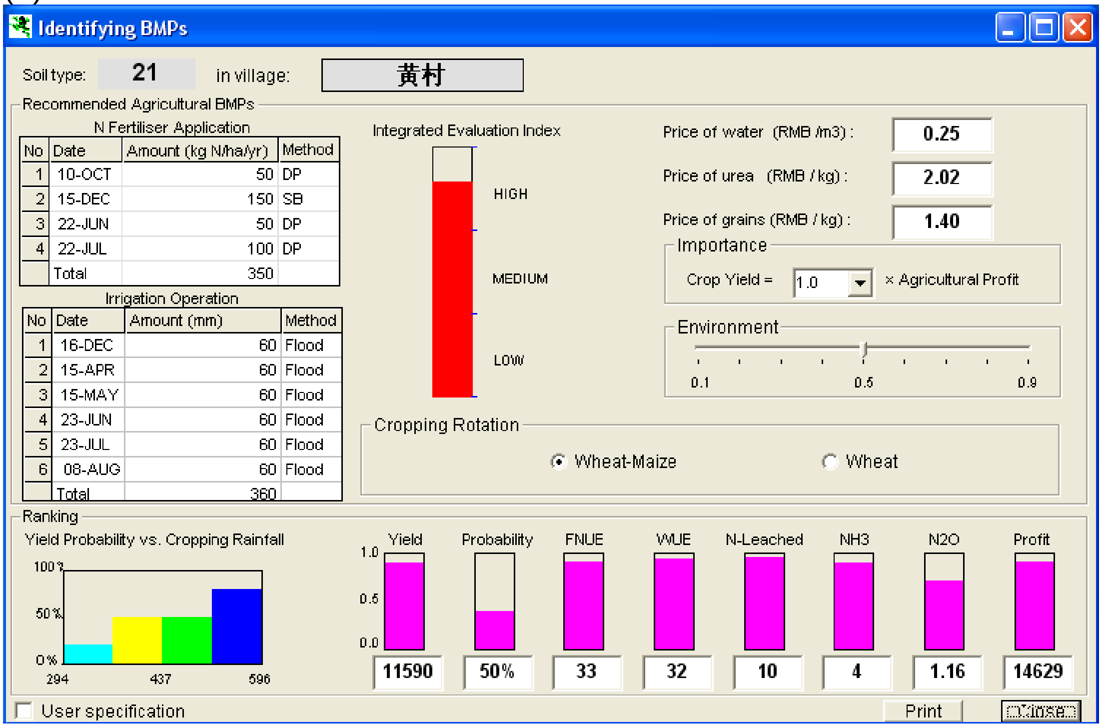


Figure 9. The interface of agricultural decision support system for Hongtong County.

By clicking at the soil maps in Figures 9-10, the BMPs for a specific soil type was identified as in Fig. 10, in which the individual indices for each BMPs were displayed and users can vary the importance of crop production against agricultural profit and the environment, and the prices of water, fertilizers and crop grains.

(A)



(B)

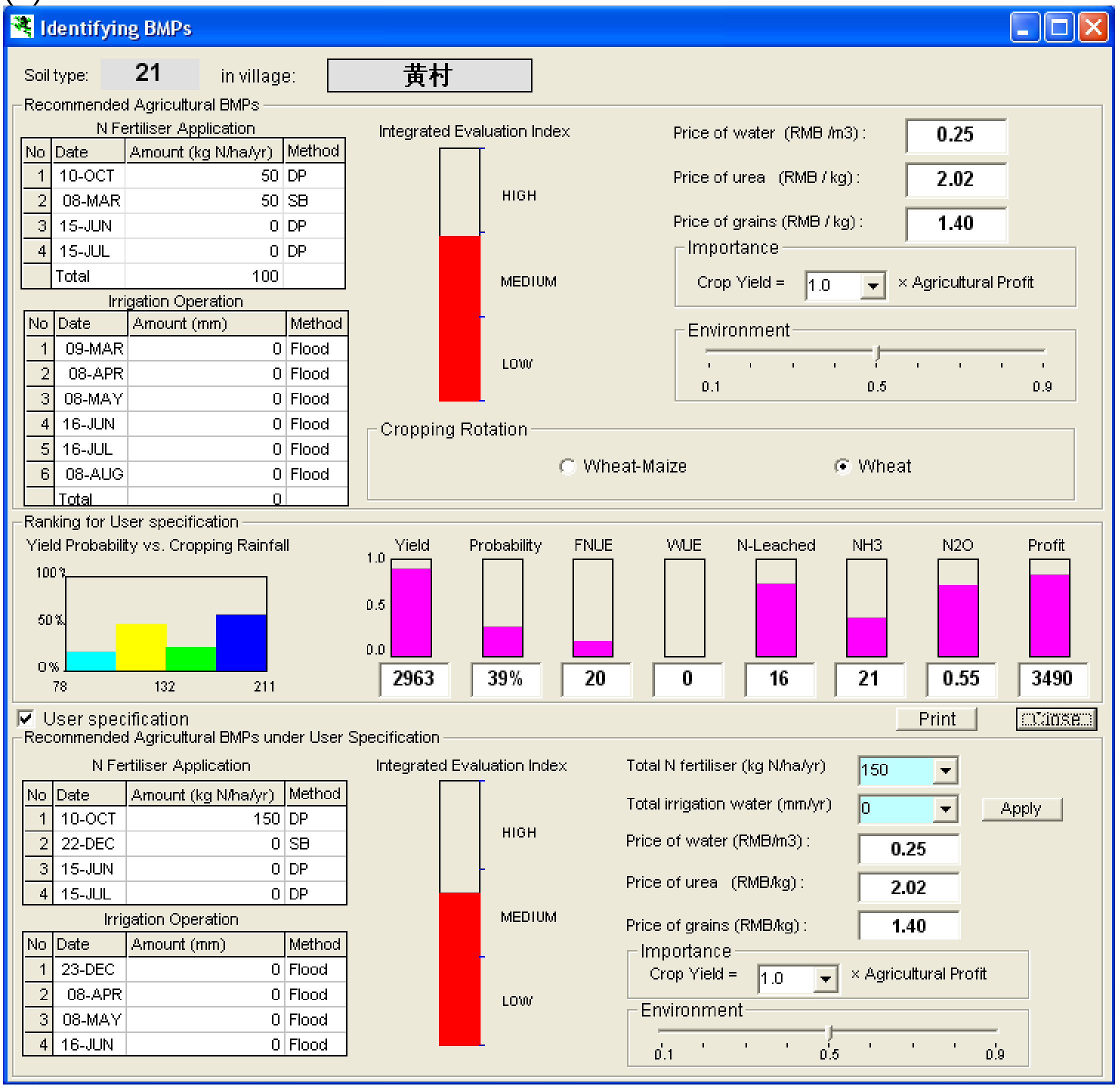


Figure 10. An example of the application of the agricultural decision support system for Hongtong County.

The system has been demonstrated to our Chinese colleagues and the local agricultural department in November 2008, and the feedback was very positive and constructive. Two major comments from them are i) they need a Chinese system; and ii) the interface needs to be simplified as it displays too much information to users.

The above agricultural decision support system was also ported into handheld computers, such as PDA and smart phones which run Windows Mobile 5-6, but with light-weight display information and using MapWindow 6 .NET technique. Such a system could be very handy and useful for the agricultural decision makers and the farmers.

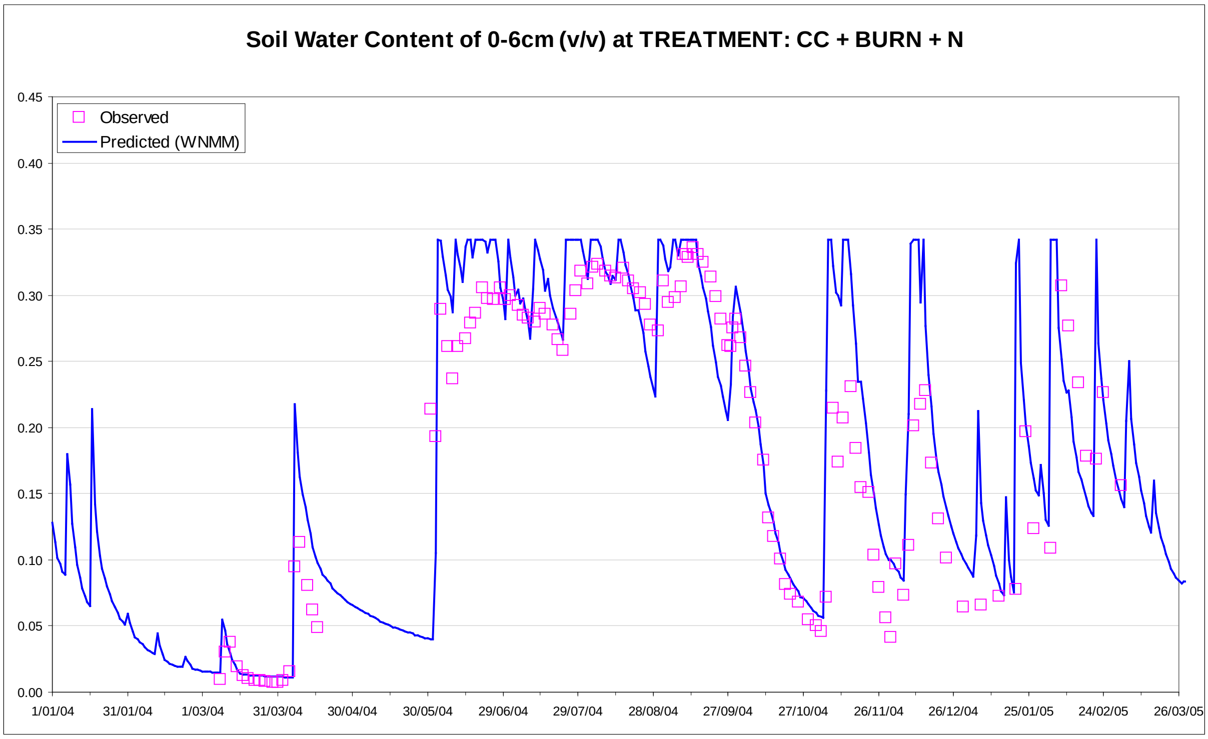
4.5 Application of WNMM to Australian rain-fed wheat and irrigated pastures systems.

4.5.1 Application WNMM in rain-fed wheat system in Victoria

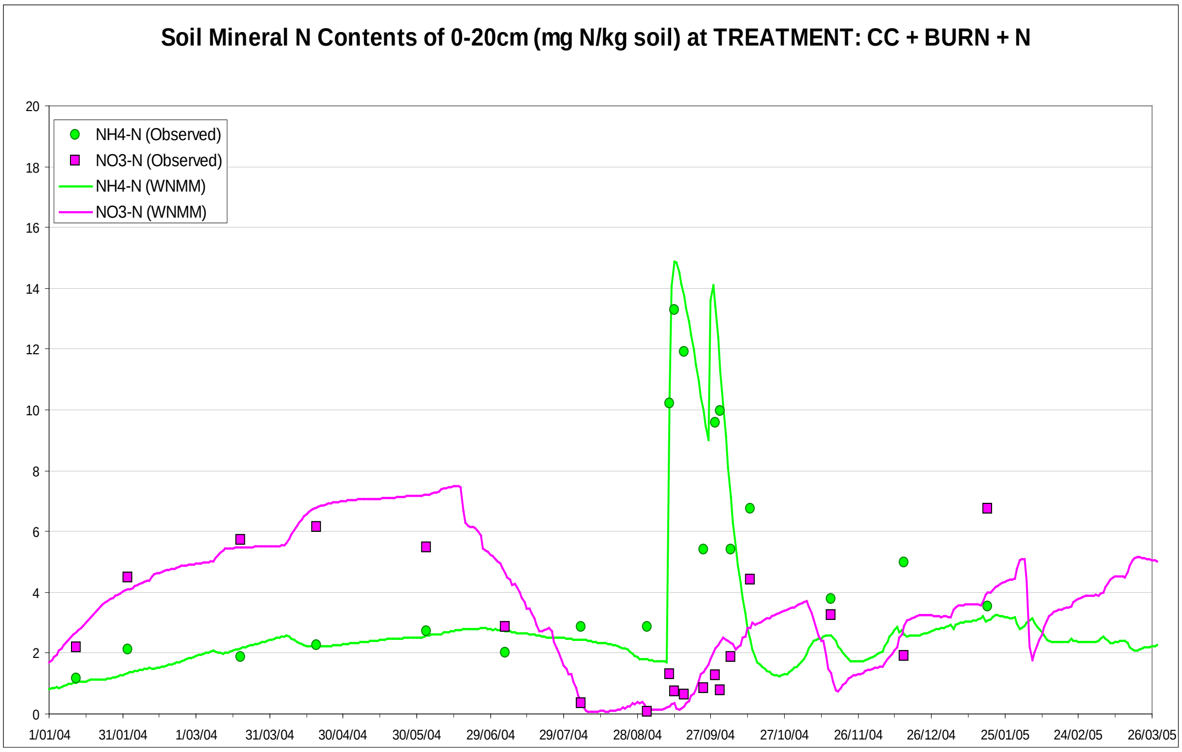
The WNMM was applied to simulate N_2O emissions from a rain-fed wheat cropping system on a loam-textured soil for two treatments, conventional cultivation with residue burn (CC+BURN+N) and direct drill with residue retention (DD+RET+N), at Rutherglen in southeastern Australia from January 2004 to March 2005. Both treatments received the same amount of nitrogen (N) fertiliser. The WNMM satisfactorily simulated the soil water content, mineral N contents and N_2O emissions from the soil, as compared with the field observations for both treatments (Fig. 11). The simulated nitrification-induced N_2O emissions accounted for 45% and 34% of total N_2O emissions for the treatments CC+BURN+N and DD+RET+N, respectively.

The calibrated WNMM was used to simulate N_2O emissions from this soil using historic daily weather data from 1968 to 2004 and applying seven scenarios of fertiliser N application. The annual N_2O emissions varied almost 6-fold, and ranged from 0.11 kgN/ha to 0.6 Kg N/ha (Fig. 12), indicating the strong impact of long term climate change on the N_2O emissions and that it is impossible to rely on the measurement alone to estimate the 'average' N_2O emission. Correlation analysis found that the annual N_2O emissions for this rain-fed wheat cropping system were significantly correlated to the annual average of daily maximum air temperature (r=0.51 for CC+BURN+N and 0.56 for DD+RET+N), annual rainfall (r=-0.56 for CC+BURN+N and -0.59 for DD+RET+N) and fertiliser N application rate (r=0.43 for CC+BURN+N and 0.31 for DD+RET+N). Based on the 37-year historic simulations, multivariate regression models for estimating annual N_2O emissions were developed to account for climatic variation, and explained about 50% of variations of annual N_2O emissions estimated by WNMM.

A.



B.



C.

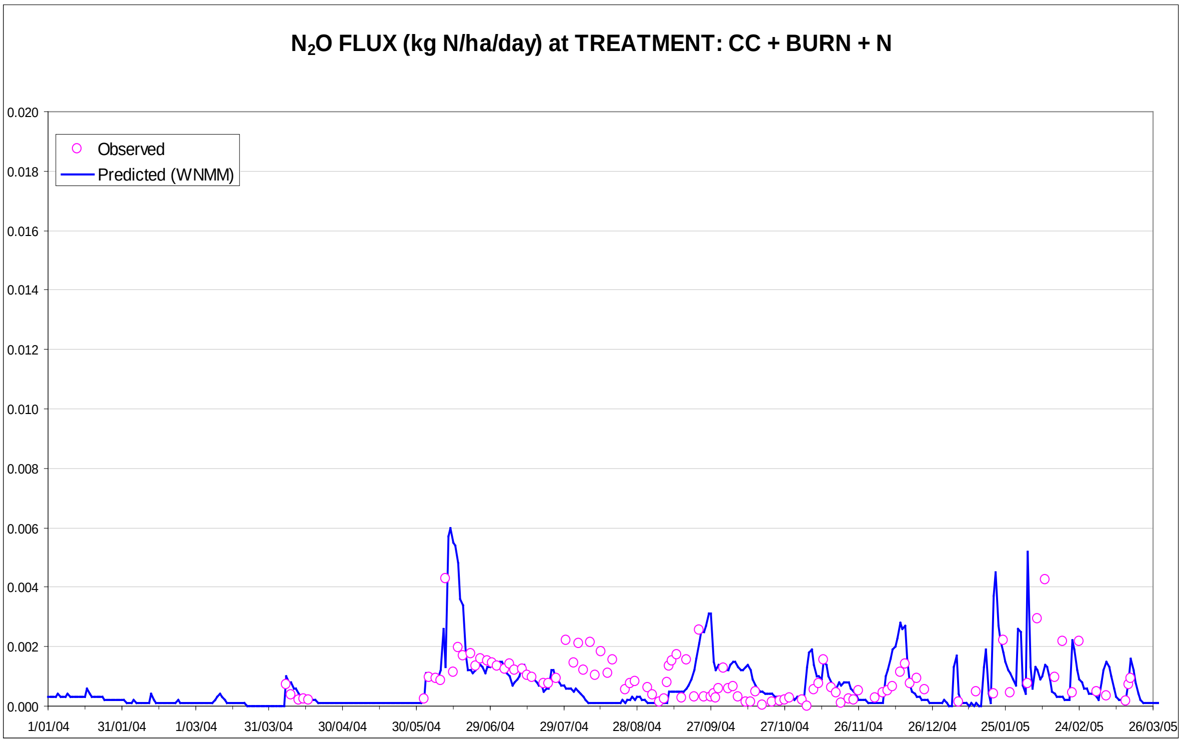


Fig. 11 Field-measured and WNMM-simulated soil water content of 0-6 cm, soil mineral N contents of 0-20 cm and N_2O emissions for the treatments of CC+BURN+N (calibration) and DD+RET+N (validation) from January 2004 to March 2005. Note that NH_4^+ is for ammonium and NO_3^- is for nitrate

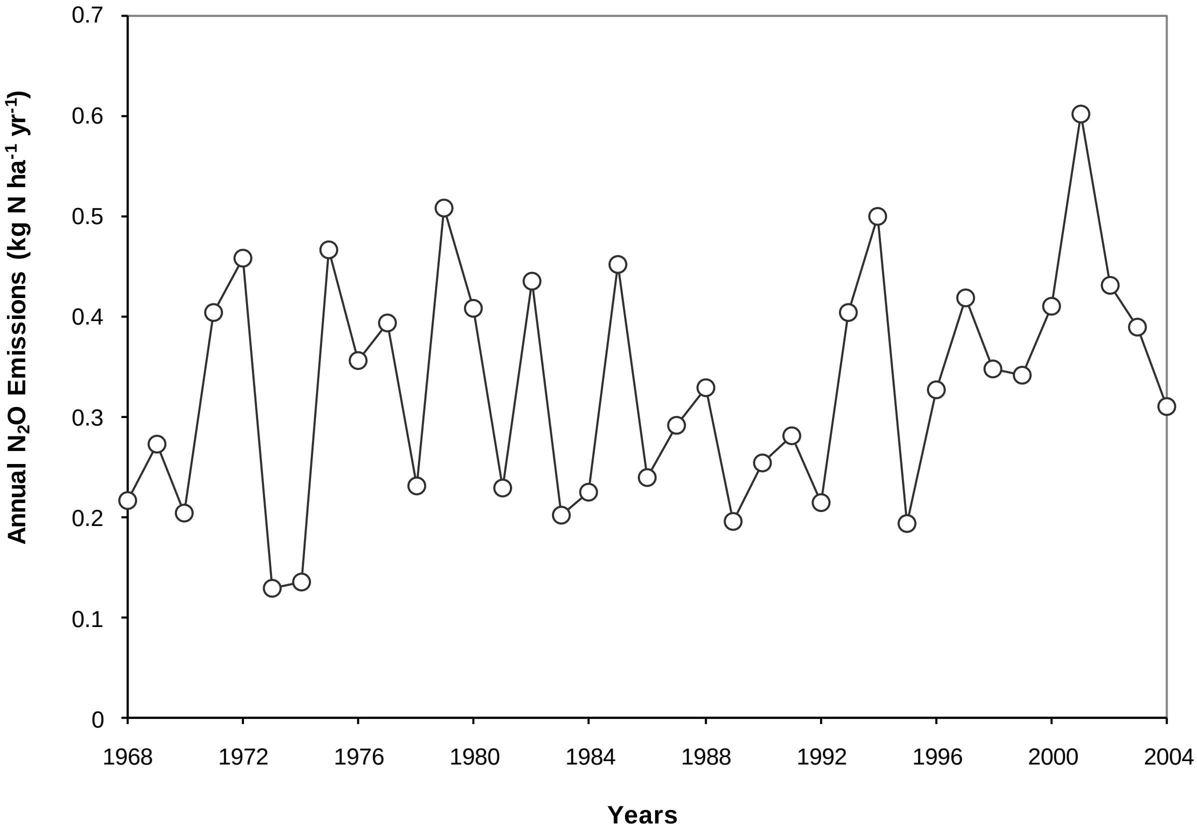


Fig. 12 Yearly variation of the WNMM-estimated annual N_2O emissions for the treatment DD+RET+N at the current fertiliser N application rate (82 kg N ha^{-1} yr^{-1}) at the Rutherglen site from 1968 to 2004.

4.5.3 Application WNMM in irrigated pasture system in Victoria

The dairy pasture system is a high input - high output production system associated with intensive irrigation and nitrogen (N) fertilizer applications. In this study, the daily and total chamber-measured N_2O emissions from an intensively-irrigated pasture grown on clay loam-textured soil for non-fertilized (CK), urea and urine treated plots at Kyabram in southeastern Australia were measured over a period of 20 months. WNMM was successfully modified to simulate water and N dynamics, pasture growth and N_2O emissions.

The simulations and statistical analysis indicated that the performance of WNMM in predicting the daily and monthly N_2O emissions for the three treatments is in the order: CK < UREA < URINE. The periodically-summed correlation analysis showed that WNMM was most reliable in predicting N_2O emissions from an intensively-irrigated dairy pasture system at a time scale of around 35 days. The WNMM-estimated N_2O emission factor for this ecosystem was around 0.5%. The proportions of nitrification-induced N_2O emissions in the simulated annual emissions were 12%, 21% and 45% for the CK, UREA and URINE treatments, respectively. WNMM has the potential to test agricultural practices, in this case irrigation and fertilizer N application, for mitigating direct N_2O emissions from intensively-irrigated pasture grown on clay loam-textured soil.

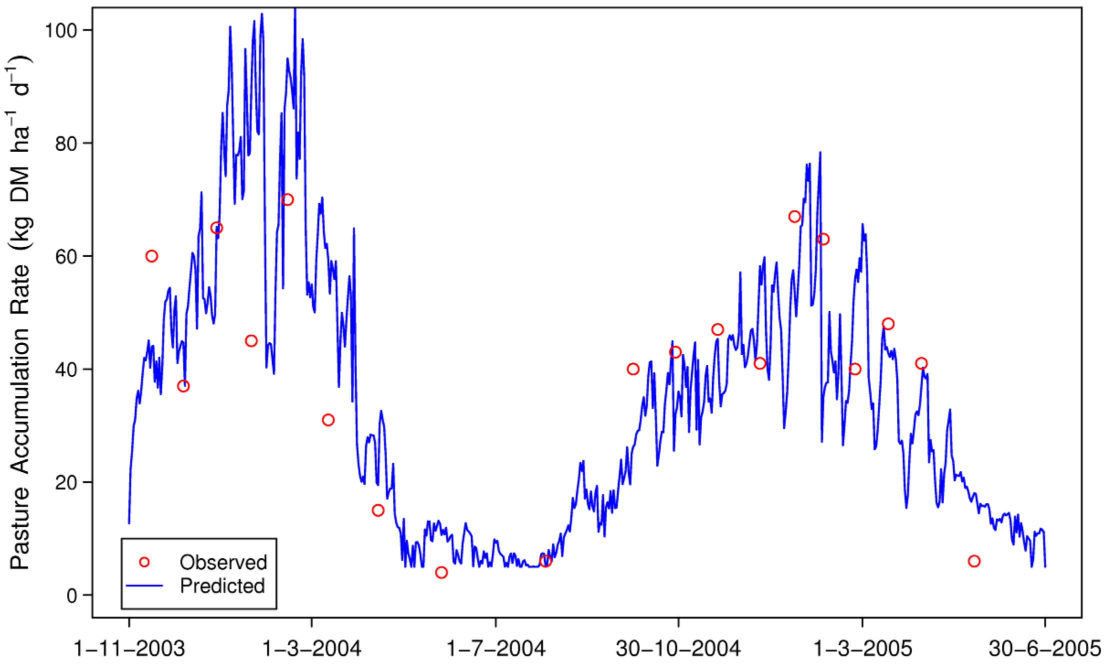


Fig. 13. Field-estimated (circle) and WNMM-predicted (line) pasture accumulation rates (kg DM ha^{-1} d^{-1}) of the UREA treatment at Kyabram from 1 November 2003 to 30 June 2005.

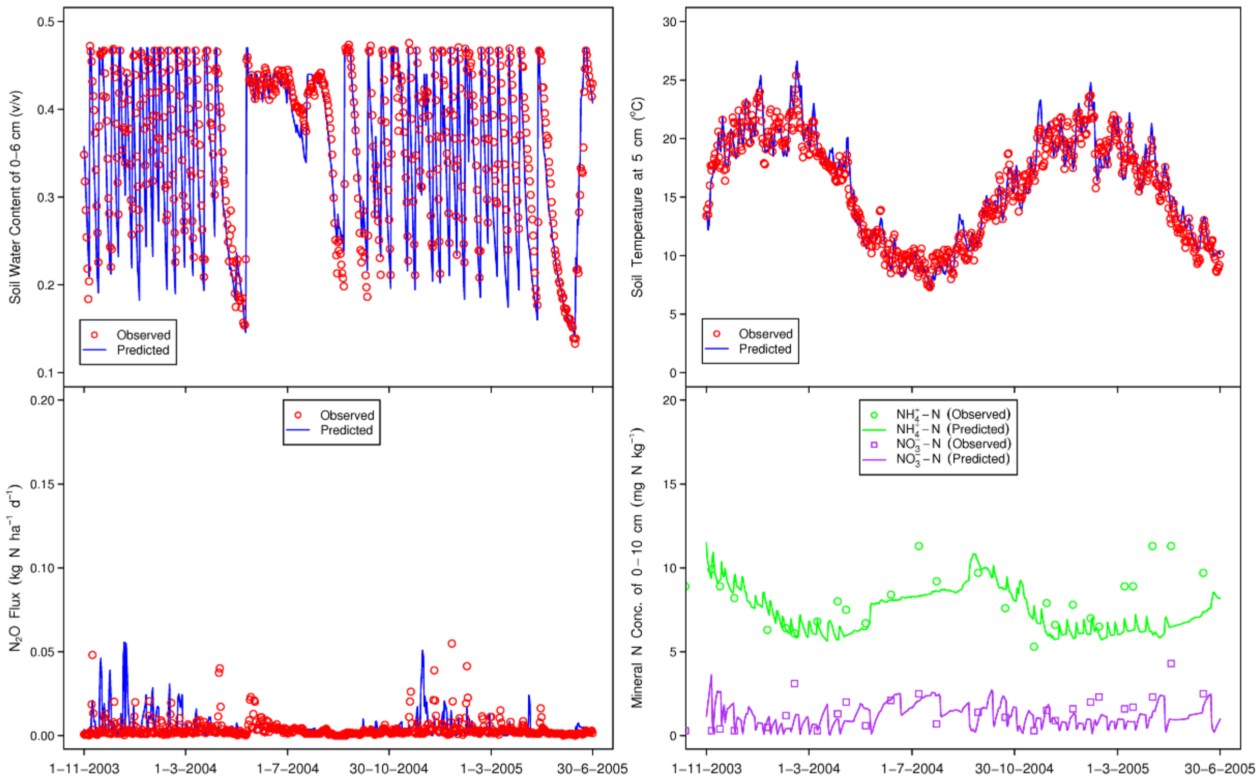


Fig. 14. Field observed (markers) and WNMM simulated (lines) soil volumetric water content of 0-6 cm topsoil, soil temperature at 5 cm, soil mineral N contents of 0-10 cm topsoil and N_2O emissions in the CK treatment at Kyabram from 1 November 2003 to 30 June 2005 (calibration).

4.6 WNMM calibrations and applications at the site and regional scales in Western Australia

Funded by AGO, N_2O emissions from wheat-cropped system were monitored by Dr Louise Barton and her team from May 2005 - May 2007 at the Cunderdin Agricultural College (31°36′ S, 117°13′ E, elevation 220 m), in the central wheatbelt of Western Australia, with the site located on a flat to gently undulating land. We have successfully simulated the two-year ecological processes of wheat growth, yield, soil water content (Figure 6), soil temperature, soil mineral N contents and N_2O emissions (Figure 15) from two treatments: CK (0 N) and fertilized (100 N split at the 40:60 ratio in July and August).

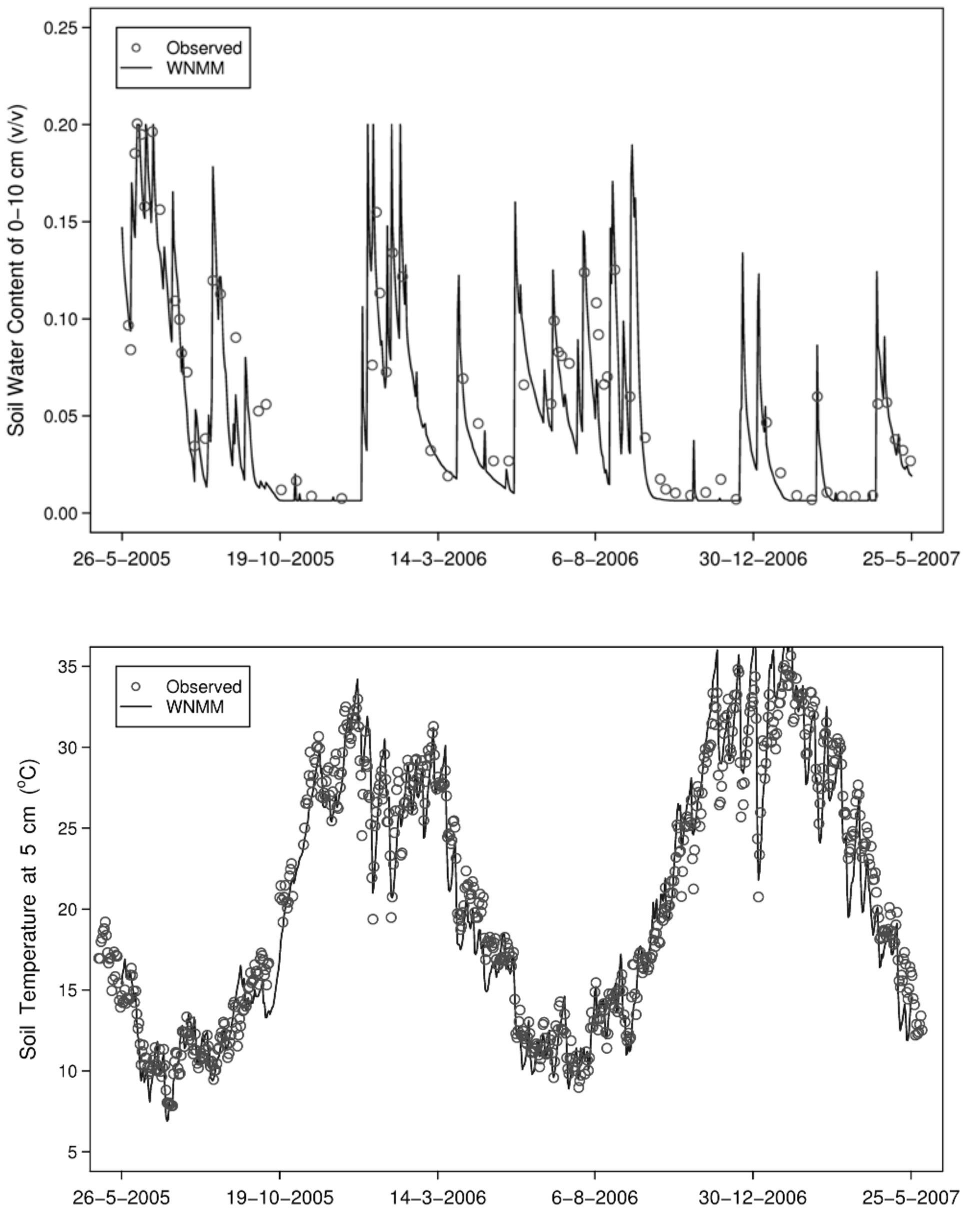


Fig. 15. Field observed (hollow circle) and WNMM simulated (solid line) soil water content of 0-10 cm and soil temperature at 5 cm for the UREA treatment at Cunderdin, Western Australia from May 2005 to May 2007.

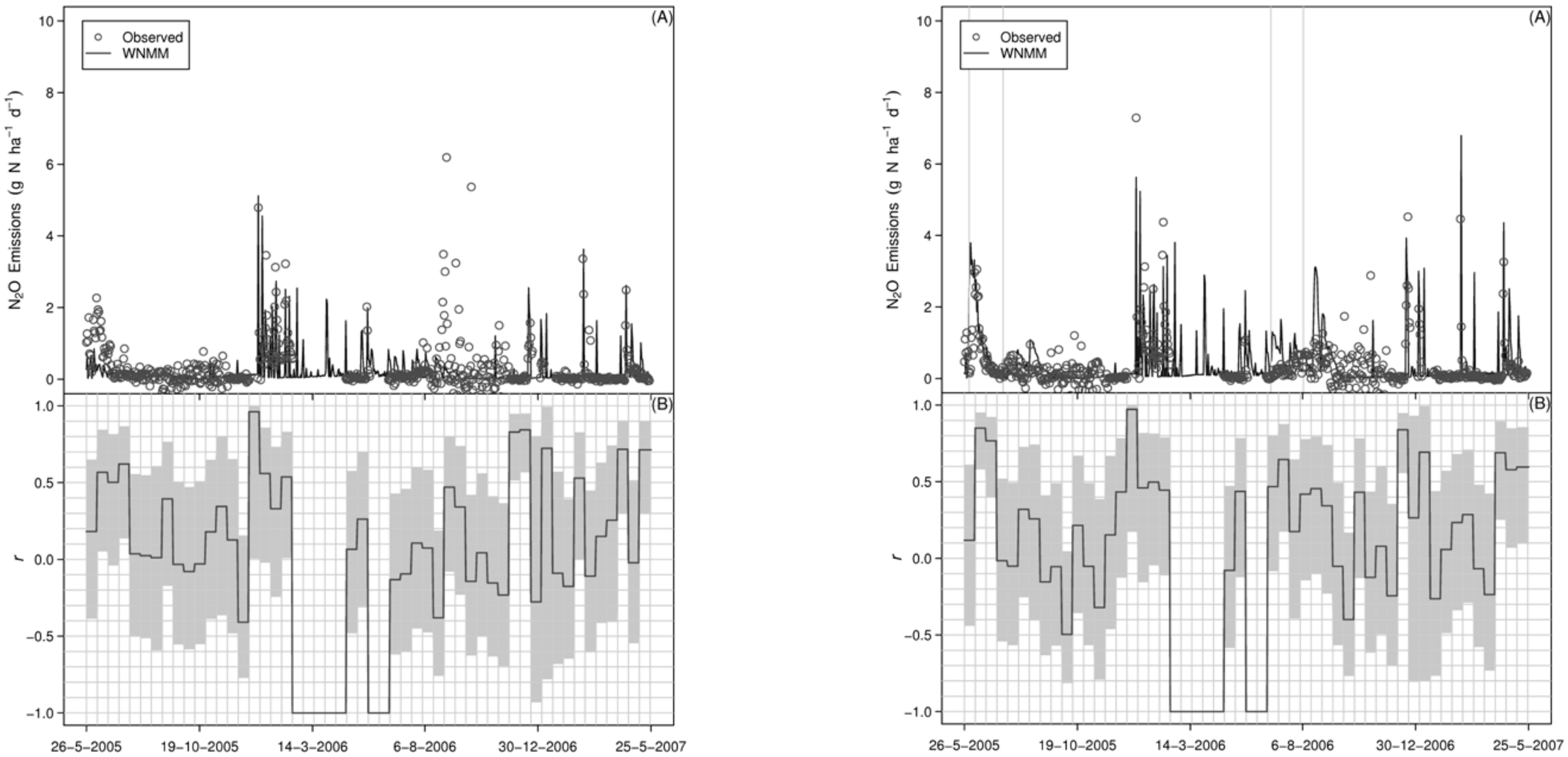


Fig 16. (A): chamber observed (hollow circle) and WNMM simulated (solid line) N_2O emissions and (B): sliding Pearson correlation between chamber observed and WNMM simulated N_2O emissions on a 14-day frequency (black solid line for correlation coefficient and gray area for 95% confidence) from the CK and UREA treatments at Cunderdin, Western Australia from May 2005 to May 2007.

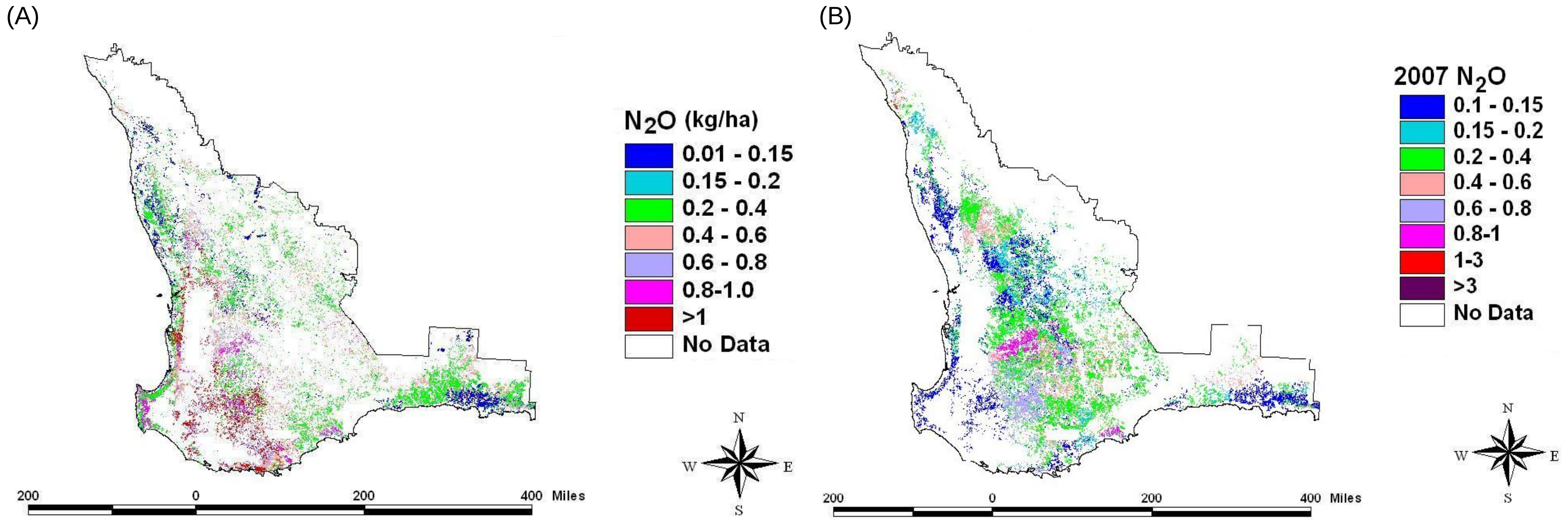


Fig. 17. N_2O emissions in the Wheatbelt region in Western Australia (kg N ha^{-1} $year^{-1}$), predicted by WNMM for (A) 2006 and (B) 2007.

The calibrated and validated WNMM above was applied in the WA wheatbelt region to estimate the regional N_2O emissions. The simulations were carried out from 1 January 2006 to 31 December 2007 with two wheat growing seasons (Fig. 17). The wheat growing areas for 2006 and 2007 were derived from the two MODIS satellite images acquired in Septembers; and the WNMM simulations were carried out only in the wheat-grown areas of Wheatbelt region in Western Australia.

Table 8. Annual N_2O emissions (tones N ha^{-1} $year^{-1}$) in WA Wheat-belt estimated by IPCC, WNMM and DCC methods

Year	IPCC (1.0%)	WNMM (0.32%-0.64%)	DCC (0.3%)	Average Rainfall (mm)
2006	4466	2844	1340	485
2007	5309	1681	1593	382

Table 8 shows the annual total N_2O emissions in WA wheat-belt by the three methods. For 2006, the WNMM estimates the total nitrous oxide emission from the wheat-belt region as 2844 tones N $year^{-1}$, which is only 64% of total emissions calculated by the IPCC method, but double the DCC estimation. For 2007, the WNMM estimation is much smaller than the IPCC estimation (only 32%). However, for this year the prediction by WNMM and DCC are very similar (around 1600 tones N $year^{-1}$). Another significant difference between the results of WNMM and the IPCC and DCC method is that the WNMM N_2O predictions vary with annual rainfalls. However, the IPCC and DCC methods give significantly higher emissions for 2007 reflecting the larger wheat growing area in 2006.

5. Development of a digital camera technique to estimate soil N supply capacity for wheat.

Spectral reflectance of cereal canopies measured with a digital camera correlated closely with N status during the vegetative and early stem elongation phases. Photos of the crops taken at a height of about 1 m, were processed to indicate the canopy cover (CC) on a 0-1 scale representing the proportion of pixels that met a criterion of greenness,

$$(1+L)\frac{Green-Red}{Green+Red+L}>0,$$

where *Green* and *Red* are reflectance values of the green and red bands of the camera's colour detector and *L* is a soil base line. The values of CC measured at one site were closely correlated with values of leaf area index (LAI), above-ground biomass and N content for two wheat cultivars with different growth habits. The functions obtained by calibration were validated on cereal crops at other sites and with different cultivars. The estimate of N content was more precise than the other crop properties. The CC values were closely correlated (R^2 2 >0.86) with the normalized difference vegetation indices (NDVI) from the commercial GreenSeeker® and Yara N-sensor, which detect the red and near infrared reflectances of the crop canopy. The images of canopy cover using a digital camera or specialised sensors provide equivalent information about crop N supply to a crop. However information is needed about crop N demand as well as N supply in order to estimate fertiliser-N requirement. The use of a handheld computer with an inbuilt digital camera offers a method of combining N supply and demand data to estimate fertiliser N requirement.

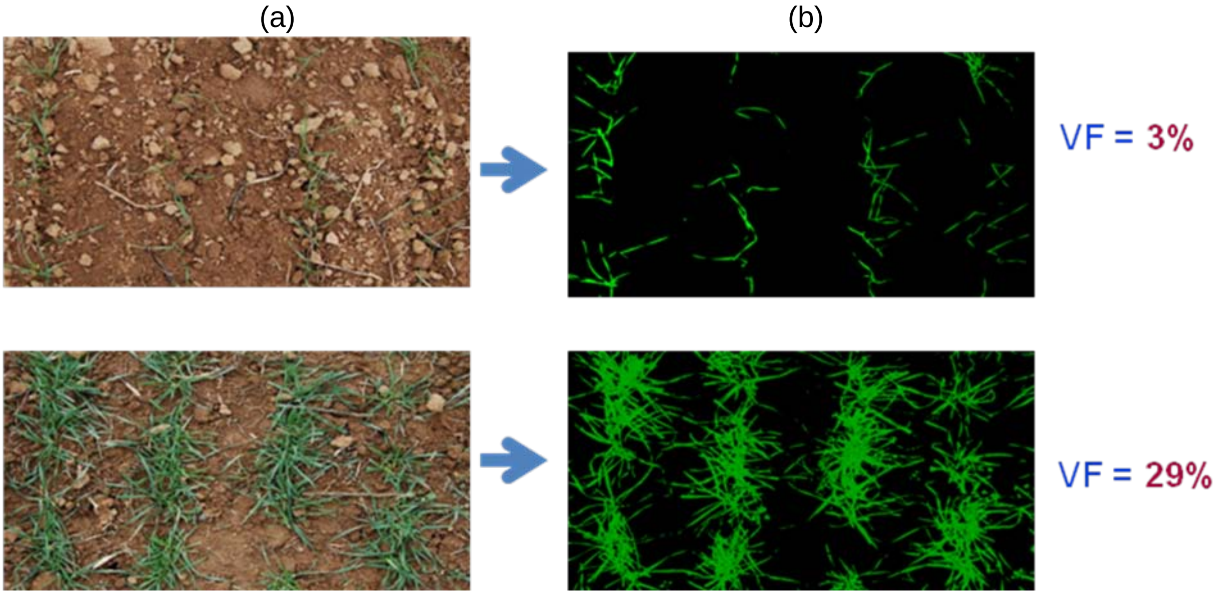


Fig. 18. Images of 0.43 m^2 of a wheat crop captured by a digital camera (a) and the same images processed to calculate the faction of canopy cover (CC).

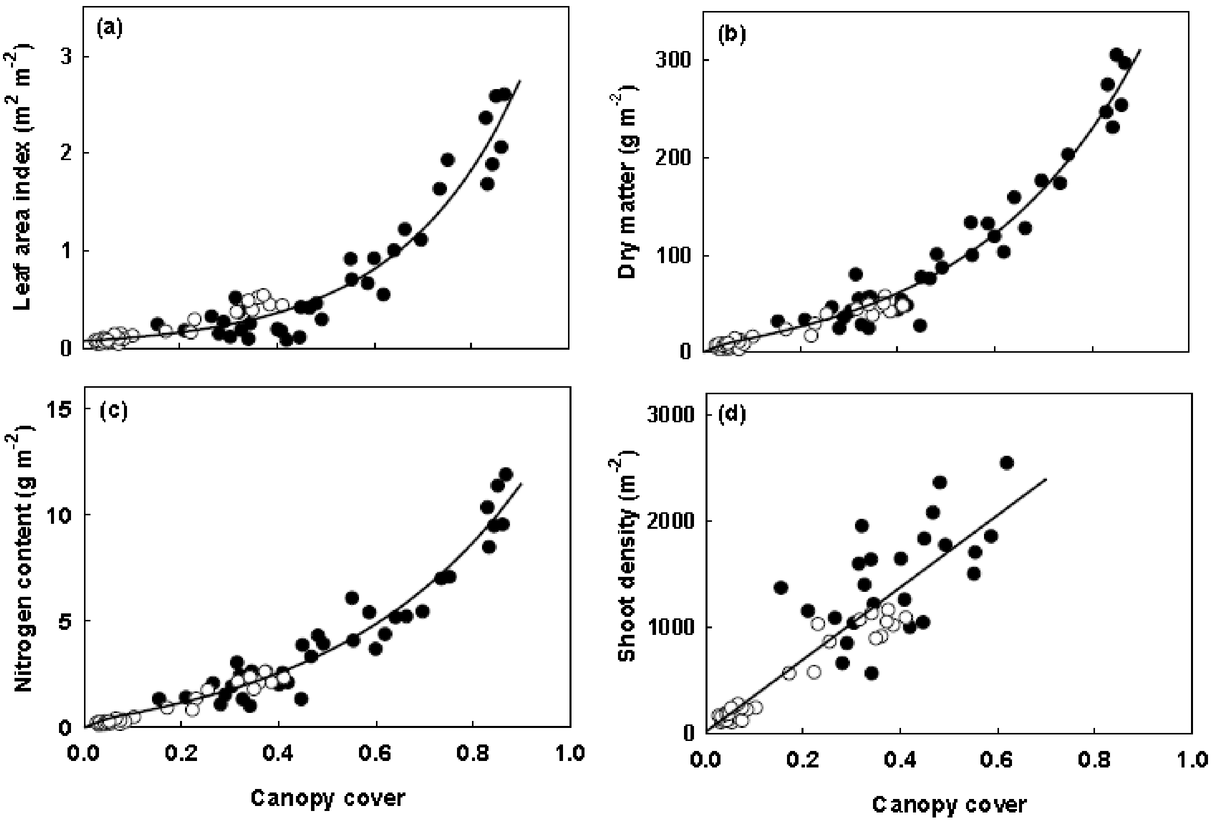


Fig. 19. Calibration of canopy cover against (a) LAI (b) above-ground biomass (c) above ground N content and (d) shoot density for the wheat cultivars Mackellar (●) and Wedgetail (○) growing at Ginninderra.

6. Resource economics and policies

6.1 An integrated economic-biophysical model for water and nitrogen management has been developed for the case study area of Fengqiu County.

An integrated model based on the Driving force–Pressure–State–Impact–Response approach was developed as a tool to assess the effects of policies for improving decision making for water and nitrogen management. An economic model was linked to a process-based biophysical model by a meta-model. Then, a holistic indicator-based impact assessment system was linked to the integrated model to assess policy instruments. The integrated model was applied in the intensive irrigated wheat-maize cropping system, Fengqiu County, North China Plain. It was shown that water pricing is a more effective policy instrument for improving the sustainability of the agro-ecosystem than increasing the price of nitrogen fertilizer. When the water price was raised to 1.0 Yuan/m^3 under a two-tariff system, the sustainability indicators for irrigation water use efficiency was found to increase from 0.37 to 0.77, the groundwater use sustainability indicator increased from 0.05 to 0.60, the nitrate leaching indicator increased from 0.48 to 0.55, while the indicators for farm gross margin, food self-sufficiency, and soil nitrogen balance remained unchanged. The results suggest the modelling approach developed here is very useful for evaluating policy options for complex natural resource management issues.

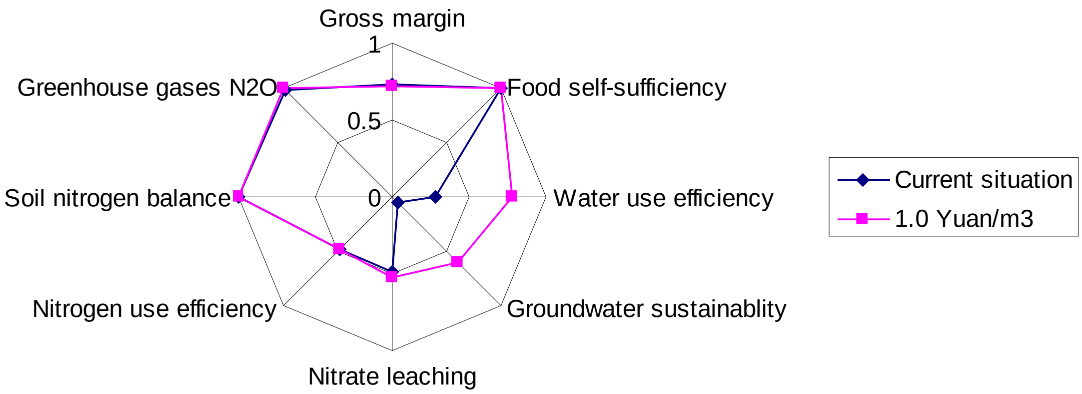
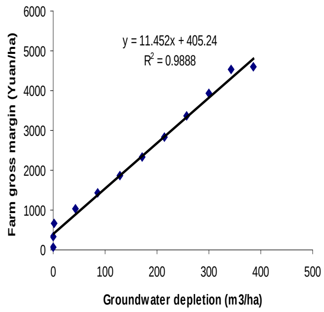


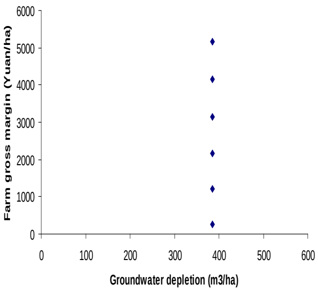
Fig. 20. Changes of each indicator after the water price rises 1.0 Yuan/m^3 in a two-tariff system

6.2 Joint effects of policy incentives on agricultural productivity and agro-ecosystem services have been evaluated for the case study area of Fengqiu County

Agricultural intensification has caused malfunctioning (dis-services) of agro-ecosystems such as land degradation, greenhouse gas emissions, eutrophication of surface water bodies, nitrate contamination of groundwater, and depletion of groundwater reserves. The integrated economic-biophysical model was applied to understand the interdependencies between multiple outputs obtaining from water and nitrogen applications in cropping ecosystems and in order to develop effective policy incentives to promote agricultural sustainability. Through the combinations of the trade-off curves between economic return and individual environmental outcomes derived from the modelling, links between mitigation goals and policy measures were established. This forms the basis for designing more effective and fewer policy incentives. The modelling was applied to the intensive maize and wheat production system of the North China Plain where both water and nitrogen management are critical for crop production and environmental quality. It was found that policy incentives should first target reducing groundwater depletion and then nitrate leaching. Water price should be the chosen policy intervention because of its potential to jointly affect both groundwater depletion and nitrate leaching.



(a) (b) (c)



(d) (e) (f)

Fig. 21. Trade-off curves between groundwater depletion (a), nitrate leaching (b) and N_2O emission (c) with farm gross margin when the water prices is increased from 0.1 Yuan/m^3 to 1.2 Yuan/m^3; between groundwater depletion (d), nitrate leaching (e) and N_2O emission (f) with farm gross margin when the nitrogen fertiliser price is increased from 3.3 Yuan/kg to 11.55 Yuan/kg

6.3 Policies to reduce nitrate leaching in the case study area at Alxa have been identified based on the integrated economic-biophysical modelling developed in Fengqiu County.

The integrated economic-biophysical model developed in Fengqiu County was applied in Alxa to identify policy incentives to reduce nitrate leaching. The modelling results show that there are “win–win” opportunities for improving farm profitability and reducing nitrate leaching. We found that 4471Yuan ha^{-1} of farm gross margin could be obtained with a reduction in nitrate leaching of 373 kg ha^{-1}. Farmers’ lack of knowledge about water and nitrogen in soil, and on crop requirements for water and nitrogen could explain the differences, so that agricultural extension is an appropriate policy incentive for this area. When the economic optimum is obtained reductions in nitrate leaching are not achievable without profit penalties and there is a “trade-off” relationship between farm profitability and groundwater quality protection. The combination of low elasticity of nitrate leaching and large elasticity of farm gross margin against water price increases results in very high costs for reducing nitrate leaching (105.6 Yuan kg^{-1}). It is suggested that if the water price increases were coupled with subsidies for adopting nitrate leaching mitigation practices, environmental gains could come at a lower cost.

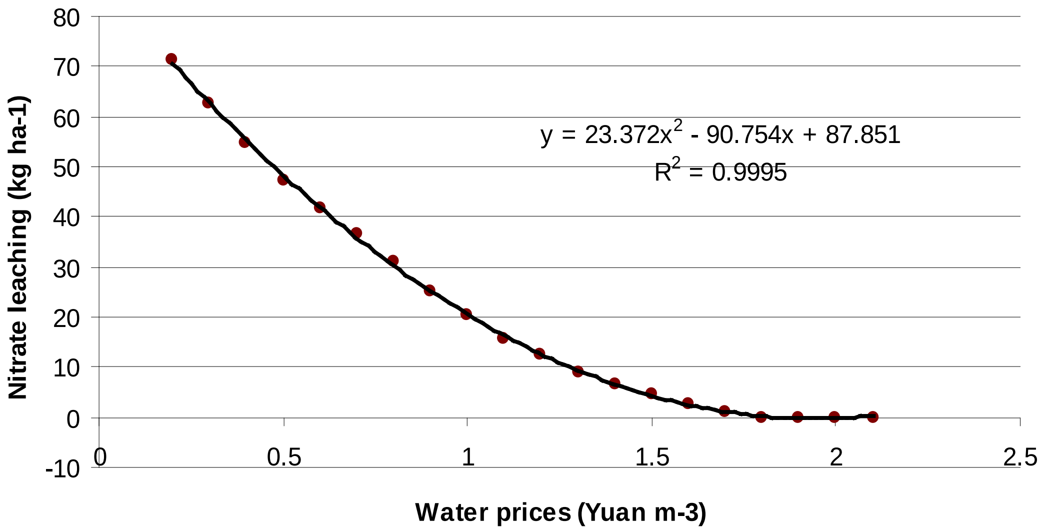


Fig. 22. Effect of water price increases on nitrate leaching

Table 9. Comparison between agronomic optimum, economic optimum and farmer practices

Scenarios	Irrigation (m^3ha^{-1})	Irrigation times	Nitrogen application ($kgha^{-1}$)	Yield ($kgha^{-1}$)	Gross margin ($Yuanha^{-1}$)	Drainage (m^3ha^{-1})	Nitrate leaching ($kgha^{-1}$)
Agronomical optimum	10240	9	0	14538	10002	1233	71.4
Economic optimum	9840	9	0	14489	10030	1141	62.6
Farmer practices	11640	6	320	11606	5558	4814	435.8

6.4 Policy options have been assessed with the approaches of natural resources economics

6.4.1 In Fengqiu

Estimating the willingness-to-pay for groundwater use

The frequency analysis results showed that the mean willingness-to-pay is 1.40 Yuan, with both the median and the mode equal to zero. The mean of willingness-to-pay was estimated to be 1.26 Yuan per household per year from the parametric model, which is roughly similar to the value (of 1.40 Yuan) specified above.

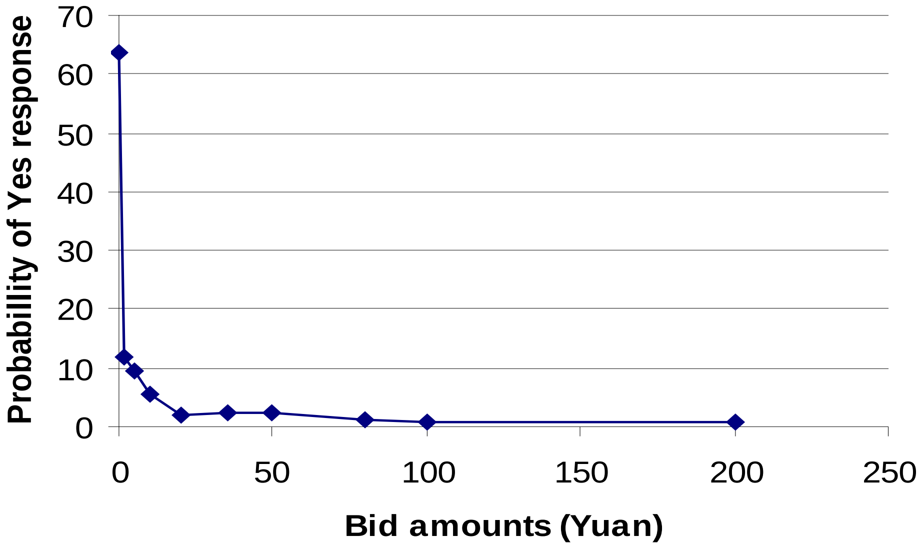


Fig. 23. Distribution of willingness-to-pay

Expanding the willingness-to-pay from the sample to the population as a whole

Annual willingness-to-pay estimation applied at the mean to only the proportion of households that responded to the survey, multiplied by the number of households in the county. Based on the method, the number of households that would be willing-to-pay is 123,455 in the county. The aggregated willingness-to-pay is 155,553.3 Yuan annually for the in-situ non-use value of groundwater subject to the over-exploitation. If it was divided by the annual over-exploitation amount of groundwater in Fengqiu County, the in-situ non use value of groundwater subject to over-exploitation would be 0.014 Yuan/m^3.

6.4.2 In Alxa

The effect of water pricing as a policy measure was simulated by the integrated economic-biophysical model (Figure 23). When the water price is increased to 1.1 Yuan/m^3 both the social and farmer benefit cost ratio would be larger than 1. That means the farming activities are feasible from the perspective of both the society and farmers. However, under this condition, the groundwater recharge cost is still very large at 8556 Yuan/ha (Table 10). Figure 23 also shows that only a small improvement in the social benefit cost ratio results from a substantial decrease in the farmer's benefit cost ratio, demonstrating that water price is very inelastic for the social benefit cost ratio.

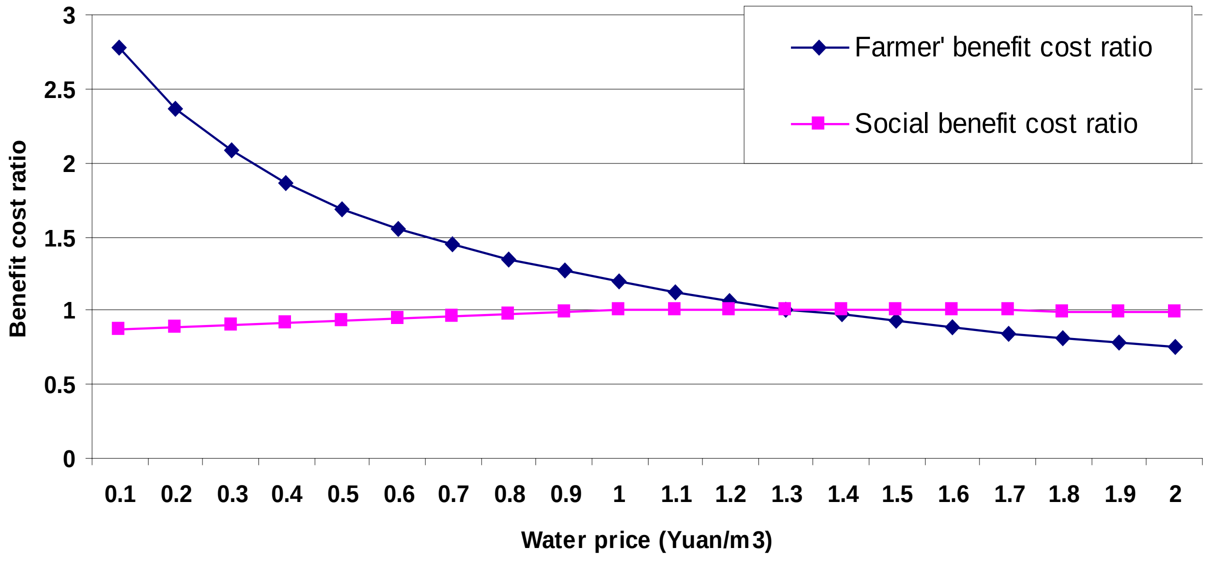


Fig. 23. Effect of water price increases on farmer's benefit cost ratio and social benefit cost ratio

Table 10. Physical measures and monetary measures of environmental externalities when both the social and farmer' benefit cost ratio are larger than 1

Water price (Yuan/ m^3)	Crop yield (kg/ha)	Ground water depletion (mm/ha)	Nitrate leached (kg N/ha)	N_2O emission (kg N/ha)	Recharge ground water cost (Yuan/ha)	Water treatment cost (Yuan/ha)	N_2O mitigation cost (Yuan/ha)	Farmer benefit cost ratio	Social benefit cost ratio
1.1	13689	744	12.3	0.35	8556	416	15.46	1.13	1.002

6.5 Farmers' Response to Potential Policy Changes in Fengqiu

Farmers' responses to increases in water prices are shown in Fig 24. Around 60 per cent of farmers would not respond to increases in the price of irrigation water. Other possible actions in response to water price rises individually account for less than 10 per cent of the total respondents. Thus, it can be suspected that the responsiveness of the quantity of water demand by agriculture to changes in its price is inelastic.

The situation for fertiliser was different to that of water (Fig 25). Approximately 60 per cent of the farmers surveyed were found to be unresponsive to a change in the price of fertiliser. However, most of the remainder suggested that if the price of fertiliser increased, their usage of it would decline.

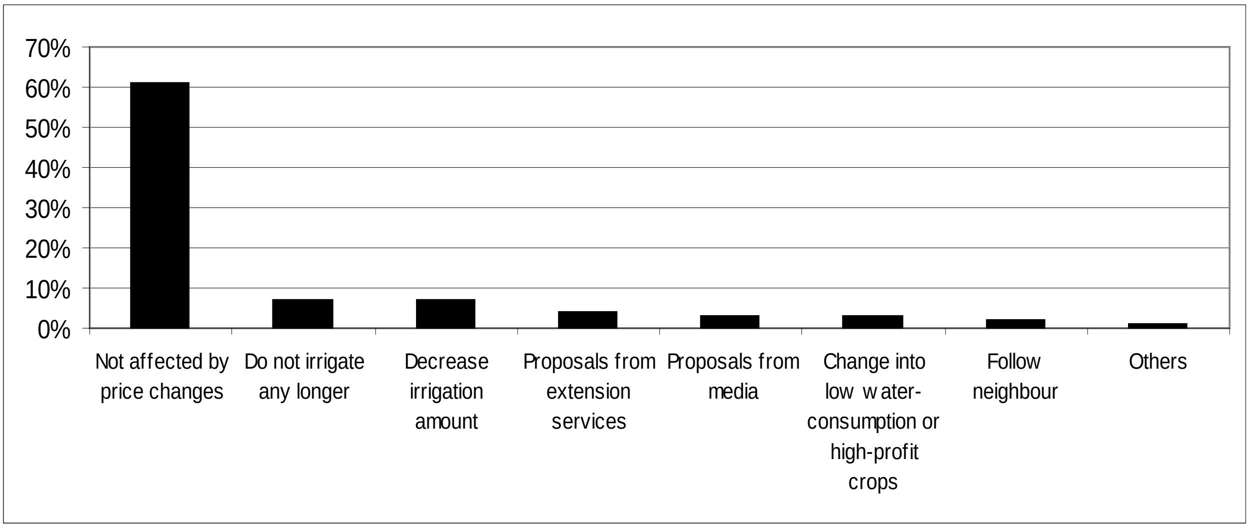


Fig. 24. Farmers' responses to water price increases

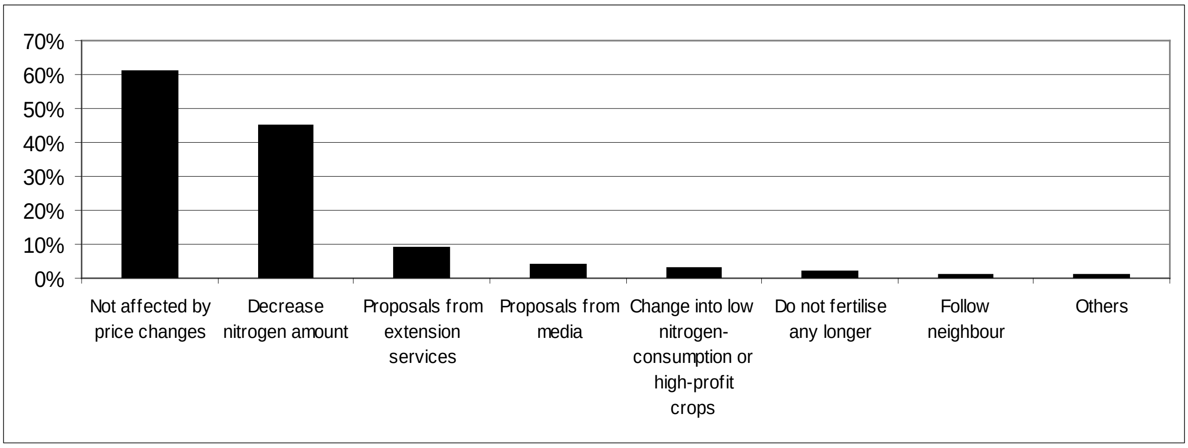


Fig. 25. Farmers' responses to nitrogen price increases

The highest price farmers would pay for water was found to be statistically significant and was positively correlated to off-farm income, farm income and the minimum field size (Table 11). It is understandable that farmers' off-income and farm income may have a positive influence on the highest water price that farmers would accept. The smaller the minimum field size farmers have, the more field blocks they have. Consequently, farmers have to pay more for water and use more labour than those with fewer field blocks, who cultivate the same area. Farm size was found to be negatively correlated to the highest water price farmers would accept to pay for water. The off-farm income, farm size, minimum field size and farm income, altogether, account for approximately 40 per cent of the changes of what farmers are willing to pay for water. The highest water price farmers were willing to accept was found to have little correlation with irrigation costs per hectare. This is further evidence of farmers' lack of awareness of irrigation costs and the inelastic nature of water prices.

Table 11. Factors affecting the highest water and nitrogen prices farmers would accept

	Factors	Coefficient	Std. Error	t-test	Significance	Adjusted R^2
Highest water price farmers could accept	Constant	1.251	0.078	16.090	0.000	0.376
	Off-income	0.433	0.053	8.169	0.000	
	Farm size	-0.965	0.161	-5.977	0.000	
	Minimum field size	0.595	0.253	2.354	0.020	
	Farm income	0.065	0.030	2.190	0.030	
Highest fertiliser price farmers could accept	Constant	1.501	0.101	19.377	0.000	0.246
	Farm size	-0.648	0.122	-5.314	0.000	
	Off-income	0.183	0.041	4.472	0.000	
	Fertiliser cost	-0.460	0.198	-2.321	0.021	

Note: The variables excluded from the regression analysis are not included in the table.

Farm size, off-farm income and fertiliser cost per hectare were found to explain approximately 25 per cent of the highest price farmers would pay for fertiliser (Table 11). Fertiliser cost per hectare and farm size are negatively related to the highest nitrogen price farmers could accept, while income levels are positively correlated to it. It is interesting to note that the cost of fertilisers was found to be significant in determining the highest price farmers are willing to pay for it, whereas a similar relationship was not found with respect to water. This further demonstrates that farmers had a higher sensitivity to fertiliser prices than irrigation costs. The explanation for farm size is similar with that for the highest water price farmers could accept. (*Wei, Y. P., Chen, D., Davidson, B. and White, R. E. and Zhang, J. B. 2006. Is pricing water and taxing fertiliser effective in controlling the inefficient use of water and fertiliser in China? A farmers' perspective. Third World Congress of Environmental and Natural Economics in Kyoto. August, 2006, Tokyo)*

6.6 Farmers' perception and adoption of sustainable agricultural management has been investigated in the case studies at Alxa and Fengiu

In Alxa

A farmer survey has been conducted to reveal farmers' perceptions of environmental degradation and their adoption of improved management practices in this poor and remote desert region. Surveys were made in villages that had been engaged in a large environmental rehabilitation and management project (ALERMP) and those that had not. The survey results (Fig. 26) showed that farmers perceived environmental degradation in terms of increased frequency and severity of sandstorms, movement of sand dunes, deterioration of pasture quality, and declines in groundwater depth and quality. Farmers had low adoption rates for improved management practices, ranging from zero to a maximum of 28.5% for the most adopted practice (Table 12). A Tobit model analysis showed that the education level of farmers, the availability of extension services, and whether farmers had participated in ALERMP were highly significantly correlated with the farmers' perception of degradation. The farmers' adoption of improved management practices was found to be significantly correlated only with whether farmers had participated in ALERMP. This shows that specific extension activities of the type possible in large and well-funded projects are required if farmers are to recognize degradation and adopt improved management practices. The promotion of farmer education and strengthening of extension services are recommended as the best policy strategies for improving environmental management in this region.

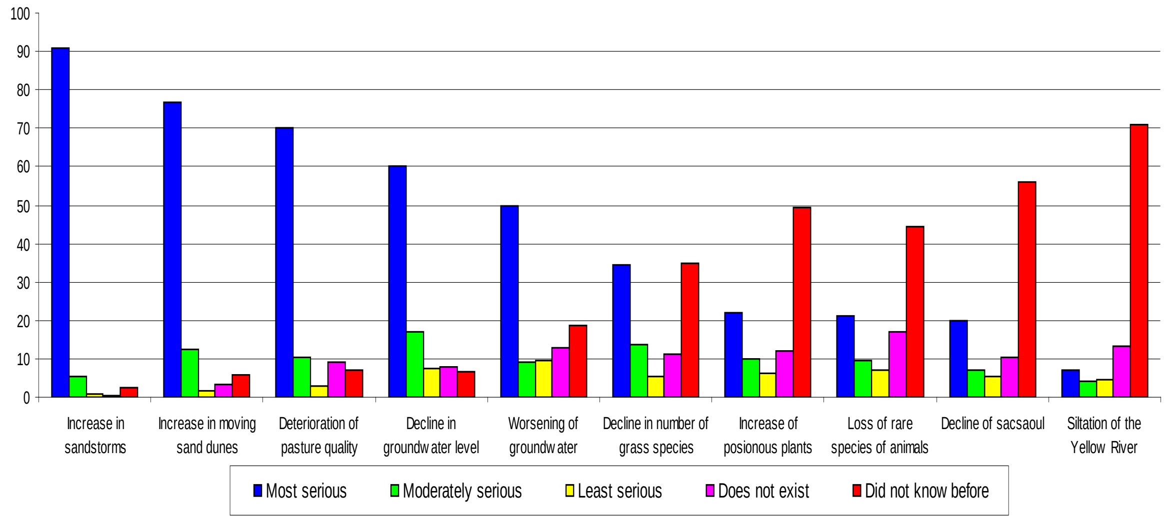


Fig. 26. Farmers' perception of environmental degradation

Table 12. Farmers' adoption of improved land management practices

Improved management practices	Percentage of farmers who adopted improved management practices
Planting of shrubs and cistanche	28.5
Young goat sales	20.7
Use of wind or solar energy	16.9
Canal lining	15.5
Sacsaoul fencing	12.5
Deferred grazing	8.9
No grazing	8.9
Broadcasting grass seeds	5.3
Introduction of improved varieties of crop and livestock	5.3
Rotational grazing	1.8
Stall feeding	1.8

Optimal fertilization practices	0

In Fengqiu

Farmers have a strong perception of farm gross margin (ITGM) and food self-sufficiency (IFS) issues. It can be seen that 93 per cent of farmers rated farm gross margin 'very important', while 98 per cent rated food self-sufficiency as 'very important' (Fig. 27). This is the result of China's long term agricultural policy of food self-sufficiency (Sonntag and Norse, 2005) and the implementation of Household Responsibility System (Chen and Brown, 2001).

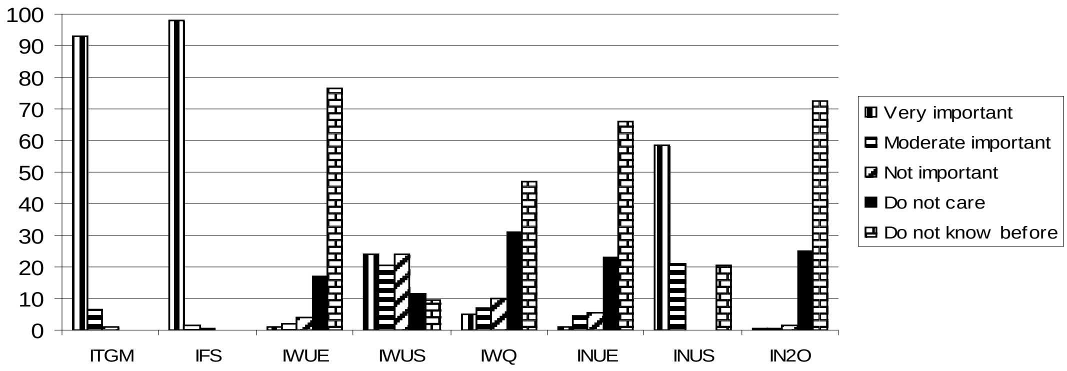


Fig. 27. Farmers' perceptions of each indicator of agricultural sustainability.

Among the indicators that make up the ecological sub-index, nearly 60 per cent of farmers have considerable awareness of nutrient balance (INUS) as 'very important'. This is possibly reflective of most farmers' experiences in trying to maintain long-term cropping practices. It was found that farmers only had a moderate perception of the sustainability of groundwater resources (IWUS), with 42 per cent providing the response 'moderately important to very important' but only 12 per cent rated nitrate leaching (IWQ) as 'moderately important to very important'. Although all the surveyed farmers applied irrigation water and fertilisers, 66 and 76 per cent did not know what was meant by fertiliser use efficiency (INUE) and water use efficiency (IIWUE), respectively. As for greenhouse gas emissions (IN_2O), 73 per cent of farmers said they did not know about the concept and another 25 per cent said they did not care about it.

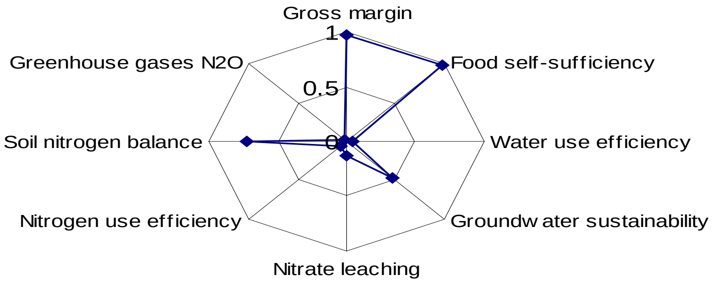


Fig. 28. Indices of farmers' perceptions of each indicator of agricultural sustainability

Factors influencing farmers' perception of the ecological sub-index

The education level of household heads, farm size, off-farm income and extension services were found to be significantly correlated with the ecological sub-index (Table 13). However, the R^2 is only 0.298. A majority of farmers made the same response to the indicator, i.e. 72 per cent of farmers rated ecological soundness 'do not know before' or 'do not care', and to some extent explains why the independent variables have only moderate explanation power in the regression model for ecological soundness. As expected, all the four independent factors have a positive influence on the farmers' perceptions. In other words, farmers' perception of environmental indicators will increase with increasing education level of household head, farm size and off-farm income and increasing times of extension times.

Table 13. Regression results for farmers' perception of ecological sub-index

Factors	Standardized coefficient Beta	*T*	Significance
(Constant)		-3.629	0.000
Education level	0.385	5.892	0.000
Farm size	0.220	3.380	0.001
Off-farm income	0.219	3.340	0.001
Extension services	0.204	2.989	0.001
R^2 =0.298			

8 Impacts

8.1 Scientific impacts – now and in 5 years

The project established the first Australian open path (laser and FTIR) micro-meteorological technique for quantifying GHG emissions from intensive agricultural systems. The newly established open-path (laser and FTIR)-micrometrological techniques for measuring N gaseous fluxes and greenhouse gas (GHG) emissions have been adopted by researchers atf DPI Victoria and the Institute of Soil Science of the Chinese Academy of Sciences.

The automatic chamber system (CAS) for continuous GHGs (N_2O, CO_2, CH_4) and NOx measurements have been adopted by the researchers in the DSE Victoria.

We also developed a world acclaimed spatially referenced and process based decision support system known as the Water and Nitrogen Management Model (WNMM) for improved irrigation and fertilizer management for agricultural productivity and environmental quality. The WNMM model is used by all DCC (Department of Climate Change) sponsored projects in Australia to simulate N_2O emissions and will be used in the new GRDC/DAFF's Future Farming-Climate Challenge program for the whole of system modelling

The WNMM model and decision support system have been adopted by the scientists in Stanford University for their long term experiment in Mexico, and by the Institute of Soil Science, Chinese Academy of Sciences, Chinese Agricultural Academy of Sciences, China Agricultural University, Shanxi Agricultural University, DPI Victoria and Queensland, South Korea and Italy. More than 15 SCI publications have been generated.

The ACIAR project provided strong leverage to obtain the following funding: DAFF-GRDC-ARC, ($650k); Incitec-Pivot, additional Enhanced efficiency fertilisers ($600k); DAFF-MLA, GHG emissions and manure management from cattle feedlot ($1.3m); CAS, Automatic chamber systems ($500k), Shanxi Provincial Government ($250k) and two IAEA projects (90,000 euro) on improving water use efficiency by reducing the evapotranspiration losses with CAS and China Agricultural University.

40 SCI papers have been published, mostly in the top tier journals of their fields. More than 30 presentations were given in the national and international workshops and conferences, including many invited keynote speeches, such as the 19th World Soil Congress, and 3rd and 4th International Soil N Congresses.

We demonstrated that ‘efficiency enhanced fertilizers’ (urease and nitrification inhibitors) effectively mitigated greenhouse gas (N_2O) emissions. Using the nitrification inhibitor DMPP, N_2O emissions can be reduced by up to 65% (Chen et al, 2010) and NH_3 losses by 80% (Turner et al, 2010).

We also developed a digital camera technique to estimate soil N supply capacity to wheat (Li et al, 2010).

Using a combination of the continuous auto-chamber method and a process based model, a revised Australian N_2O emission factor for rain-fed wheat of 0.1% and for pasture of 0.4%, rather than the IPCC default value of 1% of applied N, was obtained (Li et al, 2008; Chen et al, 2010).

Simulation of the total N_2O emissions of the WA wheat belt using WNMM has shown IPCC overestimates N_2O emission by a factor of 3.

Integration of economic modelling with WNMM has demonstrated that there is little impact on Australian farmers’ N fertiliser decision making by including N_2O emissions in the carbon emissions trading scheme (Farquharson et al, 2010).

8.2 Capacity impacts – now and in 5 years

Eleven young scientists have been trained to conduct complex laboratory and field experiments, survey and multidisciplinary research in China as this project integrates water, soil, plant nutrients, GHG, agronomy, economics, policy and modelling.

A significant capacity building impact is that more people have been trained in modelling thorough this project. Two WNMM modelling workshops in Australian and one in China have been conducted. More than 40 people have been trained to use WNMM, and two of them are capable of modifying the source codes.

Seven postgraduate students enrolled in Chinese institutions, CAU, CAAS, SAAS and CAS and three in UM have been involved in the project. Three postdoctoral research fellows in UM were also trained in this project.

Advanced field soil moisture and eddy covariance equipment have been established in Shanxi and two scientists have been trained to operate them. A state-of-the-art automated chamber system for GHG measurement has been built and fully functioning.

A new open path FTIR system has been used in Australia.

8.3 Community impacts – now and in 5 years

The project increased the awareness of farmers and local government officers that N fertilisers have been excessively used, and that this not only results in financial loss, but also increased detrimental impacts on the environment due to NO_3-leaching and N_2O emissions.

There has been a strengthening of collaboration between Chinese organisations working on the project, with significant, and hopefully ongoing, sharing of knowledge, experience and resources.

Health benefits will accrue from a decreased rate of accumulation of NO_3-N in groundwater attributed to the lower N application rate and higher use efficiency. The WHO recommended upper limit for nitrate in drinking water is 10 mg NO_3-N per L, which is widely and substantially exceeded at present in China. Through improved management practices, particularly using less N fertiliser, the project is resulting in reduced accumulation of nitrate in groundwater.

The project contributed better understanding of the dynamics of the soil-water-plant-atmosphere and human interactions that derive from the social, economic and biological research. This information enhanced the understanding of our Australian agricultural environment, as similar detailed socioeconomic-agronomic models are applied across wider areas.

8.3.1 Economic impacts

Significant amounts of N fertiliser, 30 to 40 kg N/ha (Yongji), 110 to 150 kg N/ha (Yuci) and 140 to 280 Kg N/ha (Hongtong), and irrigation water, 10 to 25%, can be saved without reducing the crop yield. Considerable numbers of farmers have already adopted the optimised management practices used in the experimental field. The net financial saving is $25 to $200/ha. The financial saving associated with the irrigation water saving is modest under current water charging conditions. The potential economic benefit of the saved water was not calculated.

Economic impacts from the use of Sulfur Coated Urea (SCU) were significant, using 42% less N but producing 8% higher maize yield and 72% lower N_2O emissions.

At the Yuci site, during the experiment period most of the farmers from the Yanwu village visited the experiment field and were made aware their practices were wasteful. About 10% (28 ha), 30% (72 ha) and 50%(140 ha) of farmers have adopted the optimum treatment management practices in 2008 2009 and 2010, respectively, with estimated fertilizer savings of 8400, 25,200 and 42,000 RMB in the three years.

In 2009 the CAAS team recommended dissemination of their outstanding results of the new fertiliser (SCU) to the Shanxi province government. The total use (purchased) in 2010 of SCU by farmers is 3.5×10^6 kg in maize fields. The new practice will increase farmers' incomes by 17.5 million RMB, and decrease N_2O emissions by 5,700 kg N in Shanxi province.

8.3.2 Social impacts

The more efficient use of N fertilizer and irrigation water is essential for sustainable agricultural production and will contribute to national food security. Potential improved financial circumstances of farmers that accrue from increased profits due to the reduced wastage of N fertilisers can be expected to contribute to the social security of small-scale farmers in the study areas.

8.3.3 Environmental impacts

One of the main purposes of the project is to reduce the detrimental impact of intensive agriculture. In China excessive use of fertilisers is the main cause of non-point source pollution, which considerably contributes to the widespread and severe groundwater and surface water pollution (such as Lake Tai). Surface broadcast of urea immediately followed by sprinkler irrigation almost eliminated the potentially large ammonia volatilisation loss from this alkaline soil. The ammonia lost to the atmosphere can be transported and deposited to other agro ecosystems resulting in enhanced indirect greenhouse gas (N_2O) emission, eutrophication and soil acidification. The reduced N fertiliser application and irrigation (not applying excessive amount) also reduced GHG N_2O emissions and nitrate contamination of ground water. The development of spatially referenced and process based modelling of N_2O emissions significantly contributed to the reduction of uncertainty in the estimation of N_2O in both Australia and China.

8.4 Communication and dissemination activities

In China, policy makers, extension officers and farmers are all considered as potential users of the research outputs. Because the rural extension systems are poorly resourced in parts of China, government officers can be influential and information dissemination is far more effective if they can be convinced to support and adopt the recommendations.

Professor Chen Mingchang's team in SAAS held regularly meetings with local bureaux of agriculture and water resources. Farmers' field days were conducted by Ms Yang Zhiping and Zhang Jingjie at Yongji and Hongtong County, Yongji and Taiyuan.

In Shanxi, there is a unique organisation, Shanxi Agricultural Comprehensive Development Office (SACDO), which provides funding for the implementation of new technology and practices. Mr Zhao Jinshen, Director of SACDO, is a member of the project advisory committee. SACDO provided 300,000 RMB (A$50,000) in March 2007 to assist the project to implement the research outcomes by establishing demonstration farms in Yongji and Hongtong counties through its county branches.

The project has also been promoted in the following programs:

1. Chinese leader, Prof Chen Mingchang, Vice President of Shanxi Agricultural Academy of Sciences, is also the advisor to Shanxi Provincial government on agriculture.

2. Joint irrigation program by FAO, Shanxi Water Department and Australian-China Water Centre (Deli Chen is the Deputy Director), - a special workshop was held in July 2007 in Shanxi.

3. High level meetings with provincial Departments of Science and Technology and Water Resources.

4. Special seminars and conference presentations: In particular, the outcome and decision support framework was presented to the 4th International N Conference in Brazil:

Chen D, Wei YP and Davidson B (2009) Joint effects of policy incentives on agricultural productivity and water ecosystem services. International Symposium on Science, Technology and Policy for Water Pollution Control at Watershed Scale. 10-12 April 2009, Hangzhou, China. (Invited keynote speech).

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Chen D, Li Y and Barton L (2008) Simulating the Impact of Climatic Variability on N2O Emissions from a Rain-Fed Wheat-Cropped Soil in a Semi-Arid Climate. 2008 Joint Annual Meeting, GAS-ASA-CAS-CSSA, 5-9 October 2008 Houston TX.

5. Mass media.

The project has been reported three times by Shanxi provincial TV, twice in Shanxi Daily.

The GIS Decision Support system has been reported by the China Science Daily as a special article on the front page "An easy to use GIS Decision Support Tool---Saves farmers 20% of fertilizer and water", Chinese Science Daily, 21 August 2008;

Animals and us, science tackles the issues, Volume 1, No 11, 6–20 August 2007, The University of Melbourne Voice;

Animal diets get the third degree, a key article in the Science Section, Canberra Times, 19 November 2007;

A skeptic of the septic, a key article in the Education Section, The Age, 19 November 2007;

Significant achievements of the ACIAR sponsored Australia-China Collaborative Research in improving Water and Fertilizer efficiency, Shanxi Daily, 20 July 2007;

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9 Conclusions and recommendations

9.1 Conclusions

1. Excessive N fertilisers applied in the intensive irrigated agricultural regions in China, have contributed to high concentration of nitrate in groundwater (Alxa) and high N_2O emissions.
2. There is large potential to improve the efficiency of the use of N fertilisers. The multiple years field experiments demonstrated that 30 to 280 kgN/ha/year N fertiliser and 20 to 30% irrigation can saved without affecting crop yields. The net financial saving is $25 to $200/ha.
3. The enhanced efficiency fertilisers (EEF) consisting of controlled release, nitrification and urease inhibitors have been shown to be very promising in reducing N losses in both China and Australia. In particular, the Chinese made Sulfur Coated Urea (SCU), was shown to be very effective - using 42% less N, but with 8% higher maize yields and 72% less N_2O emissions.
4. The open path (laser and FTIR) - micro-meteorological techniques are effective in quantifying GHG emission from intensive agricultural systems.
5. Using a combination of the continuous auto-chamber method and a process-based model, revised Australian N_2O emission factors for rain-fed wheat of 0.1% and 0.4% for pasture, rather than the IPCC default value of 1% of applied N, were established.
6. We developed a world acclaimed spatially referenced decision support system (DSS) for improved irrigation and fertilizer management for agricultural productivity and environmental quality.
7. An integrated economic-biophysical model for water and nitrogen management proved very useful for evaluating policy options for complex natural resource management issues. The policy incentives should first target reducing groundwater depletion and then nitrate leaching.
8. Water price should be the chosen policy intervention because of its potential to jointly affect both groundwater depletion and nitrate leaching.

9.2 Recommendations

1. There is large potential to improve the efficiency of the use of N fertilisers and irrigation water with net financial savings in the range of $25 to $200/ha. “Win-win” outcomes in terms of increased farmers’ incomes and environmental improvements are possible, and should be promoted at all levels in the areas studies so far (NCP, IMAR oases, and Shanxi.
2. The enhanced efficiency fertilisers (EEF) were shown to be very promising for improving efficiency of N fertiliser, reducing the environment impact and increasing farmers’ profits. It is also a potential technique to mitigate GHG emissions from agriculture. Their wider adoption in Shanxi should be promoted.
3. It is still a challenge to accurately extrapolate point measurements and outcomes to regional scale due to a lack of accurate and real time spatial input data for modelling, and spatial monitoring data for the validation. Soil sampling surveys are costly and not feasible for real time monitoring at large scale. The simple digital camera method to estimate soil N supply has a potential to be integrated with DSS. The high resolution multiple spectrum satellite imagine which is capable detecting crop N status (measuring chlorophyll) has potential to be linked to the GIS based

model and DSS to provide real time recommendation of fertiliser application and irrigation.

4. It is imperative to develop realistic policy options to assist the implementation of improved management practices. Financial incentives or an environmental pollution tax might be option, but awareness and perception are equally important. The new adaptive social leaning approach appears to be an effective approach.

The questions raised in this study relate to the sustainability of the agro-ecosystem on the NCP. It was found that the NCP suffers from both the over exploitation of ground water and excessive use of nitrogen fertilizers. While one (water) is the problem of a public good and the other (nitrogen) is a negative production induced externality, both are interrelated, as they originate from the actions and practices of farmers. These practices, it was argued, are derived from their perceptions of the problem and their objectives in cultivating the agro-ecosystem. In addition, the biophysical nature of the system means that one (water) is the transmitter of the pollutant (nitrogen). Finally, there is a spatial dimension to this problem, with not only the issue of non-point source pollution, but it also occurring over a massive area involving a vast number of producers. Policy makers face the problem of trying to trying to satisfy two seemingly irreconcilable desires: improving the environment and maintaining the welfare of farmers. Given the size and the nature of non-point source pollution, it is recognised that policy makers really could only consider a Pigouvian approach to the problem. That means imposing taxes on water and nitrogen use, which would result in increasing their prices. In this study an effort has been made to characterise, analyse and resolve this problem.

5. Policy Ramifications.

It was concluded that besides an increase in water prices, a set of other policy measures should be considered. They include improving the extension services, changing the cropping pattern, increasing farmers' farm and off-farm incomes and enhancing the groundwater management. It is hoped that these measures will directly improve the agricultural sustainability in the study area.

One interesting outcome is that the results of the farmers' survey tended to run counter to those derived from the modelling exercise. Values obtained by contingent valuation were insignificant when compared to the cost of protecting and restoring the groundwater, which is several hundreds times higher than the estimated willingness to pay. While some discrepancy was expected, the extent of this difference was unexpected. Thus, it would appear that the contingent valuation method does not provide an adequate estimate of the in-situ value of groundwater on the North China Plain. One reason for this result may be the very low income and education levels of respondents in this area. An integrated economic-ecological modelling technique is recommended as an alternative option to the contingent valuation method in this case.

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