Australian Government
Australian Centre for
International Agricultural Research

Project final report

project	**Improving the productivity and sustainability of rainfed farming systems for the western loess plateau of Gansu province, China**
date published	May 2008
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project number	CIM/1999/094
ISBN	978 1 921434 72 3
published by	ACIAR GPO Box 1571 Canberra ACT 2601 Australia

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1 Acknowledgments

We wish to acknowledge the following organisations for their generous support:

- Australian Centre for International Agricultural Research
- Crawford Fund
- Australian Youth Ambassador for Development scheme

In-kind support was provided by our host organisations:

- The University of Adelaide
- Lanzhou University
- Gansu Agricultural University
- NSW Department of Primary Industries
- CSIRO Sustainable Ecosystems

2 Executive summary

Key outputs and impacts are summarised under the headings of the four objectives:

Develop conservation tillage cropping systems

Project research has established that a range of crops can be successfully grown without tillage and with stubble retention at Dingxi and Xifeng. Prior to the project commencing there was a strong belief that tillage was essential for succesful crop growth in the target area. At Dingxi, the drier of the two sites with a lengthy fallow period, crop yields were higher under conservation agriculture (no-tillage plus retention of crop residues) compared to traditional crop practice (several cultivations plus complete removal of crop residues), most likely due to improved water soil water conditions resulting from reduced evaporation and/or increased infiltration. At Xifeng, a higher rainfall site with no fallow period, there was no consistent difference between crop yields under conservation agriculture and traditional practice. Given the lower input costs of conservation agriculture, mainly due to labour savings asociated with not cultivating the soil, the result in Xifeng is still attractive to local farmers.

While these results are very promising, a range of issues need to be addressed if conservation agriculture is to adopted on a wide scale in mixed crop – livestock farming systems of the Loess Plateau. These issues include the high opportunity cost of crop residues for livestock feed and as a source of energy for heating and cooking, access to machinery such as no-till seeders suited for animal draught, and farmer education in integrated weed management including herbicides. All of this in the context of semi-subsistence, resource-poor farmers.

Develop legume – cereal crop rotations

Field experiments included evaluation of both crop (field pea at Dingxi and soybean at Xifeng) and forage (lucerne at both sites) legumes grown in rotation with cereals. Field pea appears well adapted to the dry conditions at Dingxi, often producing grain yields close to those of spring wheat. At Xifeng, short-season soybean was grown to fit in with the three crops in two year rotation (soybean – maize – winter wheat) grown at this site and yields of soybean were often low due to the short growing season and the critical importance of sowing time and plant establishment. At both Dingxi and Xifeng, biological nitrogen fixation was relatively low due to the high levels of soil inorganic nitrogen resulting from high fertiliser nitrogen use. There appears to be considerable opportunity to

reduce fertiliser nitrogen inputs on legumes and also on cereals, particularly at the low-rainfall site.

Lucerne is well-adapted to the soils and climate of the region and produces a large amount of high-quality forage (10-15 t DM/ha/year at Xifeng). Lucerne is very effective in maintaining soil water close to the lower limit of plant available water and consequently deep drainage and runoff is minimised under lucerne. Biological nitrogen fixation under lucerne appeared to provide adequate soil nitrogen for two consecutive wheat crops, although by the time of the third crop, additional fertiliser nitrogen was needed to achieve the water-limited grain yield. The transition from lucerne to wheat needs to be managed carefully in order to minimise the chance of subsequent grain yield penalties related to dry soil profiles following lucerne.

Despite the promising potential, use of lucerne on farms remains low primarily due to the competiing demand for farm land to grow subsistence and cash crops. In addition, yields of lucerne on farmers’ fields remains much lower than research station yields. There is an urgent need for an effective campaign to work with farmers to improve basic lucerne agronomy (establishment, phosphorus fertiliser, timing of removal) lucerne utilisation (harvest scheduling, forage conservation, storage) and optimum use of lucerne as a component in livestock rations.

Analysis of current and future farming systems with the aid of system simulation models

In order to analyse current and future farming systems it was first necessary to collate data on climate, soil, crops, and management practices. Daily climate data (rainfall, maximum temperature, minimum temperature, radiation) was collated for Dingxi (1970-2006) and Xifeng (1961-2006). Automatic weather stations were installed at the main experimental sites. Plant available water capacity was determined for the two main soil types (Huangmian at Dingxi and Heilu at Xifeng) by measuring the drained upper limit and the crop lower limit for the range of crops and forages of interest. Spring wheat and field peas at Dingxi extracted soil water almost down to 2m, winter wheat at Xifeng extracted soil water down to 3m, and lucerne extracted water to much greater depths (lucerne roots were observed at 6m in Xifeng). Crop phenology observations were used to calibrate model parameters controlling time to flowering and maturity. Finally, farmer crop husbandry practices were surveyed to provide management options for sowing time, seeding rate, fertiliser type and rate, crop residue management, and tillage. In addition to providing the basis for simulation of local farming systems, this data was also invaluable for interpreting results from the field experimental program.

Using the above data, the APSIM model was able to capture most of the observed variability in soil water dynamics, development, growth and grain yield of a range of crops (winter wheat, spring wheat, maize, field peas, soybean) and forage (lucerne). Project research contributed to the development of the field pea module, previously unavailable in the APSIM suite of crops. A special challenge, not normally encountered in Australia, was simulating the winter dormancy of winter wheat and lucerne. Testing the performance of the model against observations provided many insights into the experimental dataset and assisted communication between project scientists. The application of the model to analyse key issues such as climate variability, water balance, productivity, and mangement options is ongoing.

Building the capacity of Chinese staff in all research areas listed above

In addition to formal training workshops, the main strategy for building research capacity of our Chinese colleagues was through ‘learning by doing’. Project staff gained experience in experimental design, conduct of field experiments, data management, analysis and interpretation of data, presentation and communication of results and publication. At the time of preparing this Final Report, several manuscripts have been submitted, or are close to submission, to international scientific journals.

Tangible evidence of improved capacity include career development for several key project staff and awarding of competitive research grants to Chinese partner institutions.

3 Background

In the Loess Plateau of northwest China, poor endowment of natural resources and high population pressure, combined with unsustainable agricultural practices, have resulted in widespread poverty and degradation of land and water resources. Severe erosion of topsoil is widespread, resulting in loss and degradation of arable land and heavy siltation of the river systems.

The dominant cropping system over much of the Loess Plateau is a winter wheat monoculture, which incorporates a three month fallow during the rainy summer season. On average, over 60% of annual rainfall is received in the three months, July to September. In the drier and colder cropping areas, such as Dingxi, winter wheat is replaced by spring wheat. The soil is usually cultivated two or three times prior to sowing the crop in September. At harvest, nearly all of the above ground shoot material is removed from the field. The combination of fallow-wheat monoculture with excessive cultivation and stubble removal has left the soil depleted in soil organic matter and exposed to erosion.

This situation is widespread over the Loess Plateau, but the problem is more acute in the western province of Gansu, where rural poverty is widespread and agricultural mechanisation is less developed than neighbouring provinces to the east.

The project addresses high priority research in Gansu and Australia. In southern Australia, conservation tillage is gradually gaining more acceptance among farmers, but many farmers complain of poor vigour of crops established under conservation tillage. One contributing factor to poor vigour is the changed spectrum of disease organisms that can develop in response to changes in tillage and stubble management. The NSW Agriculture component will focus on developing management systems to overcome disease constraints associated with conservation tillage. Legumes play an accepted role in Australian cropping systems, but the search for optimal productivity and sustainability has renewed interest in gaining a more detailed understanding of soil water and soil nitrogen dynamics in response to legume – cereal sequences. Developments in system simulation provide a new and powerful tool for analysis and interpretation of rotation experiments and rotations practised on-farm.

Accelerating development in the western region of China has been given the highest priority by the Chinese government. This priority recognises that the western region is relatively less developed compared with the eastern and coastal regions of China, and that the majority of people living under poverty conditions in China are located here. Among the estimated 14 million people living in poverty in China, about 11 million are located in Gansu (about 40% of the total population of Gansu).

The western region of China is also one of the most ecologically fragile regions of the country. Severe erosion is characteristic of the Loess Plateau and produces the vast quantity of sediment carried by the Yellow River. Effectively addressing the soil fertility, erosion and siltation problems are high priorities for the central and Gansu governments.

This project addresses existing research priorities identified by GGERI and Gansu Agricultural University (GAU). In addition, the project objectives are closely aligned to

ACIAR's main strategy in China, which has a strong emphasis on increasing productivity and sustainability of agricultural systems in NW China.

In response to widespread recognition of the problems of land and water resource degradation on the Loess Plateau, Chinese authorities have implemented major policy changes. A high priority within current Government policy is to retire agricultural land to either forestry or permanent grassland. This policy will benefit protection of land and water resources, but does have major social and economic costs associated with loss of rural communities that have traditionally relied on cropping. The Australian perspective is that sustainable cropping can continue in some land systems with appropriate agronomic practices such as stubble retention, direct drilling, and diverse pasture – crop rotations. This policy can deliver protection of land and water resources and increase productivity and the well-being of rural communities.

4 Objectives

The overall aim of the project was to increase farm productivity and profitability while at the same time improving use of natural resources and reducing soil erosion.

The project had four related objectives:

- develop conservation tillage cropping systems
- develop legume – cereal crop rotations
- analysis of current and proposed new farming systems with the aid of system simulation models
- building the capacity of Chinese staff in all research areas listed above.

5 Methodology

5.1 General approach

This project involved both research and capacity building activities. There were also some demonstration activity associated with on-farm experimental sites. The capacity building component included improving field experimental methodology, implementing participatory action research (PAR) approaches to farming systems research, and training scientists in the use of agricultural system simulation computer software.

The research component is necessary to enable measurement of treatment effects under local conditions, demonstration of results to other researchers, advisers, and farmers, and for parameterisation of simulation modules. This research was conducted on both government experiment stations and in farmers' fields.

The research was conducted in two contrasting and complementary locations. Dingxi County represents a drier climate (400 mm average annual rainfall) with spring wheat as the dominant crop. Higher average annual rainfall (550 mm) is received in Xifeng County where, at the commencement of the project in 2000, winter wheat accounted for 80% of the arable land area. In addition to average rainfall, the two locations differ in common crop rotations practised and general level of income. Results from these two locations will be representative for a large proportion of the 45 million hectares covered by the Loess Plateau. At Xifeng, the research was located on the relatively flat tableland landscape, whereas at Dingxi the research was located in an undulating hill landscape. In both landscapes traditional farm practice involved integration of crop and livestock production.

Further description of the climate, soils and farming systems of the study regions can be found in Appendix 11.1 (Nolan, S, Unkovich, MJ, Shen,Y, Li, L and Bellotti, W.D. (2008) Farming systems of the Loess Plateau, Gansu Province, China. *Agriculture, Ecosystems and Environment*. (Available online from November 2007).

The conservation tillage component of this project involved the establishment of medium-term, factorial experiments at Dingxi and Xifeng. At both sites, tillage (conventional or no-tillage) was factorially combined with stubble (stubble removed or stubble retained) to allow the separate effects of tillage and stubble management to be measured and interpreted. Full details of the experimental methodology can be found in Appendix 11.2 (Huang, GB, Zhang, RZ, Li, GD, Li, LL, Chan, KY, Heenan, DP, Chen, W, Unkovich, MJ, Robertson, MJ, Cullis, BR, Bellotti, WD. (Submitted) Productivity and sustainability of a spring wheat – field pea rotation in a semi-arid environment under conventional and conservation tillage systems. *Field Crops Research* (re-submitted December 2007)).

The legume – cereal rotation component was studied in two experimental approaches. Firstly, crop legumes were evaluated as a component of the rotation in the conservation tillage experiments described above. Field peas were grown in rotation with spring wheat at Dingxi, and soybean was grown in rotation with maize and winter wheat at Xifeng. Secondly, the impact of the perennial forage legume, lucerne, on soil water, soil nitrogen, and productivity of following wheat was studied in short-term experiments at Xifeng and Dingxi. This latter experiment was designed to assist with simulation modelling of lucerne-wheat cropping systems. A detailed description of methodology is provided in Appendix 11.3 (Shen, Y, Li, L, Chen, W, Robertson, MJ, Unkovich, MJ and Bellotti, WD (Submitted) Productivity, soil water and resource use efficiency of lucerne-wheat rotations on the Loess Plateau, north-west China. *Field Crops Research* (submitted 15 June 2007)).

In the final two years of the experiment, project resources shifted from a ‘proof-of-concept’ experimental focus, to an on-farm, farmer-participatory research approach. The aim of this work was to understand farmer concerns with the adaptation of conservation tillage to their specific conditions. This on-farm research was supported with farmer interviews and surveys of current farmer practice, and farmer attitudes towards research technologies.

5.2 The research team

Project team members were drawn from five institutions and contributed to the four main project objectives as follows:

Conservation tillage

This component was led by Dr Damian Heenan and Dr Yin Chan (NSW DPI) and Professor Huang Gao Bao (GAU). Dr Guangdi Li took over the responsibilities of Dr Heenan on his retirement.

Legume – cereal rotations

This component was led by Dr Bellotti (AU) and Professor Nan Zhi Biao (LU - GGERI), with support from other project scientists. Dr Murray Unkovich (consultant) provided expertise in the measurement of biological nitrogen fixation.

System simulation

This component was led by Dr Michael Robertson (CSIRO Sustainable Ecosystems), Dr Bellotti (AU) and Professor Nan Zhi Biao (GGERI).

Capacity Building

All project staff were involved in this component of the project. In addition to those listed above; Dr Guangdi Li (NSW DPI), Dr Jeremy Whish and Dr Merv Probert (CSIRO SE), Professor Zhang Renzhi, Dr Li Lingling (GAU), Professor Shen Yuying, Mr Gao Chongyue (GGERI).

6 Achievements against activities and outputs/milestones

Objective 1: To develop conservation tillage.

no.	activity	outputs/milestones	completion date	comments
1.1		New crop establishment systems.	Aug 02	Crops were successfully established using no-till seeders in most situations.
1.2		New methods for retaining stubble and greater water storage in field.	Dec 03	Commercial (machine harvest) stubble retention practices will be an improvement over the experimental procedures employed. Some evidence of higher soil water storage under CT.
1.3		Demonstration of higher grain yield and less erosion.	Dec 04	Grain yields were generally higher at Dingxi, while there was no overall increase in grain yield at Xifeng. Some indications of reduced erosion under CT.

PC = partner country, A = Australia

Objective 2: To integrate legumes into cereal dominated cropping systems.

no.	activity	outputs/milestones	completion date	comments
2.1		Diversified cropping systems with forage and/or crop legumes.	Dec 03	Crop legumes (peas, soybeans, lentils) well adapted to local conditions. Lucerne very productive in local environment.
2.2		Demonstration of greater crop water use and grain yield.	Dec 04	Lucerne is able to maintain soil water close to the crop lower limit to depths > 3m. Wheat grain yields after lucerne can be high, but need to manage risks associated with soil water and nitrogen supply to crops following lucerne.
2.3		Mechanisms of flow-on effects (water, N, etc.) from legume to cereal understood.	Dec 04	Water and N dynamics generally understood. Soil water dynamics feature a temporal disconnection between receival of rainfall and plant water use made possible by soil water storage. Nitrate-N dynamics generally understood, but still uncertainty over Ammonium-N dynamics in local soils.

PC = partner country, A = Australia

Objective 3: To adapt existing simulation models to local current and new farming systems.

no.	activity	outputs/milestones	completion date	comments
3.1		Capacity to predict the consequences of current cropping systems.	Jun 05	APSIM performance able to capture observed variation in soil water, soil nitrate, crop and forage production and grain yield. Crops simulated include winter wheat, spring wheat, maize, field pea, soy bean and the forage lucerne.

3.2		Capacity to explore new and better cropping system options in simulation models, leading to clear recommendations on new technologies and farming systems.	Dec 05	Capacity exists to analyse crop (and forage) rotations at the field scale, although this capacity has not been fully exploited at his stage. Preliminary analyses have provided valuable insights to soil water dynamics and productivity. Further research is needed to develop this capacity to include household livelihood analysis and livestock production enterprises.

PC = partner country, A = Australia

Objective 4: To build research capacity.

no.	activity	outputs/ milestones	completion date	comments
4.1		Improve capacity in experimental design, analysis and interpretation.	Jul 06	Project partners have benefitted greatly, evidence includes lead authorship on international journals and new research grants.
4.2		Develop understanding of Participatory Action Research.	Jul 06	Partners engaged in PAR, and gained experience in conduct of farmer surveys, on-farm research, and participatory research in the context of farmer evaluation of conservation tillage.
4.3		Train selected scientists in use of APSIM.		Several partner scientists received formal and informal training and support in use of APSIM. Benefits include improved understanding of systems analysis and ability to interpret integrated datasets. Ongoing independent use remains limited.

PC = partner country, A = Australia

7 Key results and discussion

Key results are presented using the four project objectives as main headings.

Conservation tillage

For detailed results and discussion see Appendix 11.2 (Huang, GB, Zhang, RZ, Li, GD, Li, LL, Chan, KY, Heenan, DP, Chen, W, Unkovich, MJ, Robertson, MJ, Cullis, BR, Bellotti, WD. (2008) Productivity and sustainability of a spring wheat – field pea rotation in a semi-arid environment under conventional and conservation tillage systems. *Field Crops Research* 107, 43-55). Key results and conclusions are listed below:

- At Dingxi, grain yields under no-tillage stubble retention (NTS) were consistently higher than under traditional practice (T). Average (4 seasons) spring wheat grain yield was 2.1 (T) and 2.4 t/ha (NTS), with the corresponding field pea grain yields of 1.5 and 1.8 t/ha.
- Grain yield under the no-tillage stubble removed treatment (NT) was consistently low yielding, indicating the unsuitability of this treatment in the short-term, as well in the long-term from a soil fertility perspective. In the short-term, soil water relations under NT are less favourable for crop growth due to higher runoff, less infiltration and greater evaporation from the bare soil surface. In the long-term, lack of organic inputs to the soil results in declining soil fertility and deteriorating soil physical characteristics.
- Grain yields under a plastic mulch treatment were similar to those in the NTS treatment, but higher input costs, soil organic matter decline, pollution from plastic detritus and soil erosion are serious problems with this treatment.

- At Xifeng, there were no consistent differences in grain yield between treatments. Significant treatment differences were recorded within seasons, but no overall trend was evident. The finding that there was no grain yield penalty associated with NTS is important as lower input costs associated with NTS make this treatment more profitable.
- From the perspective of local farmers, reduced labour and cost inputs associated with no-tillage were very attractive, and in some cases this factor alone was enough reason for them to consider adopting conservation tillage. Conservation agriculture has great potential to release farmers from much of the drudgery associated with traditional, labour-intensive practices such as conventional ploughing and manual harvesting and threshing of crops. The cost saving associated just with omitting two plough operations is ¥30/mu ($71/ha).
- There is potential for further reductions in crop inputs, such as N fertiliser rate and seed rate, delivering further increases in profitability without compromising crop yields.
- The gap between average farmer crop and forage yields and yields achieved under researcher-managed experiments indicate large potential for productivity gains using existing technology. For example, for the low-yielding 2003 season in Lijiabu village (Dingxi), spring wheat yield under farmer conditions was just 1.0 t/ha, compared to 1.4 t/ha under best-practice traditional management, and 1.8 t/ha under conservation tillage management. For field peas the corresponding yields were 0.8, 0.9 and 1.3 t/ha. At Shishe (Qingyang) during the average-yielding 2003 season, average farmer maize yield was just 6 t/ha compared to 9.1 and 10 t/ha under best-practice traditional practice or conservation tillage respectively. Soybean yields also increased under best-practice and conservation tillage while winter wheat yields were unchanged.
- Overall, an average 20% improvement in productivity over current levels through adoption of existing technology appears entirely feasible. Profits may be further improved through reducing inputs of nitrogen fertiliser, seeding rates, and labour (reduced tillage), while maintaining productivity.
- Despite these important advantages, significant impediments to widespread adoption of conservation tillage remain. These centre around the traditional high opportunity cost of crop stubble, lack of access to capital to invest in no-till seeding machinery, and knowledge of new crop agronomy, including weed management based on herbicides.

In Australia

- Research conducted by NSW Department of Primary Industries followed a long history of observation that early growth is sometimes reduced in crops sown without cultivation, and an equally long history of inconclusive research into the reasons why. It specifically followed ‘promising’ work at Wagga by Dr Stephen Simpfendorfer, that suggested that the effect was associated with toxins from (not populations of) inhibitory Pseudomonads.
- This was not a new hypothesis, but it was supported by the isolation of a particularly ‘virulent’ ecotype (266) and fumigation and other studies supporting the toxin theory.
- Whilst this early work had shown that the reduced early growth was apparently biological in origin (effect removed by fumigation), it did not establish the effect of any interacting variables on either the bacteria or the ‘host’ plant (such as abiotic stress), nor establish that the 62% of affected crops showing reduced early growth (in one survey) were all affected by the one cause (inhibitory Pseudomonads).

- Thus it was against a rather complicated and inconclusive background that this part of the ACIAR project commenced. Despite an impressive amount of research on the topic, the NSW DPI team was still unable to reliably reproduce plant symptoms, and remained at a loss to explain how the organism, if indeed it is responsible, brings about its effect.
- Experimental results suggested that nutritional interactions seemed to be important. Interestingly, an ‘accidental’ result suggested that P deficiency may induce symptom expression in plants growing in agar inoculated with strain 266. How this relates to earlier work, showing that nutritional concentrations in the medium used to grow the inoculum were not a factor, remains to be seen.
- Although it is noteworthy that one result was in the inoculum manufacture phase, the other was in the plant growth phase. It is also noteworthy that the P concentrations at which strain 266 was most effective was much lower than Hoaglands or even 1/10 Hoaglands, being closer to what might be in soil solution concentrations, at 0.01% P.
- At the time of completion of this research the potential role of Pseudomonads in reducing crop vigour of crops sown without cultivation remains unresolved.

Benefits of legumes in crop rotations

For detailed results and discussion see Appendix 11.3 (Shen, Y, Li, L, Chen, W, Robertson, MJ, Unkovich, MJ and Bellotti, WD (Submitted) Productivity, soil water and resource use efficiency of lucerne-wheat rotations on the Loess Plateau, north-west China. *Field Crops Research* (re-submitted April 2008)). Key results and conclusions are listed below:

- Suitable legume crops are available in Dingxi (field peas and lentils) and Xifeng (soy bean) for incorporation into wheat-based rotations. General adaptation and grain yield potential is good. Field peas appear particularly well adapted in the Dingxi environment and provide locals with a high protein grain and profitable cash crop option.
- The nitrogen fixing potential of grain legumes is not being realised due to high fertiliser N rates applied to legumes and generally high soil inorganic N levels. Further research to realise the N-fixing benefits of grain legumes should increase profitability (reduced fertiliser inputs) and sustainability (less nitrate leaching) of wheat-based systems.
- The perennial forage legume lucerne is well adapted and very productive in the Xifeng environment. Forage yields of 10-15 t/ha, based on three cuts per season were regularly achieved under research station management. The yield potential under drier conditions at Dingxi is much less, although no reliable data was collected in this project.
- Lucerne forage yield under farmer conditions was much less than under research station management indicating potential for an extension program to assist farmers to make up the difference. Areas for improvement include P fertiliser management, inoculation with suitable rhizobia, timing and height of harvest procedures, forage conservation through hay and/or silage making, and utilisation of harvested forage in livestock diets.
- Lucerne – wheat rotations were highly productive and utilised a high proportion of available soil water. The transition from lucerne to wheat requires deliberate timing of the removal of lucerne to minimise the risk of lower wheat grain yields associated with dry soil profiles after lucerne. Nitrogen supply from the lucerne phase to following wheat crops appeared adequate to meet the demand of the first two crops, but additional fertiliser N was needed for the third consecutive wheat crop.

- Higher soil water use under lucerne results in less deep drainage and eventually reduced recharge to underground aquifers and river systems. The possibility for negative impacts of widespread planting of lucerne on regional water resources needs to be analysed.
- Lucerne forage yields also show large potential for improvement, with farmer yields averaging just 6 t/ha compared to >10 t/ha under research station management in Qingyang. Further gains can be expected from improved utilisation (timing and intensity of defoliation, cutting hay or silage) of forage, and improved feeding strategies.
- While lucerne is productive and contributes to sustainability of local farming systems, widespread adoption will require more detailed analysis of farm resource use at the household livelihood scale. Allocation of scarce land, subsistence food production, availability of labour, technical knowledge, and market access are some of the issues involved.

In Australia

For detailed results and discussion see Appendix 11. 5 (Harris RH, Clune TS, Peoples MB, Swan AD, Bellotti WD, Chen W, Norng S (2007). The importance of in-crop lucerne suppression and nitrogen for cereal companion crops in south-eastern Australia. *Field Crops Research*, 104, 31-43). Key results and conclusions are listed below:

- Research conducted by the University of Adelaide investigated the potential of growing wheat in association with a living stand of lucerne, so-called companion cropping. The context for this research was the need to reduce deep drainage while maintaining crop and pasture productivity.
- Research at Roseworthy was conducted in the 2003, 2004 and 2005 growing seasons, characterised by late starts and/to low rainfall.
- Grain yield reductions from cereals growing with lucerne were recorded across southern Australia and ranged from 16-26% compared with cereals growing in monoculture.
- N fertiliser application to cereals growing with lucerne can increase cereal grain yields, but only when accompanied by favourable growing season rainfall and low available soil N levels.
- In-crop lucerne suppression was effective at reducing cereal grain contamination by lucerne pods and flowers, but was less effective under dry conditions.
- Further research utilising system simulation modelling is needed to account for forage production benefits and costs, and to analyse the impact of climate variability on overall system performance.

Analysis of farming systems using simulation models

For detailed results and discussion see Appendix 11.4 (Chen, W, Shen YY, Robertson, MJ, Probert, ME, and Bellotti, WD. (2008) Simulation of lucerne – wheat crop rotation on the Loess plateau of northwest China. *Field Crops Research* (accepted April 2008)). Key results and conclusions are listed below:

- Climate, soil and crop data was collated to allow running the APSIM model for local conditions.
- The parameterised model performed well, simulating observed variability in soil water, soil nitrate, and crop development, growth and yield.

- Application of the model provided new insights into the experimental dataset, and facilitated detailed communication of results within the project team. Understanding of climate variability, soil water dynamics, resource use efficiency and the relative importance of research results was enhanced through simulation modelling. For example, the importance of stored soil water from late summer –autumn rain for spring production of crops and lucerne was elucidated through model output. Similarly, the potential for mineralisation of nitrogen to supply plant N demand was explored using model analyses. Another example was the use of the model to explore crop response to fertiliser nitrogen under variable climate conditions.
- Further application of systems analysis is necessary in order to identify clear extension messages arising from the research, and to extend the results from the field to the farm (and/or village) scale.

In Australia

- Project research in Australia and Gansu led to the development of the APSIM Field Pea module. This module adds to the suite of crop and forage species available in APSIM. Field peas are the most important pulse crop in south-east Australia and are important in western China. This new modelling capacity will find many applications including disease management in field peas and cereal-legume crop rotation studies.
- Performance of the APSIM lucerne module was further tested and developed under Chinese and Australian conditions in this project. In Australia, the performance of the lucerne module was improved through enhancements to the process of autumn decline in shoot productivity. In China the lucerne module was adapted to cope with winter dormancy and spring re-greening associated with the harsh Gansu winter.

Capacity building

The main benefit to research capacity of our Chinese research partners was through active participation in the conduct of project research. Capacity was enhanced along the full pipeline of research activity from problem definition, through the design and conduct of experimental research, management analysis and interpretation of experimental data, application of simulation modelling to experimental datasets, communication and publication of research results. Publication of project research is an ongoing activity.

In addition, specific training activities have included workshops on laboratory techniques, simulation modelling, participatory research, and written communication and publication.

- Research methodology including definition of research question, experimental design, data collection and management, data analysis, presentation of results, interpretation of results, and publication of research in leading international journals has been enhanced through the conduct of this project.
- Specific skills were developed including measurement of plant available water capacity, monitoring of soil quality indicators, measurement of nitrogen fixation by legumes, measurement of infiltration and runoff, calculation of resource use efficiency, management and interpretation of large and complex databases, conduct of participatory research and simulation modelling.
- Oral and written English language skills have improved.
- Training in the use of new experimental equipment including no-till seeders, soil quality measuring equipment (infiltrometers, penetrometers), and rainfall simulators has been provided.

8 Impacts

8.1 Scientific impacts – now and in 5 years

Project scientists have a greater awareness of the need for and methodologies of agricultural systems analysis research. This has led to Professor Huang Gaobao receiving research funding for research on irrigated agriculture in Hexi corridor, and Professor Shen Yuying receiving funding for research on resource use efficiency in mixed crop-livestock farming systems in eastern Gansu. In addition, Professor Shen and Dr Murray Unkovich were successful in receiving DEST and MoST funds for research on biological nitrogen fixation. Other Chinese research institutions, eg. Institute for Soil and Water Conservation (CAS, Yangling), have expressed interest in future research partnerships.

Chinese partner scientists have presented project research at international conferences including the International Crop Science Congress and the International Soil and Tillage Research Organisation. Several Chinese project scientists have been promoted on the basis of their participation in this project, e.g. Professor Shen Yuying and Dr Li Lingling.

Many Chinese undergraduate and postgraduate students have been exposed to project research activity. Greater than 1500 undergraduate students have been exposed to farming systems research concepts. Fifty final students, 11 Masters, and 4 PhD students worked on project related research projects. Chinese university staff are routinely using farming systems research concepts and terminology in their undergraduate teaching practice.

Project research has contributed to simulation modelling capacity in Australia, eg. The APSIM Pea module was developed with support from project resources and is now used widely in Australian research.

8.2 Capacity impacts – now and in 5 years

Project partners have a greatly enhanced capacity for analysing agricultural systems. This has already been recognised by the Chinese government throughthe awarding of new research grants (see above). Specific areas of research that have been enhanced include integrated database management, farmer survey, on-farm research and simulation modelling.

Project scientists have developed their scientific skills, including publication skills, and this is leading to greater recognition, enhanced reputation, promotion and leverage of additional research funding. Collaboration between Lanzhou University (GGERI) and Gansu Agricultural University at the scientist and senior management level has been enhanced.

Specialised research equipment has been purchased with project funds. Items include no-till seeders, rainfall simulators, soil penetrometers, and disc permeameters. These items were supplied to both LU and GAU. This equipment has already been utilised in project researh and postgraduate research projects, and has improved the attractiveness of the Chinese partners for further research investment. Long-term, conservation tillage research sites have been established, providing an opportunity for continuing research into soil quality changes over time and an asset to attract additional research funding.
Specific experimental methodology has been developed in areas such as; soil water monitoring using Neutron Moisture Meter and capacitance sensors, description of plant available water capacity, soil inorganic nitrogen sampling and laboratory determination, measurement of a range of soil quality indicators (organic carbon, microbial biomass,

surface infiltration, runoff, soil strength, aggregate stability), biological nitrogen fixation determined by the ^{15}N natural abundance technique, and runoff – infiltration relationships using rainfall simulators.

8.3 Community impacts – now and in 5 years

The project has achieved direct impact on farming practice of local farmers that have become aware of the potential of conservation agriculture through exposure to project research. One of the great appeals of conservation agriculture to local farmers is the significant input cost savings associated with no-tillage. Combined with similar or increased grain yields, this advantage will drive farmer interest in conservation agriculture in the short- to medium-term. These positive findings support existing and planned extension programs aimed at increasing adoption of conservation agriculture in western and northern China. However, it should be acknowledged that despite these advantages, significant barriers to adoption remain. These points are elaborated below.

8.3.1 Economic impacts

Direct economic benefits to farmers adopting conservation tillage arise from increases in productivity and reductions in crop inputs. Grain yields under conservation tillage increased by 0-20% compared with grain yields under traditional practice. Crop input costs (labour, seed, and fertiliser) may be reduced by around $100/ha. The cost saving associated just with omitting two plough operations is ¥30/mu ($71/ha). Despite these economic advantages, the level of adoption remains low and few farmers have realised these benefits.

The observation that crop yields in experimental treatments aimed at reproducing farmer practice were on average 20% higher than neighbouring farmer managed crop yields indicates the potential for an effective extension campaign to assist farmers to realise benefits available through adoption of existing technology. Further research to identify the key factors responsible for this difference in grain yield is needed, but time of seeding and fertiliser (both nitrogen and phosphorus) management are likely contributing factors.

8.3.2 Social impacts

Conservation tillage represents a radical move away from traditional soil management and crop establishment practices. The transition from traditional to conservation tillage has implications for farm labour allocation, draught animal power requirements, availability of crop residues for animal feed and household energy use, and weed management systems. The potential social impacts are profound.

Firstly, the release of farm labour from the drudgery of traditional tillage and crop harvest practices means that scarce labour resources can be directed to more profitable activities, e.g. livestock production. Alternatively, the reduced labour requirement of conservation tillage allows cropping to continue even after family members have left the farm to seek more profitable work options.

Secondly, the retention of crop residues in the field for maintenance of soil fertility means less crop residues are available for livestock feed. This may be a good or bad development depending on the emphasis given to livestock production under conservation tillage.

Thirdly, the reliance on herbicides for weed management under conservation tillage delivers further labour savings, but reduces the contribution from weeds to livestock nutrition, and creates an urgent need for training farmers in the safe and effective use of herbicides.

8.3.3 Environmental impacts

Conservation agriculture can deliver significant environmental benefits including reduced soil erosion from surface runoff, reduced soil erosion from wind, reduced pollution from plastic mulch, and reduced reliance on fertiliser N due to greater use of crop and forage legumes in crop rotations.

High water use cropping systems based on lucerne may reduce deep drainage of water and consequent recharge of aquifers. Surface water flow may also be reduced with greater use of conservation agriculture. While these impacts are positive at the individual farm-scale, they may have unintended consequences for water resources at catchment and regional scales.

8.4 Communication and dissemination activities

Project results have been communicated at local field days, national and international conferences in China and Australia. Several media articles have featured project research. Details are provided below:

Field days

Field days featuring project research have been held at Dingxi and Xifeng for local farmers and extension officers. Field days at Xifeng were held on 18 August 2003 (200 farmers attended), 16 June 2005 (70 farmers), and 24 January 2006 (50 farmers). Local extension agents and agricultural companies also attended.

Conferences

Project research has been presented at international conferences (International Grassland Congress, International Soil and Tillage Research Organisation, International Crop Science Congress, China-Korea-Japan Sustainable Grasslands Conference), national and local conferences. See project publication list for details.

Media

Project research has featured in Chinese print and electronic media. The Xifeng City TV station reported project research on August 20, 2003. The Gansu Provincial TV station reported on a meeting between the project team and Gansu Vice-governor, Mr. Yuan Xiao-Su, in Lanzhou City in spring of 2001.

9 Conclusions and recommendations

9.1 Conclusions

Conservation tillage

Major local crops can be successfully grown without tillage and with stubble retention on the Loess Plateau of China. In this region of China there is a widespread and continuing belief that tillage is necessary for successful crop production. While this research clearly demonstrates that this widely held belief is not based on fact, widespread adoption of conservation tillage will require ongoing research, development and extension.

Even under traditional management practices (tillage and stubble removal), grain yields of researcher managed crops were much higher than crops under farmer management, indicating large potential for an effective extension campaign based on existing knowledge and technology. Research is needed to identify the key factors responsible for this difference bit it is likely that crop sowing time and fertiliser (nitrogen and phosphorus) management are significant factors.

No-tillage systems must be integrated with stubble retention systems for potential soil and crop benefits to be realised. No-tillage without stubble retention was low yielding and likely to degrade soil resources even more than traditional tillage practice. Given the high value of crop residues for animal feed and/or energy for heating and cooking, there exists a temptation to promote no-tillage while still allowing traditional removal of all crop stubbles. This situation should be resisted strongly. There remains a need for research to explore optimum trade-offs between use of crop residues for conservation tillage and traditional uses.

A key attraction of conservation tillage for local farmers is the cost and labour saving associated with not tilling the soil. Maintaining grain yields while reducing crop inputs (tillage, N fertiliser, seeding rate) is a promising pathway to improving profitability. This labour advantage of conservation tillage is likely to become more important as farm labour continues to move toward better paid labouring jobs in the cities.

Despite these important advantages, significant impediments to widespread adoption of conservation tillage remain. These centre around the traditional high opportunity cost of crop stubble, lack of access to capital to invest in no-till seeding machinery, and knowledge of new crop agronomy, including weed management based on herbicides.

Legumes in rotations

A range of crop legumes (field peas, lentils, soybean) and the forage legume lucerne are well adapted, productive, can be utilised in wheat-based cropping systems in the region. The nitrogen fixing benefits of legumes (particularly the crop legumes) are not being realised under present management conditions due to high fertiliser N applications to the legumes and generally high soil inorganic N levels. Further research to increase the contribution of biologically fixed nitrogen to crop production in the region is needed.

A lucerne phase can provide the nitrogen demand for at least two consecutive wheat crops, but additional fertiliser N is required to meet crop demand for the third and later crops. Lucerne – wheat rotations provide the opportunity to utilise deep stored soil water, and lucerne can maintain soil water at close to the crop lower limit under most circumstances. The transition from lucerne to wheat requires deliberate timing of the removal of lucerne to minimise the risk of lower wheat grain yields associated with dry soil profiles after lucerne.

While lucerne is productive and contributes to sustainability of local farming systems, widespread adoption will require more detailed analysis of farm resource use at the household livelihood scale. Allocation of scarce land, subsistence food production, availability of labour, technical knowledge, and access to forage and/or livestock markets are some of the issues involved.

Simulation modelling of local agricultural systems

The APSIM model was able to capture most of the observed variability in soil water, soil inorganic nitrogen, and crop and pasture production. Significant research input was required to assemble local climate databases, characterise local soils, and parameterise local crop and forage varieties. An important task was to adapt the model to accommodate winter dormancy in winter wheat and lucerne.

Application of the APSIM model provided new insights into the experimental dataset, and facilitated detailed communication of results within the project team. Understanding of climate variability, soil water dynamics, resource use efficiency and the relative importance of research results was enhanced through simulation modelling.

Further application of systems analysis is necessary in order to identify clear extension messages arising from the research, and to extend the results from the field to the farm (and/or village) scale. Specific developments required include the inclusion of a capacity for simulating livestock production, and the capacity to scale out from the field to farm and/or village scale.

9.2 Recommendations

1. It is recommended that project results be made available to local extension agencies to support existing extension programs. Current extension programs on conservation tillage, and on expanding the area of lucerne, will find great value in experimental data from this project. Local scientists and extension agents need to be encouraged to repackage project research into forms suitable for local farmers.
2. It is recommended that current and future research and development into conservation agriculture follow a systems analysis approach. This project has demonstrated the importance of taking a systems approach to analysing current and future farming practice. The need for a systems approach is clearly evident in the many interactions between components of the farm, for example, the use of crop residues for animal feed or the allocation of land to crop or livestock enterprises. Rather than ignore these important cross-discipline and cross-commodity interactions, there is a strong need to focus on these interactions at the scale of the household farm.
3. It is recommended that current local government programs to increase livestock production be supported by participatory research. A household livelihood approach is needed to develop livestock feeding systems that make best use of all feed resources; forage, crop residues, weeds, common land, concentrates. The integration of lucerne into wheat-based cropping systems provides increased forage production, but at the expense of a reduction in the area devoted to wheat. Overall system productivity and sustainability can be enhanced, but the transition from lucerne to wheat needs to be managed carefully, and trade-offs between forage and crop production needs to be communicated clearly. This system of integrated crop-livestock production provides a useful option for increasing livestock production and overall farm profitability at a time when government agencies are seeking to promote meat production and consumption.
4. It is recommended that ACIAR and MoST consider funding a new follow-on research project. A tentative title for this new proposal is “Resource use efficiency of crop-livestock farming systems in western China”. This proposal would build on the systems analysis capability developed in the previous ACIAR project. Project methodology will combine on farm experimentation with systems analysis tools (databases, simulation modelling, economic analysis) while focussing on integration of crop and livestock production. Emphasis would be given to productivity, water-use efficiency and whole farm economic performance. Local farmers and extension agents would be integral to the research and project benefits would be intended to be delivered to farmers within five years of project completion. Project performance and eventual impact would be monitored.

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11 Appendixes

11.1 Farming systems of the Loess Plateau, Gansu Province, China. Agriculture, Ecosystems and Environment

Nolan, S, Unkovich, MJ, Shen,Y, Li, L and Bellotti, W.D. (2008) Farming systems of the Loess Plateau, Gansu Province, China. *Agriculture, Ecosystems and Environment*. 124, 13-23.

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Agriculture, Ecosystems and Environment 124 (2008) 13–23

Agriculture Ecosystems & Environment

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Farming systems of the Loess Plateau, Gansu Province, China

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Abstract

Gansu Province in north western China contains a large portion of China's rural poor. Within this province we compared extant farming systems in lower and higher rainfall areas of the Loess Plateau. The farming systems were dominated by subsistence winter wheat production in the higher rainfall more productive area (Qingyang), and subsistence spring wheat in the lower rainfall less productive area (Dingxi). Once household grain production is satisfied, remaining land is allocated to cash crop and livestock enterprises. Similar farm sizes (ca. 1 ha) in both areas meant that farmers in the more productive Qingyang area were easily able to meet household food needs and produce more cash income from sale of produce. They have reinvested this into their farms and are now developing new enterprises, particularly livestock and co-operative trading arrangements. This has allowed many of these farmers to move away from subsistence grain production, such that 72% of household income is now derived from sale of farm produce. However, many farmers in Qingyang indicated a lack of technical agronomic support and limited access to reliable markets as barriers to diversification. In Dingxi, many farmers struggle to grow sufficient grain for household use and generate very little cash income, often insufficient to provide basic needs such as education. Potatoes, pea and oilseeds are the most common cash crops here, but livestock enterprises are poorly developed. In this area only 28% of household income is generated on farm, and young males often leave the farm to work in larger cities, leaving farming decisions to the elderly, women, and children, who are left behind to manage the farm. High illiteracy rates in this group reduce assimilation of new information. Farmers in Dingxi indicated that restricted access to capital, lack of technical agronomic support and little access to trading markets were serious impediments to the development of more profitable enterprises.

Keywords: Subsistence agriculture; Livestock; Adoption; Poverty

1. Introduction

Despite China's booming economy, income disparity between rural and urban populations (effectively western and eastern provinces) is amongst the highest in the world (Chang, 2002). The bulk of the rural poor come from the north western provinces, where an estimated 53% of the Chinese rural population (totalling 900 million) live on less than US$ 2 per day (World Bank, 2005). Gansu Province in north western China, is home to approximately 40% of China's rural poor. Across the Province, household income averages only Y1946 (US$ 243) per year, 70% of which is gained from agricultural activities with the remainder from wages earned off farm (MOA, 2001). A lack of land and capital resources, combined with high population densities has led to widening disparity between rural and urban incomes. This is particularly evident in one of Gansu's poorer counties, Dingxi, where the average per capita income for urban residents in 2002 (Y5015, US$ 627) was more than triple the earnings of local rural populations (Y1412, US$ 176 (Anon., 2004)).

Gansu Province sits on the Loess Plateau, a geographical feature located in the middle reaches of the Yellow River, the

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doi:10.1016/j.agee.2007.08.009

plateau covers >400,000 km^2 over five provinces. Some parts of the region have been cultivated for 6000 years. Soil type, slope, rainfall patterns and cultivation mean that soil erosion here (3720 t km^{-2} year^{-1}, rising to maxima of 20,000 t km^{-2} year^{-1} (Liu, 1999)) is the highest in China, and indeed amongst the highest in the world (Fu, 1989). Erosion is principally caused through run off during the rainy season (July–September), resulting in gully erosion and high sediment loads to the Yellow River. While erosion is reduced by perennial forest or grass cover, most of these areas have diminished due to increased subsistence arable agriculture and overgrazing (Rui et al., 2002). This has further eroded the natural resource base and resulted in low crop yields and low farm incomes over much of the region.

Addressing poverty and improving the environment across the Loess Plateau has become a priority of government policy. In Gansu, Provincial strategies aim to reduce farmer reliance on grain production, increase the production of cash crops and livestock and relocate farming villages to more fertile lands (MOA, 2001). Supporting this policy is a heavy investment in rural infrastructure and transport networks by government, and a recent revegetation campaign that encouraged farmers to replant slope land with forage legumes in exchange for grain (Feng et al., 2003). This policy has proved to be popular with most farmers while the grain and cash subsidies have reached the farmers, but as with all such policies, there are concerns over what will happen if and when this program has been withdrawn. Indeed in the study areas there is already evidence that farmers are reverting to previous cropping practices. While there is evidence of progress in some areas (Shi and Shao, 2000; Rui et al., 2002; Zhang et al., 2004), little is known about the way farmers in different agro-climatic zones are able to respond to government policy and market signals. Some regional statistics show that farmer incomes are improving, but it is difficult to gauge whether this is due to farmer innovation, improvement in commodity prices, off farm income sources or the success of government policies.

While erosive processes (e.g. Fu, 1989; Shi and Shao, 2000) and some aspects of crop agronomy (Li et al., 2000b; Huang et al., 2003) have been well studied, there has been little published on extant farming systems of the region. One study (Hardiman et al., 1990) in eastern Gansu's Qingyang County identified three different subsistence farming systems, based on landscape (slope), farm size and labour units household^{-1}. The most common farming system was located on productive tablelands, experiencing high grain yields, with livestock enterprises focussed on rabbit skin and wool production. Of the other two farming systems, one occupied sloping land, resulting in high erosion rates and poor grain yields and was therefore more focussed on livestock enterprises. The other occupied the small amounts of land within wide river valleys and consisted of a productive wheat–maize based system with no reports of other cropping enterprises.

The aim of the present study is to provide insight into extant farming systems and farmer opinions in two climatically contrasting environments in Gansu Province (Qingyang and Dingxi Counties), using a combination of available data, extensive farmer surveys and interviews in 125 households. We hypothesize that differences in farmer ability to change in response to government and market forces will be strongly moderated by local biophysical and socio-economic constraints.

2. Study area

2.1. Biophysical environment

The Loess Plateau is mostly 1000–1500 m in altitude, extending to >3000 m and consists of highly erodible hills, slopes and tablelands. Chinese farmers first began to build terraces in the region for crop production on sloping land more than 500 years ago, and while mechanisation has greatly increased the rate of terracing in the last 50 years, much is still done by hand (Zhengsan et al., 1981). Although the soils are deep, free draining and able to hold appreciable plant-available water (130 mm m^{-1}) for long periods of time (Zhu et al., 1983), a combination of low clay content and cultivation methods results in poor organic matter retention, structural instability (erosion) and low fertility for crop production (Catt, 2001).

Two localities, Qingyang County and Dingxi County, are chosen to represent the principal land systems and contrasting environments of the region. In biophysical terms, the areas differ in their position in the Loess landscape, with Qingyang (35.40′N, 107.51′E, elev. 1298 m a.s.l.) on tableland in eastern Gansu and Dingxi (36.03′N, long 103.53′E, elev. 1517 m a.s.l.) occupying Loess hills in central Gansu. Dingxi comprises of a number of small farming villages typically situated within narrow valleys that are surrounded by terraced mountains, where the majority of farmland is located. Soils are infertile sandy loams with a high silt content.

2.2. Climate

The region experiences cold dry winters and warm wet summers (Figs. 1 and 2), with annual rainfall ranging from 600 mm in the south east of the province to <100 mm in the north west (Li et al., 2000a). Rain falls sporadically over a short summer period but is highly variable from year to year with variability in monthly rainfall (CV) between years ranging from 45 to 100% for both Dingxi and Qingyang. The additional 155 mm of annual rainfall in Qingyang (551 mm) than in Dingxi (396 mm) provides the basis for greater fallow water storage (Li et al., 2000b) and much higher crop growth and grain yields than in Dingxi. In 2003, the year of our study, rainfall in Qingyang was 794 mm, more than double that of Dingxi (380 mm). Winter wheat (*Triticum*

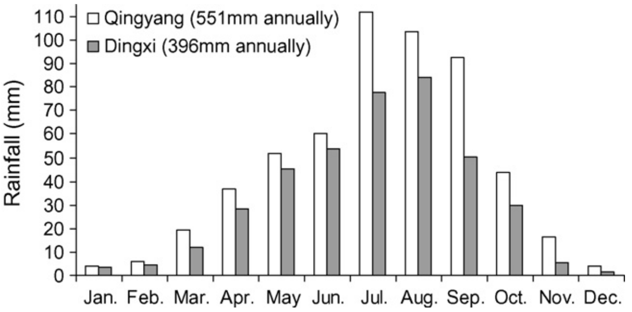

Fig. 1. Average monthly rainfall for Qingyang (1961–2003) and Dingxi (1970–2003). Annual variability is great with monthly coeffcients of variation ranging from 44 to >100% at both sites.

aestivum L.) is grown in Qingyang but this is not possible in Dingxi where there is less snow cover and more severe radiation frosts in winter. The growing season at both sites approximates the period when minimum temperatures above 0 °C (Fig. 2) coincide with significant rainfall (approximately April–October; Fig. 1). These combinations of factors result in a longer, more benign, growing season at Qingyang compared to Dingxi.

3. Methods

3.1. Surveys

Data from surveys were used to describe local farming systems and help identify farmer inputs to cropping systems and yields obtained. Developed with volunteer farmers in Qingyang during July 2003, finalised surveys were conducted in Shi She and Waxie townships in Qingyang Prefecture during August, before being adapted to the different cropping systems in Dingxi. Surveys were bilingual and contained standardised questions on household socio-economic data and conventional farming practices.

The majority of surveys were completed on local market days with farmers who were purchasing or selling goods at the market. Farmers were selected primarily to represent the broad range of age, products sold, and socio-economic status apparent. At the conclusion of the study, a total of 125 households had been surveyed from five villages in Qingyang and Dingxi. The results of the surveys thus provide a snapshot of farming systems in localised areas within Qingyang and Dingxi Prefectures.

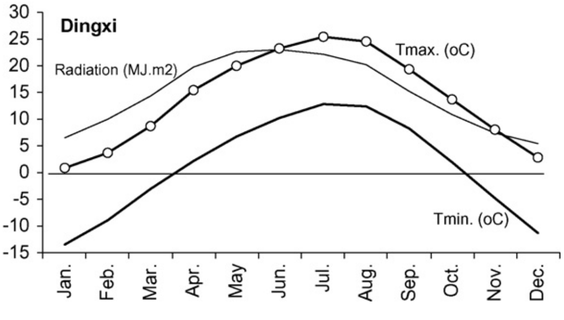

Fig. 2. Average daily maximum ($T_{\max}$) and minimum ($T_{\min}$) temperature (°C) and average daily radiation (MJ m^{-2}) for each month for Dingxi (1970–2003). Data for Qingyang are closely similar.

3.2. Interviews

Farmers were interviewed to obtain information about their farming practices and incomes, attitude to new farming technology and the effect of government policy on their farms. Participants were chosen to represent a range of ages, farming enterprises and socio-economic standing. In most cases, farmers were happy to participate in this study. They were then interviewed one-to-one or in groups in their homes or at the Qingyang Research Station, depending on convenience and interest in the study. Group interviews were very beneficial in generating discussion amongst farmers about topical issues and to cater for substantial farmer interest in the study. Each interview asked farmers a range of standardised open-ended questions, with points of interest followed up where the need arose.

Five group interviews were conducted in Qingyang between April and June 2003, with 30 farmers participating from three farming villages. Similar numbers of farmers were involved in interviews in Dingxi between October and November in 2003.

4. Results

4.1. Regional crop statistics

From the 3,649,900 ha under cultivation across Gansu Province in 2002, approximately 29% was used for the production of wheat for household use, giving rise to a traditional wheat monoculture rotated periodically with maize (*Zea mays* L.) or crop legumes (Gansu Statistic Bureau, 2003). Across the Province spring wheat (378,000 ha) accounts for 35% of total wheat sowings, the remainder being winter wheat. Provincial data indicates cash crops are sown on ca. 12% of the total arable land in both study areas, but the type grown varies between sites (Table 1), with apples (*Malus domesticus* Bork.), vegetables, soybean (*Glycine max* (L.) Merr.) and oilseed crops (canola, rapeseed (*Brassica rapa*/*B. napus* L.)) being important in Qingyang, and potatoes (*Solanum tuberosum* L.), chinese herbs and linseed (*Linum usitatissimum* L.) in Dingxi. In general, agricultural activities employ approximately 85% of the adult labour force (Yao, 2002).

4.2. Extant farming systems

Data from the farmer surveys (Table 2) indicates that farms average almost 1 ha in size, and are predominantly sown with wheat (30–50% of area), maize (Qingyang 23%

Table 1
Areas of principal sown crops (10^3 ha) in Gansu Province and in Dingxi and Qingyang Prefectures within Gansu for 2002 (source: Gansu Statistic Bureau, 2003)

	Gansu Province	Dingxi Prefecture	Qingyang Prefecture
Wheat	1074.0	102.4	192.0
Maize	497.9	25.2	57.0
Linseed	140.1	33.0	23.4
Rapeseed	136.5	8.6	20.6
Sunflower	15.2	0.0	6.5
Millet	91.9	4.5	45.7
Soybean	81.8	0.1	40.9
Millet (*Setaria*)	34.0	6.3	7.9
Sorghum	18.8	0.4	5.8
Forage crops	181.0	18.8	13.2
Potato	484.9	193.7	36.4
Orchards	262.2	10.0	36.0
Vegetables	200.7	15.3	25.6
Chinese herbs	132.8	75.0	3.8
Tobacco	9.4	0.0	8.0

of area) or legumes (Dingxi field pea 17% and some lucerne (*Medicago sativa* L.). The larger farm size in Dingxi may result from a greater proportion of sloping land and the lower productivity due to the lower rainfall. While wheat occupies a similar land area per farm at both sites, in Qingyang winter wheat is typically grown for 2–3 seasons before the yield declines and a break crop (predominately maize) is incorporated. In Dingxi, spring wheat is grown in yearly rotations with field pea (*Pisum sativum* L.), with an occasional break crop of potatoes, linseed or lentil (*Lens culinaris* Medik.) In both areas crop stubbles (often including roots) are almost always removed after harvest and fed to livestock or used as household fuel for cooking and heating. This leaves the soil bare and exacerbates erosion problems.

Cash crops in Qingyang account for 28% of the cultivated area and include fruit, vegetable and feed crops. In Dingxi, cash crops are grown on approximately 20% of the cultivated area and are dominated by potatoes, lentils and linseed. Fruit and vegetables, which are grown as a cash crop for sale in regional centres, are more common at Qingyang than in Dingxi due to the higher rainfall. Average yields from crops in Qingyang from the farmer survey in 2003 were 3.5 t ha^{-1} for winter wheat, 6.5 t ha^{-1} for maize and 1.8 t ha^{-1} for soybean. Crop yields in Dingxi in the same year were a half to one third, averaging 1.0 t ha^{-1} for wheat and 0.8 t ha^{-1} for pea.

Farmers in Qingyang also have more livestock, with well developed sheep (*Ovis aries*) or goat (*Capra hircus*) enterprises and an average of 1.7 pigs (*Sus scrofa*) $\mathrm{household}^{-1}$. Dingxi farmers have fewer sheep/goats and pigs. Cattle (*Bos taurus*) are used for draught in Qingyang whereas donkeys (*Equus asinus*) are used in Dingxi.

4.3. Cropping system inputs

Inputs for staple food crops include fertilisers (organic and inorganic), seed, pesticides, herbicides and in some

Table 2
Summary of data on farming systems from farmer surveys in two contrasting environments on the Loess Plateau, Gansu Province

	Qinyang ($n = 80$)		Dingxi ($n = 55$)	
	Average (ha)	Comments	Average (ha)	Comments
Area of holdings	0.73	Range 0.4–2.1 (ha)	0.99	Range 0.2–1.5 (ha)
Winter wheat	0.36	Range 0.1–1.3 (ha)	Not suited to the area, killed by radiation frosts	
Spring wheat	Not grown in region, winter wheat more productive		0.31	Range 0–1 (ha)
Maize	0.17	Range 0.1–0.5 (ha), used for feed and food	–	Minor crop here
Legumes	–	Soybean is a minor crop	0.17 (pea)	Range 0–0.8 (ha)
Other cash crops	0.21	Sorghum, soybean, watermelon, millet, flax, peaches, apples, tobacco, vegetables, rapeseed/linseed, medicinal herbs	0.19	Potato, lentils, millet, forage sorghum, maize, lucerne
Typical rotation	Wheat–wheat–wheat/fallow–maize–soybean or linseed		Field pea–wheat–potato, lentil or linseed	
Slopeland/wasteland	Limited in Qingyang, slopes in very steep gullies may be grazed in some instances		0.3	Most farmers have some slopeland allocated, used for grazing, occasionally sown to lucerne
Livestock	80% of farmers have livestock		96% of farmers have livestock	
	Units/farm		Units/farm	
Cattle	1.0		0.26	
Sheep/goats	4.5		0.46	
Donkey	–		1.0	
Pigs	1.7		0.76	
	Rabbits and horses are also common in Qingyang area			

Table 3
Average inputs and input costs for grain crops from a survey of farmers in two contrasting environments on the Loess Plateau, Gansu Province in 2003

Inputs	Qingyang ($n = 75$)			Dingxi ($n = 54$)	
	Winter wheat	Maize	Soybean	Spring wheat	Field pea
Seeding rate (kg ha^{-1})	171	40	50	193	175
N as urea or $(NH_4)_2PO_4$ (kg N ha^{-1})	162	182	51	46	40
P as s-superphosphate (kg P ha^{-1})	9	13	5	19	19
Compound fertilisers (kg ha^{-1})	54	102	0	0	56
Animal manure applied[a] (t ha^{-1})	22	152	0	>7.5	7.7
Pesticide and herbicide cost (Y mu^{-1})	0.9	3.8	0	1	0.4
Cost of plastic (Y mu^{-1})	0	16	0	0	0
Cost per ha (Y)	1386	1722	933	497	477
Cost per ha (US\$)	173	215	117	62	60
Grain yield per ha (kg ha^{-1})	3628	6032	1770	976	790
Average percentage of crop kept	90	14	80	95	47

Note: All of these data relate to the crop harvest in 2003. For the purposes of this work a conversion of 1 Yuan to US\$ 0.125 has been used. Most values have been rounded to the nearest whole number. The standard unit of area in Chinese agriculture is the mu, of which there are 15 to the ha.

[a] Manure is usually mixed with soil prior to application to land, hence the values seem high, the fraction of this that is actually manure would be small.

situations, plastic mulch for soil moisture retention (see Li et al., 2004). Average usage rates obtained from the farmer surveys are listed in Table 3, along with approximate costs per unit area sown.

Overall, maize requires the greatest fertiliser input but provides the highest yields and the highest returns per unit area. In Qingyang in 2003 we calculated the gross margin of maize to be Y298 mu^{-1} (US\$ 559 ha^{-1}). However, in 2003 farmers only sold an average of 86% of their maize crop, and with average sowings of 0.17 ha farm^{-1}, this would equate to an income of US\$ 82 maize crop^{-1} farm^{-1}. The most profitable cash crops in Qingyang have been oilseed crops, apples and watermelon, which are grown by the majority of farmers. Orchard fruits provided an average yearly profit of ca. Y2500–Y4000 per mu (US\$ 4687–7500 ha^{-1}), but these require substantial capital and thus are usually established at the village level. Profits from cash crops and livestock sales commonly made up 60% of household income in Qingyang, whereas farmers in Dingxi indicated that only 28% of household income was generated on farm, mainly from potato and oilseed crops. In Dingxi, field pea was the principal cash crop sold. However, production of field pea carries the high opportunity cost of loss in wheat production for household use. Furthermore, after the costs of ploughing and broadcasting (estimated to cost >Y30 mu^{-1}, US\$ 56 ha^{-1}), profits from food crops in Dingxi are too small to support rural households and 72% of household income is derived from off-farm activities.

4.4. Livestock

Major livestock enterprises are outlined in Table 4 and Fig. 3. While almost all farmers (96%) in Dingxi had some livestock, 20% of farmers in Qingyang had none. However, the livestock data in Dingxi are skewed by the use of donkeys for draught, as although 78% of farmers had donkeys, 35% of farmers had no livestock other than the one donkey. The donkeys are relied on for labour and transporting of produce, and are favoured over cattle in Dingxi due to their lower cost and suitability to the more mountainous terrain. Farmers in Qingyang did not have donkeys and indeed only 30% of farmers there owned draught animals (i.e. cattle). Mechanized sowing and harvesting is more common here due to larger tracts of flatter land and higher farm incomes. Households in Dingxi with one donkey negotiated non-monetary agreements with other farmers during ploughing seasons for a second donkey to draw a plough. Non-monetary agreements were not common in Qingyang, and thus cattle owners obtained income by providing ploughing services to farmers without cattle, at 15 Yuan plough^{-1} mu^{-1} (US\$ 28 ha^{-1}).

Important feed sources for sheep, goats and cattle, include grazing on roadsides and other wastelands, crop residues after harvest and lucerne hay if it is available. Grazing and browsing of pastures and forage would be restricted to Dingxi farmers who might have access to sloping lands, but in Qingyang grazing is rarely practised as farmers there are more reliant on cut and carry livestock feeding systems. Maize and sorghum provide important feed for cattle in Qingyang, and other forage and grain crops and crop by-products are valuable there for pig production. Differences in livestock systems become more apparent in Fig. 3, where it can be seen that many more Qingyang farmers had more intensive livestock production enterprises than farmers in Dingxi. For example, in Qingyang, pork enterprises contained up to 30 animals, whereas in Dingxi

Table 4
Percentage of farmers surveyed in Qingyang and Dingxi maintaining different types of livestock or with no livestock

	Qingyang	Dingxi
Cattle	30	20
Sheep/goat	47	17
Pig	50	45
Donkey	0	78
No livestock	20	4

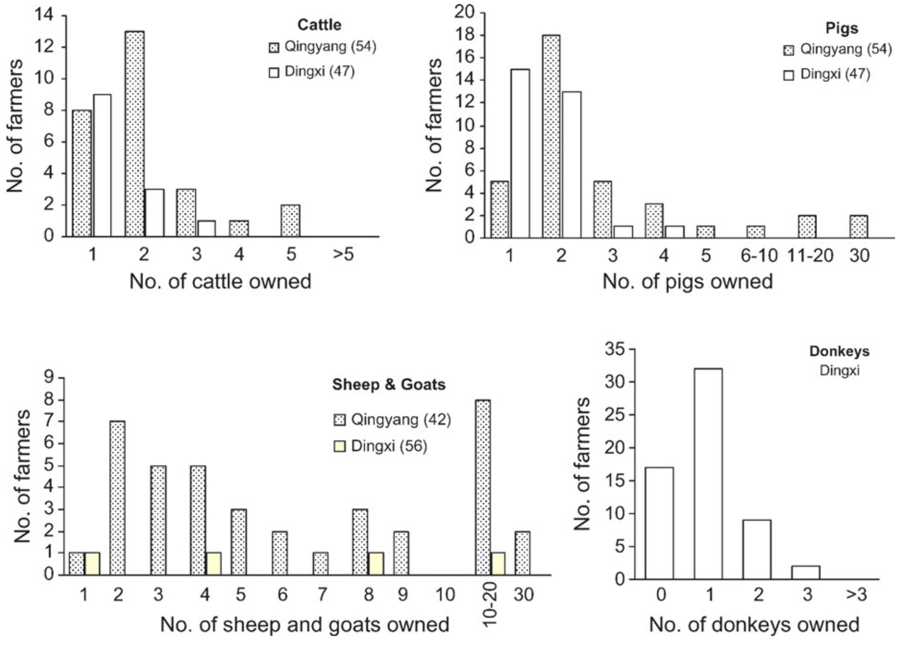

Fig. 3. Number of cattle, pigs, sheep (or goats) and donkeys owned by farmers surveyed in Qingyang and Dingxi districts. Values in brackets beside site names are the number of farmer respondents who had none of those livestock units. No farmers in Qingyang had donkeys.

farmers owned 0–2 pigs, with only exceptional farmers having three or four pigs. In Dingxi livestock are typically only sold in the case of crop failure or emergency. Introduced varieties of sheep (mainly Australian merino) and goats were common in Qingyang, with 10 farmers owning herds numbering 10–30 animals. In terms of profit, farmers indicated that 25 sheep can provide an income through the sale of lambs and wool of up to Y2400 (US$ 300) per year (based on July 2003 prices). This is ca. 23% more than the average yearly income for Gansu Province, and more profitable than breeding cattle, the traditional livestock enterprise in the region. Pigs were owned by half of all farmers at both sites, most often being kept in pens close to the home where they survive on household food scraps.

At both sites a number of small-scale enterprises were reported using specialist types of livestock imported from overseas. Representing large investments, these animals are bred to take advantage of growing niche market opportunities in city centres that favour quality meat, milk, wool and skin products. Specialist breeds included alpacas, chinchilla rabbits (similar to Hardiman et al., 1990), mohair and South African goats, yellow beef cattle (Europe) and dairy cows. The cost of establishing these types of enterprises is prohibitive for many farmers in Qingyang and most in Dingxi. For example, purchasing one productive dairy cow costs between 5000 and 10,000 Yuan depending on age (US$ 625–1250, based on July 2003 prices). This is 1.5–5 times the average yearly household income in Gansu Province. The most common way for specialist livestock to be introduced into rural villages is through a government or bank loan, or loans from city relatives, allowing the most affluent farmers to purchase one or two livestock for breeding. The majority of farmers however are excluded from such schemes and are unable to borrow against their farms or cash crop produce.

4.5. Barriers to adoption of new enterprises/technology

Farmers were invited to outline the issues that they considered needed improvement in order to remove any barriers to the development of new enterprises. Their responses (Table 5), ranked according to the farmers' priority, encompass economic, social and environmental issues. The issues were mostly common across sites, but the importance given to each varied, reflecting differences in climate and development of infrastructure between the two areas. Not surprisingly, low and variable rainfall and risk of subsistence crop failure was rated much higher in Dingxi than Qingyang. While a lack of starting capital was indicated as a constraint to farm development in both regions, it was seen as a greater constraint in Dingxi than Qingyang. Conversely, Qingyang farmers indicated problems with infrastructure, and support for new enterprises (trading networks, technical knowledge, veterinary support) was of higher concern than starting capital.

During the course of the interviews and surveys it became apparent that in both areas there were some innovative farmers that had been able to respond positively to opportunities (early adopters), and others that had not (conservative). Based on the survey data we allocated the farmers to each of these groups (Table 6). Early adopting farmers earned above average profits from cash crop and livestock enterprises through the adoption of new varieties and technologies. When questioned, they had implemented change on their farms in the past 2 years gaining information on how to do so from newly available resources, such as

Table 5
Barrriers to further development of agricultural enterprises as nominated by farmers surveyed in Qingyang and Dingxi

	Qingyang	Dingxi
General		
Aging labour base	*	*
Cropping		
Lack of starting capital	*	**
Declining land areas	*	**
Risk—low rainfall and yield (crop failure)	o	**
Risk—moving away from grain production	*	**
Lack of market and trading network for new varieties	**	*
Lack of knowledge for management of new varieties	**	*
Lack of suitable new varieties	*	*
Livestock		
Lack of starting capital	*	**
Access to veterinary advice	**	*
Animal nutrition, husbandry, diagnosing problems	**	o
Lack of market and trading network for new varieties	**	o
Lack of knowledge for management of new varieties	*	o
Risk—moving away from traditional cattle/donkey systems	o	**
Lack of suitable new varieties	o	*

Asterisks (**) indicate that this point was raised as an area of high concern amongst farmer participants, (*) of moderate concern and (o) of little concern.

farmer workshops, demonstration sites and through agricultural literature. These farmers were typically literate and actively participated in provincial trading. Conservative farmers were classified as those more traditionally minded who typically had a ‘wait and see’ approach toward new practices. In this group knowledge about farming practices is often intergenerational and localised, with farming advice typically sought through social networks, principally other farmers or the interpretation of first hand information. Livestock are considered important to the conservative systems for ploughing (cattle and donkey), organic manure production and their ability to feed on wheat straw and stubble.

5. Discussion

Farms in these two regions vary in their crop and livestock enterprises, and in the productivity of those enterprises. Working in eastern Gansu, Lu et al. (2003) indicated that ca. 30% of the arable area might be needed for subsistence grain production, close to the value (31%) obtained in the Dingxi survey, but lower than the 49% in the Qingyang farmer survey. Qingyang farmers are thus easily able to provide for their own food needs. However, in Dingxi where rainfall is lower and more variable, farmers are much less able to provide for their own subsistence grain needs, and to derive income from cash crops to further develop their enterprises. Indeed in Dingxi, in years of low rainfall, many farmers would struggle to be self-sufficient. Growing more wheat for household use in Dingxi would result in less cash crop income. Recognising the difficulties in accurately assessing gross margins (Chang, 2002; Yao, 2002), we calculated returns from spring wheat (US\$ 144 ha^{-1}) and field pea (US\$ 145 ha^{-1}) in Dingxi in 2003 that would be similar to those in many areas of the developed world. However, comparison of gross margins on a hectare basis is hardly relevant when the total area of sowings are small, and 100% of the wheat is retained for household use. Some of the inputs to cropping in Gansu may be higher than warranted. For example, in Dingxi, the sowing rates for wheat (193 kg ha^{-1}) and peas (175 kg ha^{-1}) seem inordinately high compared to other regions of the world, and the

Table 6
Characteristics of farmers and farming enterprises between innovative, early adopting and conservative farmer practices at Qingyang and Dingxi

	Early adopters	Conservative farmers
Percentage of farmers		
Qingyang	58	42
Dingxi	22	78
Years of education		
Qingyang	9	7.5
Dingxi	6	5.5
Key information sources		
Qingyang and Dingxi	Television, research stations/demonstration sites, Chinese agricultural journals, newspapers, farmer workshops	Other farmers, local markets, television (some), extension agents, agricultural store workers
Livestock enterprises		
Qingyang	Beef and dairy cattle, Chinchilla rabbits, introduced sheep (e.g. Merino) and goats	Traditional cattle systems
Dingxi	Dairy cattle, long tailed sheep, pigs	Traditional cattle systems
Cash crops		
Qingyang	Apples, watermelon, canola, now investing in lucerne	Mostly grain production and, some cash crops
Dingxi	Potato, linseed, peas, some investment in lucerne	Mostly grain production and, some cash crops

application of 40 kg N ha^{-1} to a N_2 fixing crop legume such as pea may not be required at all (Unkovich and Pate, 2000). It may thus be possible to reduce input costs for some of these crops. Nevertheless, when providing grain for household consumption and meeting village grain quotas, Dingxi farmers receive little cash, and often not enough to adequately feed, clothe and educate rural households. This is illustrated in the two examples below, obtained during the interviews.

One younger male farmer (45) has a wife and 2 grandchildren and grows 3 mu of wheat from a total of 8 mu. To ensure an adequate yearly supply of grain, he must purchase 300 kg of surplus wheat from government sources. He is only able to do this by selling the piglets produced by his 2 pigs and selling the yield from his 1 mu of field pea (Dingxi).

One female farmer (36) is able to grow 9 mu of wheat as she consolidated her land with that of her parents (now totalling 15 mu). She must swap half of her field pea crop (7 mu) for enough grain to feed a family of six. This means that her family only has the yield from 3.5 mu of field pea from which to derive a yearly cash income. In a good year, this would equate to 150 Yuan (US$ 18.75), which is not enough to send one child to the local school for one year (currently 200 Yuan per annum) (Dingxi).

In Qingyang farmers also keep almost all of their wheat for household use, but are able to sell surplus maize and soybean as well as various fruit and vegetable crops and livestock. One option for farmers to increase income is through increases in productivity. Although wheat yields in this region may be similar to comparable areas of the world (Sadras and Angus, 2006), there is good evidence that improved practices in the region can increase grain yields above those currently obtained (Huang et al., 2003; Lu et al., 2003). In Qingyang this is likely to result in considerable increases in farm income. However, for farmers in Dingxi, this is unlikely to be of sufficient benefit to relieve their poverty as less than one third of those surveyed indicated that they could live off income generated on the farm. Rozelle et al. (2002) similarly showed that farmers totally dependent on farm production for income were likely to be below the poverty line. Working in another province, McCulloch and Calandrino (2003) found that poverty in low-income rural households was often transient rather than chronic, and there is no doubt that in years when there are low yields or crop failures, farmers in Dingxi especially, will remain unable to feed themselves. While some farmers did their best to minimise risk by storing 2 years of grain yield and keeping adult cattle or donkeys to sell in case of emergency, in times of sustained crop failure they would have no choice but to rely on food aid programs. Substantive benefits from increased grain productivity in Dingxi would only come if coupled with increased areas of sowing/household. In some districts government policy is actively aimed at reducing the rural population density and so some gains may be made in this arena.

In Dingxi the low and variable rainfall and mountainous terrain limits the types of produce that can reliably be grown, and as farming cannot return adequate household income, young household members are obliged to work off farm to support their families, providing 72% of household income. With younger males gone, farming decisions are often left to the elderly, women and children that are left behind to manage the farm (see Jacka, 1997). High illiteracy rates in this group reduce assimilation of new information and exclude farmers from accessing information through agricultural literature. Conservative farmers were often reliant on other farmer's interpretation of their problem or information. As highlighted by Zhen et al. (2005), this may result in the misinterpretation of seeding, fertiliser, herbicide rates, etc. Farmers stated that expertise was difficult to access in current extension networks which remain under resourced (Sonntag et al., 2005). Other studies (e.g. McCulloch and Calandrino, 2003) correlate low education rates with poverty, showing that lower schooling rates contribute to a reduction in crop productivity and household income.

Farmers explained that they had little access to veterinary advice and little idea about animal nutrition, husbandry or the diagnosis of disease. The situation was considered critical and most farmers had lost a mature cow or a calf over the past 10 years. However, early adopting farmers were found to have a higher literacy rate than conservative farmers, giving them access to a wider variety of information about new innovations. Sources included agricultural television programs, Chinese agronomy journals and newspapers. These were important for providing advice on problems with new varieties and were also used to anticipate market prices and demand in city centres. This was a key difference to conservative farmers who relied on social networks for information. Two pertinent examples from the interviews are highlighted below.

Two Qingyang farmers commented, 'I don't think the old practices are good, we can do better'. After reading a journal article, the two farmers were using wider row spacing and a lighter seeding rate than traditional methods. Today, they were experiencing much higher yields and are now selling 100% of the crop. They are actively encouraging other farmers to follow and are no longer planting wheat.

One participant had attended an agricultural exhibition at a local university and brought back seeds for a new apple variety that he was trailing with other farmers on his plot. Together they planned to graft the variety with Fuji apples to lessen the risk of selling the new product (Qingyang).

Other sources of information that were considered to be valuable involved visits to local government demonstration areas showcasing new livestock breeds and cash crops suited to the region. In interviews however, farmers commented that there was rarely anybody at these sites to seek advice from, and farmer workshops were rare. Visits were also made to the local research station in Qingyang whose research director had become a much sought after and trusted source of advice on farming problems. Trust was a priority for early adopting farmers hoping to lower the risk of losing capital in new markets. Given the importance of local social networks and trust for adoption of new enterprises (McWaters and Templeton, 2005) we suggest support for local 'champion' farmers (i.e. early adopters) to participate in on-farm research trials, as farmers at both sites stated that they would feel more comfortable in visiting a local farmer's plot than trials at an unfamiliar research station. If local champion farmers were trained in basic experimental principles, then accurate local technical information could be passed verbally from farmer to farmer.

The capacity of early adopting farmers to generate a sustained income from their farming practices improved the economic resilience of their households. Income was generated through sale of cash crop and livestock produce in large cities, which was occasionally sold through farmer cooperatives. With better information about market opportunities, early adopters were often selling produce in provincial and eastern city markets at prices that were 30–50% higher than those offered by the State. In Qingyang, early adopters were successful to the point that ca. 60% of household income was gained exclusively from cash cropping and sheep enterprises. Profit was commonly reinvested into the farm or saved for emergencies.

Movement into new rural enterprises, requires capital and also carries an element of risk. This study found that while the majority of farmers would like to adopt a form of innovation into their farming systems, entering new markets had proved to be a high-risk venture, with some losing their initial investments through price fluctuations or uninformed management. Barriers to adoption of new enterprises highlighted by the farmers included climatic risk (Dingxi), insufficient technical agronomic information, lack of capital, market access and price volatility.

Farmers attempting to enter new markets in Dingxi, lacked both the knowledge of suitable varieties and the capital required to make initial purchases. Most were ineligible for a bank loan, leaving them reliant on the small amounts of money sent from younger household members working away from the farm, or on informal lending agencies (at very high rates). At present, no formalised micro-finance loans appeared to be available to farmers, leaving them to rely on informal and unregulated money lending networks. In some cases, a lack of capital was found to be extreme and farmers were borrowing against projected crop yields in order to purchase the inputs required for their next crop. Experiences from other countries show that a lack of a regulated rural banking system reduces growth in the rural sector and retards poverty alleviation efforts (Sonntag et al., 2005). Partnerships need to be formed between farmers and government or industry, to share with farmers the risk of entering new markets (see McWaters and Templeton, 2005).

To minimise the risk of entering new markets, some farmers were growing new varieties in small co-operatives, producing consignments large enough to attract traders from the eastern provinces and allowing farmers to negotiate a better price for their produce. Additional benefits included the opportunity to be part of an information-sharing network that also had greater access to extension services. Examples of farmer cooperatives are provided below.

Small numbers of farmers in Dingxi were growing an American variety of potato that met the requirements of large corporations that made French fries.

A group of eight farmers in Qingyang heard about the higher prices of canola oil in the eastern Provinces and had formed a cooperative. Using techniques gained from agricultural television programs, these farmers were now producing a higher quality product and sending consignments to Shanghai.

14 households in a village of 77 have decided to not plant wheat this year for the first time and instead are sharing the risk of establishing an apple orchard for the village by each donating some land. This enterprise will take four to ten years to become productive (Qingyang).

In Qingyang, farmers emphasised that entering new markets was still high risk, as they lacked secure access to trading networks and price guarantees. Returns from new enterprises were never guaranteed. Farmers explained that if a local government policy promotes the production of specific crops or livestock, this drives the price of the commodity temporarily up. While well-placed farmers are able to take advantage of such price increases, the majority (conservative farmers) are left scrambling to purchase at inflated prices. Very quickly, the market becomes oversupplied and prices fall dramatically, as illustrated by one livestock farmer below.

On the 22nd of April, he sold 4 newborn lambs and received 900 Yuan. Ten days later the price of sheep had dropped and 4 adult sheep were only worth 150 Yuan each.

This is an important example of Government policy driving up prices, leading to oversupply and low prices that hurt followers. The lucerne on sloping land policy is another example, the price of lucerne hay now having fallen in some areas due to oversupply. The low price is a disincentive for new lucerne plantings and once the Government policy changes the situation is likely to be worse than if they had not had the policy at all, and instead placed emphasis on supporting and regulating the development of markets for new products.

Farmers suggested that agribusiness companies could ‘loan’ new seeds to farmers, including for initial trial periods and, if successful, recover costs through a percentage of profits from sale. Incentives for farmer participation could include a compensation agreement for failed cropping trials as grain subsidies or cash. Farmers also suggested that to improve rates of mechanisation, machinery needs to be pooled at a village level and hired or loaned to farmers as required. Farmers should be able to pay for the service after sale as the current system of paying up front excludes poorer farmers.

Government policies aimed at facilitating sowing of perennial forages and movement into livestock enterprises and away from grain cropping are likely to have a number of benefits in the longer term, especially in Dingxi. Erosion is likely to be reduced, and cultivation of lucerne (*M. sativa*) for green fodder should improve animal nutrition substantially. By providing animal feed on a cut and carry basis, livestock will not need to be grazed in marginal areas, reducing soil degradation further, and also saving scarce farm labour as animals will not need to be shepherded in marginal areas and wastelands. Furthermore, improved livestock breeds (e.g. Merino sheep and South African goats), which are already introduced in Qingyang, sell for considerably more than traditional breeds and demand for quality produce will increase in line with the rise in disposable incomes (Longworth et al., 2001).

Deng et al. (2005) examined the contributions of irrigation, labour, fertiliser, mechanization and total factor productivity to farm growth in NW China. In Gansu Province they found fertiliser (22%), mechanization (29%) and TFP (28%) contributed to >80% of productivity increase between 1978 and 1998. Irrigation contributed to 9% of growth but this is limited in the region by a shortage of water resources, although significant gains in water use efficiency are probably achievable (farm labour contributed 11%). Levels of mechanisation in Qingyang were modest, but increasing, but in Dingxi almost non-existent. Mechanisation should bring with it environmental benefits if it means that some crop stubbles can be retained in situ, reducing erosion and increasing water infiltration and soil water storage for crop growth (Bissett and O’Leary, 1996; O’Leary and Connor, 1997). However, for this to be achieved, alternative household fuel sources will need to be available and affordable. It has previously been pointed out (Xu et al., 2006) that Gansu’s poor natural resource base and social infrastructure (science, education and management) seriously limit agricultural productivity. We would also maintain that the government’s *Grain for Green* policy is likely to reduce grain production more in Gansu than other provinces, and more in areas with sloping land like Dingxi than in flat areas like Qingyang, Seventy percent of our study population in Dingxi were required to convert cropping land located on slopes to perennial cover, further reducing the capacity of the poorest farmers to provide for their own food needs. Average wheat yields of flat or gently sloping land (<15°) are estimated to be about three times (3.8 t ha^{-1}) those on sloping (>15°) ground (1.2 t ha^{-1}; Feng et al., 2003). Those households with sloping land relied heavily on government wheat subsidies. However, as this program may be withdrawn in some areas, some farmers are having to revert to crop production on sloping land. In higher rainfall areas of the plateau such land use change has been achieved successfully through the implementation of a combination of social, economic and environmental policies (Zhang et al., 2004).

The present study has described two farming systems in China’s poorest rural province. Since the size of the survey was limited to five villages and a total of only 125 farming families the results may only be representative of some local areas of Gansu Province, nevertheless the results presented here provide insight into two contrasting farming systems. One (Qingyang), in a relatively higher rainfall zone, and based on winter wheat, maize, fruit and a range of livestock enterprises, provides sufficient cash flow for farmers to invest in new enterprises, especially livestock, diversifying their portfolio and increasing their capital and reducing risk. Here >70% percent of household income is derived from farming activities. The other farming system, in Dingxi, a lower rainfall area, and including some sloping land, is based around spring wheat, peas, lentil, oilseed crops and potatoes. Here farmers struggle to provide sufficient grain for their own household use, and have insufficient cash flow to invest in new, possibly more profitable enterprises. Rural householders here obtain >70% of income from off-farm sources. In order for farmers in Dingxi to progress away from subsistence farming and rural poverty the following will be required:

(a) starting capital, through microcredit lending schemes or partnerships with industry or government.
(b) greater access to reliable and accurate information about new crop varieties and livestock breeds.
(c) management trading networks and co-operatives to ensure reliable markets and reliable supply from growers.
(d) further consolidation of farm size into larger units.

Government policies aimed at reducing population density in rural areas are also likely to be of considerable benefit. In higher rainfall Qingyang, farm productivity is such that cash crops provide resources for farmers to invest in new enterprises, however, here problems with a lack of technical agronomic and veterinary support, and unreliable markets make many farmers cautious about new enterprises. In this case better agricultural extension networks and partnerships with industry and suppliers is likely to be of great benefit. Increasing crop yields through improved agronomic management will be valuable in both regions, but the social and economic framework required to realise these potential gains needs to be addressed. This is particularly the case for lower income, resource poor farmers of Dingxi.

Acknowledgements

We are grateful to the Australian Centre for International Agricultural Research (ACIAR) who provided support for the senior author under the The Australian Youth Ambassador for Development (AYAD) Scheme. The support of the ACIAR project (LWR2/1999/094) team is acknowledged. Thanks to Gao Chongyue for critical local advice and Mr. Li in Dingxi for assistance with translation in the field, to Jocelyn Davies for editing and field support and Oliver Percovich for comments on an earlier draft.

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Huang, GB, Zhang, RZ, Li, GD, Li, LL, Chan, KY, Heenan, DP, Chen, W, Unkovich, MJ, Robertson, MJ, Cullis, BR, Bellotti, WD. (2008) Productivity and sustainability of a spring wheat – field pea rotation in a semi-arid environment under conventional and conservation tillage systems. *Field Crops Research* 107, 43-55.

Available online at www.sciencedirect.com

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Field Crops Research 107 (2008) 43–55

Field Crops Research

www.elsevier.com/locate/fcr

Productivity and sustainability of a spring wheat–field pea rotation in a semi-arid environment under conventional and conservation tillage systems

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Received 25 August 2007; received in revised form 18 December 2007; accepted 19 December 2007

Abstract

A long-term rotation experiment was established in 2001 to compare conservation tillage techniques with conventional tillage in a semi-arid environment in the western Loess Plateau of China. We examined resource use efficiencies and crop productivity in a spring wheat (*Triticum aestivum* L.)–field pea (*Pisum arvense* L.) rotation. The experimental design included a factorial combination of tillage with different ground covers (complete stubble removal, stubble retained and plastic film mulch). Results showed that there was more soil water in 0–30 cm at sowing under the no-till with stubble retained treatment than the conventional tillage with stubble removed treatment for both field pea (60 mm vs. 55 mm) and spring wheat (60 mm vs. 53 mm). The fallow rainfall efficiency was up to 18% on the no-till with stubble retained treatment compared to only 8% for the conventional tillage with stubble removed treatment. The water use efficiency was the highest in the no-till with stubble retained treatment for both field pea (10.2 kg/ha mm) and spring wheat (8.0 kg/ha mm), but the lowest on the no-till with stubble removed treatment for both crops (8.4 kg/ha mm vs. 6.9 kg/ha mm). Spring wheat also had the highest nitrogen use efficiency on the no-till with stubble retained treatment (24.5%) and the lowest on the no-till with stubble removed treatment (15.5%). As a result, grain yields were the highest under no-till with stubble retained treatment, but the lowest under no-till with no ground cover treatment for both spring wheat (2.4 t/ha vs. 1.9 t/ha) and field pea (1.8 t/ha vs. 1.4 t/ha). The important finding from this study is that conservation tillage has to be adopted as a system, combining both no-tillage and retention of crop residues. Adoption of a no-till system with stubble removal will result in reductions in grain yields and a combination of soil degradation and erosion. Plastic film mulch increased crop yields in the short-term compared with the conventional tillage practice. However, use of non-biodegradable plastic film creates a disposal problem and contamination risk for soil and water resources. It was concluded that no-till with stubble retained treatment was the best option in terms of higher and more efficient use of water and nutrient resources and would result in increased crop productivity and sustainability for the semi-arid region in the Loess Plateau. The prospects for adoption of conservation tillage under local conditions were also discussed.

Keywords: No-tillage; Stubble retention; Plastic film mulch; Grain yield; Water use efficiency; Nitrogen use

1. Introduction

Semi-arid areas on the western Loess Plateau, China are characterized by serious soil erosion (Fu, 1989; Liu, 1999), at least partly due to years of intensive tillage. The common practice is to prepare a seedbed by 3 ploughs and 2 harrows,

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doi:10.1016/j.fcr.2007.12.011

which is believed to capture and store more precipitation in soils during the fallow season in this low and extremely variable rainfall environment. Furthermore nearly all stubble and crop residues are normally removed from the field at harvest for animal feed or fuel for heating or cooking (Lal, 2007). The soil surface is thus normally left bare for the 7–8 months after harvest in late summer, until early spring (April) next year when the following crop is sown. In this region there is only one crop each year, which coincides with part of the wet season in July–September. All these practices have been shown to exacerbate degradation of soils, promote erosion and reduce production potential (Hobbs, 2007).

The severe erosion has been recognized by central and provincial governments of China. In the late 1990s, the Gansu provincial government implemented strategies to reduce farmer reliance on grain production and retire cropland to trees or pastures (MOA, 2001; Feng et al., 2003). However, the western Loess Plateau is an area with a long history of crop production and local farmers are reluctant to convert their cropland to trees and/or pastures (Rui et al., 2002). In addition, the local, mainly subsistence farmers are unwilling to forgo the use of biomass either as fodder or as fuel for heating by leaving it in the field, and thus many are trapped in a cycle of soil degradation. Therefore, development of an effective agronomic practice is needed to reduce erosion while also increasing crop productivity.

Conservation tillage (CT), no-till with stubble retention, has been found to have many long-term benefits around the world, including improvement in water infiltration and reduction in soil erosion (Freebairn and Boughton, 1985), increasing soil organic carbon content (Chan and Heenan, 2005), and improving soil physical properties (Fabrizzi et al., 2005). As a result, crop productivity is often improved. In addition to providing higher grain yields, CT can reduce input costs by eliminating a series of conventional tillage operations (Landers et al., 2001; Hobbs, 2007). Most economic analyses have confirmed the superiority of CT compared to traditional conventional tillage systems (Brown et al., 1989; Williams et al., 1990).

Conservation tillage research in China started in the early 1990s. Research in Shanxi and Shaanxi Provinces, commenced in 1992, showed that CT can help ease environmental problems, improve crop productivity, and increase sustainability of rainfed agriculture (Gao and Li, 2003). However, little research on CT had been undertaken in the semi-arid areas on the western Loess Plateau. In 2001, an international collaborative project was established to examine and promote conservation tillage techniques on the western Loess Plateau. This study tested the hypothesis that resource use efficiencies and crop productivity could be increased with a combination of no-tillage and stubble retention compared with current farming practices in this low rainfall environment. Local authorities have promoted the use of clear plastic film to conserve soil moisture and raise seedbed temperatures in spring and for this reason two plastic film mulch treatments were also included in the experimental design.

2. Methods and materials

2.1. Site description

The field experiment was conducted from 2001 to 2005 at the Dingxi Experimental Station (35°28′N, 104°44′E, elevation 1971 m a.s.l.) of Gansu Agricultural University, Anding County, Gansu Province, northwest China. The site had a Huangmian soil (Chinese Soil Taxonomy Cooperative Research Group, 1995), aligning with a Calcaric Cambisols in the FAO soil map of the world (FAO, 1990). It is a sandy-loam with low fertility soil organic carbon below 7.63 g/kg and Olsen P below 13.3 mg/kg (Table 1), representing the major cropping soil in the district (Zhu et al., 1983) and one of two dominant soils on the Loess Plateau. Long-term annual rainfall at Dingxi averages 391 mm, ranging from 246 mm in 1986 to 564 mm in 2003, with about 54% received between July and September. Daily maximum temperatures can reach up to 38 °C in July, while minimum temperatures can drop to −22 °C in January. Hence, summers are warm and moist, whereas winters are cold and dry. Annual accumulated temperature >10 °C is 2239 °C and annual radiation is 5929 MJ/m^2 with 2477 h of sunshine. The site had a long history of continuous cropping using conventional tillage. The crop prior to the experiment commencement in 2001 was flax (*Linum usitatissimum* L.).

2.2. Experimental design and treatment description

The experiment had a fully phased 2 × 3 factorial design, 2 phases, replicated 4 times (blocks). Spring wheat (cv. Dingxi

Table 1
Soil chemical and physical properties at the start of experiment

Depth (cm)	pH (water)	Organic carbon (g/kg)	Total N (g/kg)	Total P (g/kg)	Olsen P (mg/kg)	Available K (mg/kg)	Bulk density (Mg/m^3)
0–5	8.3	7.63	0.85	1.89	13.3	349.6	1.29
5–10	8.4	7.46	0.87	1.92	11.5	330.2	1.23
10–30	8.3	6.93	0.78	1.82	4.9	244.0	1.32
30–50	8.3	6.63	0.78	1.72	1.8	173.0	1.20
50–80	8.3	7.29	0.81	1.71	2.1	123.1	1.14
80–110	8.4	7.49	0.80	1.75	2.1	101.5	1.14
110–140	8.4	6.60	0.73	1.71	1.6	102.5	1.13
140–170	8.4	6.51	0.66	1.71	1.8	102.0	1.12
170–200	8.4	6.15	0.59	1.70	2.2	104.1	1.11

No. 35) and field pea (cv. Yannong) were sown in rotation in both phases represented in each year. Phase 1 started with spring wheat, followed by field pea and phase 2 started with field pea, followed by spring wheat. Therefore, there were 48 plots in total. Plots were 4 m wide × 17 m long in block 1, 21 m long in blocks 2 and 3 and 20 m long in block 4.

The treatments were split into 2 groups due to different sowing machines used. In group 1 (treatments 1–4), all crops were sown by a small no-till seeder (5–6 rows in 1.2 m width) designed by the China Agricultural University. The no-till seeder, drawn by a 13.4 kW (18 HP) tractor, was designed to place fertilisers below the seeds using narrow points followed by concave rubber press wheels in one operation. In group 2 (treatments 5 and 6), all crops were sown by a locally designed seeder. The local seeder, drawn by animal power, was designed to form a ridge, lay the plastic film, sow the seeds and apply fertilisers in one operation.

2.2.1. Conventional tillage with stubble removed (T)

Seedbed was prepared by 3 ploughs and 2 harrows using animal power, then sown by the no-till seeder. Cultivation started immediately after harvest of the previous crop (July–August), with a second ploughing before winter (October) and third cultivation prior to sowing in spring (March–April), all to a depth of 10–20 cm. Harrowing was carried out prior to sowing in spring. All stubble was removed before cultivation. This represents the typical tillage practice in the western Loess Plateau.

2.2.2. No-till with stubble removed (NT)

No cultivation was performed throughout the season. The crops were sown with the no-till seeder. All the stubble was removed at crop harvest.

2.2.3. Conventional tillage with stubble incorporated (TS)

Cultivation was the same as treatment for T, however all stubble from the previous crop was returned to the original plot immediately after threshing and then incorporated into the soil with the first cultivation. In 2001, chopped wheat straw (5–10 cm in length) was used at 6.8 t/ha on both the field pea and wheat plots. The crops were sown with the no-till seeder.

2.2.4. No-till with stubble retained (NTS)

No cultivation was performed throughout the season. All the stubble from the previous crop was returned to the original plot on the soil surface without incorporation. Chopped wheat straw was used as described in treatment 3 in 2001. The crops were sown with the no-till seeder.

2.2.5. Conventional tillage with plastic film mulch (TP)

Plots were cultivated 3 times and harrowed twice before the plastic film (0.5 mm thick) was laid out in October. All stubble was removed before cultivation. The clear plastic film was laid out using the local seeder which was also was used to sow both spring wheat and field pea.

2.2.6. No-till with plastic film mulch (NTP)

All stubble was removed before plastic film (0.5 mm thick) was laid out in October. The crops were sown by the local seeder.

2.3. Sowing rate, fertilisers and field management

Spring wheat was sown at 187.5 kg/ha in mid-March and harvested in late July to early-August each year. Field pea was sown at 180 kg/ha in early-April and harvested in early-July each year. The row spacing was 20 cm for spring wheat and 24 cm for field pea for group 1 treatments using the no-till seeder. For group 2 treatments, crops were sown in paired rows on both sides of the furrow, 10 cm apart, providing alternate 10 and 40 cm row spacing, averaging 25 cm using the local seeder.

Nitrogen and phosphorus were applied at 105 kg N/ha as urea (46% N) and at 45.9 kg P/ha as calcium superphosphate (6.1% P) for spring wheat, and 20 kg N/ha and 45.9 kg P/ha for field pea. No farm manure was used in this experiment. Field peas were not inoculated when sown as no appropriate rhizobia were available on the market. However, the site had history of field pea in the previous 3 years.

Roundup® (glyphosate, 10%) was used for weed control during fallow after harvesting as per the product guidelines. During the growing season, weeds were removed by hand. Pests and diseases were monitored and controlled as per conventional practice in the area. The plastic film was removed from plots after crops were harvested.

2.4. Measurements

2.4.1. Climatic data

Climatic data were collected between 2001 and 2005 at the Dingxi Experimental Station, 1 km from the experimental site, including daily precipitation, recorded manually; air temperature and solar radiation, recorded automatically hourly and every 5 min, respectively, using a TinyTag™ data logger. Historical climatic data were obtained from the nearest weather station located at Dingxi city, 15 km from the experimental site.

2.4.2. Seedling density

Seedling density was measured at 6–8 weeks after sowing using a quadrat (3 rows × 1 m), replicated 3 times in each plot.

2.4.3. Dry matter (DM)

Dry matter was measured at seedling (3–5 leaf stages), anthesis (80% flowering) and harvest stages, using quadrat cuts (3 rows × 1 m), replicated 3 times in each plot.

2.4.4. Grain yield

The whole plot was harvested manually using sickles at 5 cm above ground. The edges (0.5 m) of the plot were trimmed and discarded. Samples were then processed to obtain grain yield, straw and chaff. All straw and chaff from stubble incorporated treatments and stubble retained treatments were returned to the original plots immediately after threshing.

2.4.5. Soil moisture

A 2-m long aluminium access tube was installed in each plot when the experiment started in August 2001. Soil moisture content was measured using a Neutron Moisture Metre (NMM, Campbell Pacific, CPN 503) every 2 weeks at 10–30, 30–50, 50–80, 80–110, 110–140, 140–170 and 170–200 cm. The soil moisture contents at 0–5 and 5–10 cm were measured gravimetrically every 2 weeks. The NMM was calibrated following the procedure described by Greacen and Hignett (1979). The drained upper limit (DUL) and crop lower limit of water extraction (CLL) were determined as described in Dalgliesh and Cawthray (1998).

2.4.6. Soil bulk density

The bevelled stainless steel ring, 100 cm^3 with 5.05 cm in diameter and 5.00 cm in height, was used to measure soil bulk density (Carter, 1993) in a soil pit near the experimental site in 2002. Two soil cores were taken at 0–5, 5–10, 10–30, 30–50, 50–80, 80–110, 110–140, 140–170 and 170–200 cm as duplicates. In the laboratory, the soil cores were carefully trimmed at both ends, then oven-dried at 105 °C to determine bulk density.

2.4.7. Soil nitrogen

Soil samples were taken at 0–5, 5–10, 10–30, 30–50, 50–80, 80–110, 110–140, 140–170 and 170–200 cm before sowing and after harvest each year, ten cores per plot for the top 3 depths, bulked into one sample for each plot, and one core for the remaining depths for each plot. Nitrate nitrogen (NO_3^--N) in the soils was determined using $FeSO_4$/Zn reduction method described by Carter (1993).

2.4.8. Plant nitrogen

Nitrogen in grain and crop residues (straw and chaff) were determined using the method described by Lu (2000).

2.4.9. Nitrogen fixation

Nitrogen fixation by field pea was estimated in 2005 using the method of ^{15}N natural abundance as described by Armstrong et al. (1994). At anthesis, 5 individual field pea plants were cut at ground level from each plot, bulked into one sample and dried at 60 °C for 24 h. At the same time, 5 non-legume plants (weeds) from the plot were also collected and oven-dried at 60 °C as ‘reference plants’. Both the legumes and reference plants were ground through 1 mm mesh, then sub-sampled and finely ground prior to analysis of ^{15}N natural abundance using continuous flow isotope ratio mass spectrometry (Dawson and Brooks, 2001).

2.5. Calculations

2.5.1. Soil water storage

Soil water storage (mm) at a given depth increment was calculated as the volumetric soil moisture (%) multiplied by depth of soil (cm) divided by 10 and the total soil water storage for the whole profile (mm) is the sum of soil water storage for all depth increments.

2.5.2. Evapotranspiration

Evapotranspiration (ET, mm) was calculated as the difference between precipitation (mm) and the change in soil water storage (mm) over the observation period. There was no runoff observed during the period of the experiment. The soil water content at depth never approached the drained upper limit and so it could safely be assumed that there was no drainage.

2.5.3. Water use efficiency

Water use efficiency (WUE, kg/ha mm) was calculated as grain yield divided by ET. Fallow efficiency was calculated as the percentage of stored soil water over the total rainfall during the fallow period (Felton et al., 1987).

2.5.4. Nitrogen fixation

Nitrogen fixation by field pea was calculated as follows:

$$\%\text{Ndfa} = \frac{\delta^{15}\text{N(weeds)} - \delta^{15}\text{N(legume)}}{\delta^{15}\text{N(weeds)} - B} \times 100 \qquad (1)$$

where %Ndfa is the percentage of plant total N derived from fixation; δ^{15}N(weeds) is the natural abundance of ^{15}N in reference plant (weeds); δ^{15}N(legume) is the natural abundance of ^{15}N in legume (field pea), and B represents a measure of the isotopic fraction associated with redistribution of N between roots and shoots.

2.5.5. Nitrogen use efficiency

Nitrogen use efficiency (NUE) for spring wheat was calculated as follows:

$$\%\text{NUE} = \frac{\text{Plant N uptake}}{\text{NO}_3^-\text{N at sowing} + \text{Fertiliser N}} \times 100 \qquad (2)$$

In this calculation, NH_4-N was not included as NH_4-N concentrations were very low ($\leq$1 mg/kg). Nitrogen mineralized from soil organic matter during the growing season was not included either.

2.5.6. Nitrogen balance

Nitrogen balance was calculated over 4 years with two complete rotation cycles. Nitrogen inputs included N in fertilisers and N in seeds. The N in straw brought into the system (6.8 t/ha) in 2002 was also taken into account for TS and NTS treatments. Total N output includes grain N and stubble N if stubble was removed (e.g. T, NT, TP and NTP treatments). Nitrogen fixed by field pea in 2001–2004 was extrapolated using data in 2005 as no data were available in 2001–2004.

2.6. Data analysis

Agronomic traits, changes in soil water storage over time and soil water profiles, evapotranspiration and water use efficiency were considered in the analysis. Plant N uptake for spring wheat, N fixation for field pea and the overall nitrogen balance over two rotational cycles were also analysed. A linear mixed model was used to perform the analysis of variance. This mixed model included random effects which accounted for design and randomization structure (spatial variability) as well as accounting for the serial dependence in the sequences (temporal variability) of repeated measurements on each plot and block. Effects of tillage (conventional tillage vs. no-till), stubble (stubble removed vs. stubble retained) and their interactions were taken into account in group 1, whereas only the tillage effect was compared in plastic film mulch treatments. The fixed effects were tested using an approximate F-test and the random effects were tested using a Chi-squared test based on the residual maximum likelihood ratio test. All data were analysed using ASReml (Gilmour et al., 2004).

3. Results

3.1. Soil water storage

It was a wet year in 2003 and a dry year in 2004 (Table 2). In August 2003, rainfall was 148.7 mm, much higher than the long-term average (82.6 mm), whereas in August and September 2002, the rainfall was only 51% and 52% of the long-term average in those months, respectively. The in-crop rainfall for the study period (2002–2005) ranged from 120 to 176 mm for field pea, and from 178 to 298 mm for spring wheat (Table 2). Soil water storage to 200 cm depth was closely related to the seasonal rainfall pattern with the wettest soil profiles (up to 385 mm) in early-November 2003 and the driest soil profiles (down to 217 mm) in mid-December 2002 for all treatments in both phases 1 and 2 (Fig. 1). Crop lower limit was 189 mm for spring wheat and 241 mm for field pea; drained upper limit was 554 mm.

There were no statistically significant differences for the soil water storage in the 0–200 cm soil profile between either tillage or ground cover treatments at sowing. However, there were significant difference in soil water storage at 0–30 cm between tillage treatments, and between stubble treatments ($P < 0.001$) in group 1, but no difference in soil water storage between tillage treatments under plastic film mulch at 0–30 cm. In group 1, the NTS treatment had the highest soil water storage whereas the T treatment had the lowest for field pea (60 mm vs. 55 mm) and spring wheat (60 mm vs. 53 mm) in 0–30 cm at sowing (Table 3). Plastic film mulch treatments had the similar soil water storage to the NTS treatment in group 1. Overall, there was 23 mm more water under spring wheat than field pea at sowing in the 0–200 cm soil profile.

There was always a higher soil moisture content at 10–30 cm than at 0–5 and 5–10 cm except for some treatments in 2003 and 2005 (Fig. 2). The treatments with stubble retained (TS and NTS) had more soil moisture than treatments with stubble removed (T and NT) at 10–30 cm ($P < 0.05$). However, the soil water profiles were well below the drained upper limits. In fact, none of the soil profiles amongst the different treatments had filled to the drained upper limit (DUL) for the duration of the experimental period, even in the wettest year (2003) with 564 mm of rainfall (Fig. 1). The soil moisture content was close to crop lower limit (CLL) in the soil profile below 100 cm for field pea in 2002 and 2003 (Fig. 2). In 2002, the soil moisture content at 0–5 cm for all treatments except for NTS was below crop lower limit (CLL) for field pea. In 2004, soil profiles of all the treatments were wetter compared with other years, due to the above average rainfall in autumn in 2003.

There was a significant interaction between stubble and tillage in group 1 treatments for water use efficiency (WUE, $P < 0.001$), but no significant differences in WUE between tillage treatments under plastic film mulch. The WUE was highest in the NTS treatment for both field pea (10.2 kg/ha mm) and spring wheat (8.0 kg/ha mm), but lowest on the NT treatment for both field pea (8.4 kg/ha mm) and spring wheat (6.9 kg/ha mm) within group 1 treatments (Table 3). Plastic

Table 2
Annual rainfall (mm) at the Dingxi site in 2001–2005, and long-term average rainfall (mm) and minimum (Min T) and maximum temperatures (Max T, °C) at the nearest weather station at Dingxi City

	Rainfall in 2001–2005					Long-term average[a]		
	2001[b]	2002[b]	2003[b]	2004[b]	2005[b]	Rainfall	Min T	Max T
January	9.2	4.8	6.5	7.4	3.9	3.3	−13.5	0.9
February	9.4	9.2	0.0	1	11.6	4.6	−8.9	3.7
March	0.0	15.8	36.4	9.5	11.7	12.1	−2.9	8.9
April	36.1	28.3	22.0	2.8	30.9	28.0	2.2	15.7
May	11.6	69.1	66.8	49.4	80.9	44.6	6.8	20.1
June	55.0	60.0	57.5	49.1	43.0	53.4	10.2	23.2
July	64.1	62.3	84.5	69.6	124.5	77.4	12.8	25.4
August	57.7	42.5	148.7	62.0	38.3	82.6	12.4	24.5
September	88.2	25.9	66.9	69.3	66.9	49.5	8.1	19.3
October	21.3	27.7	65.2	14.0	36.2	28.5	1.9	13.6
November	0.0	2.7	10.0	5.8	4.6	5.3	−4.7	8.0
December	3.9	2.4	0.0	4.6	0.0	1.6	−11.2	2.7
Annual rainfall	357	351	565	345	453	391		
In-crop rainfall (from sowing to harvest)								
Field pea	–	167	176	120	170			
Spring wheat	–	219	298	178	282			

[a] 36 year average from 1970 to 2005.

[b] Year.

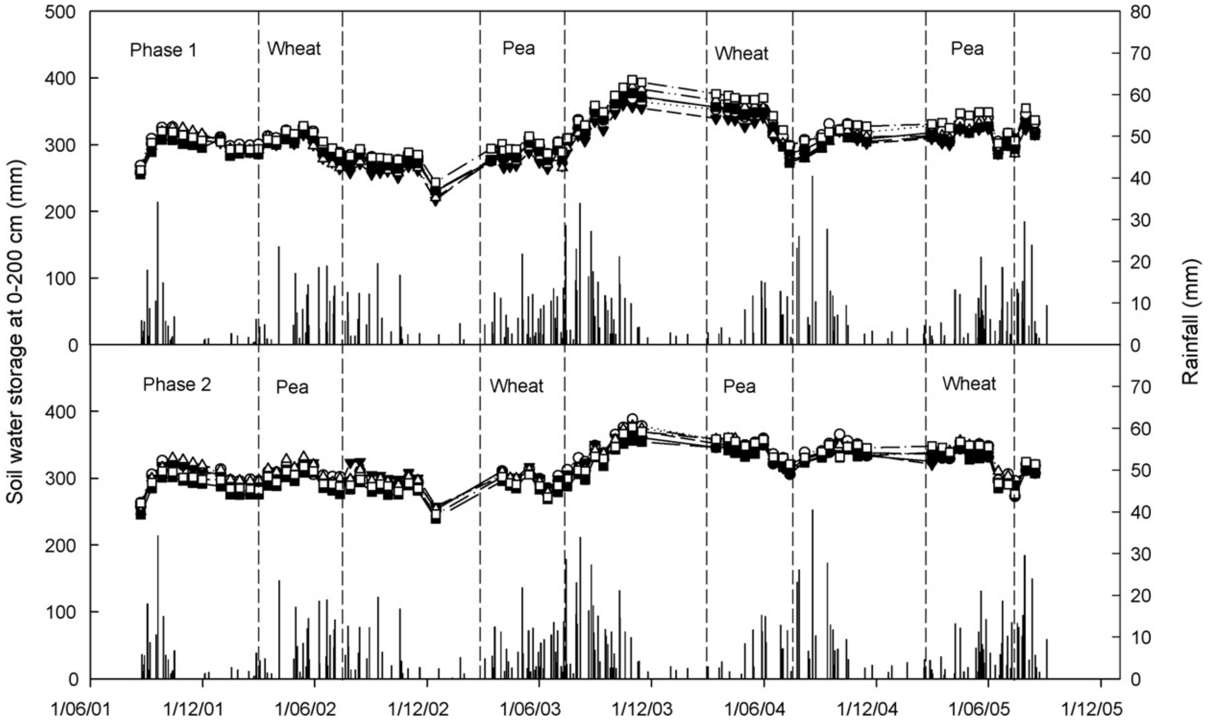

Fig. 1. Dynamics of soil water storage at 0–200 cm and rainfall (vertical bars) in 2001–2005. Phase 1, wheat/pea/wheat/pea; phase 2 pea/wheat/pea/wheat. (●) Conventional tillage with stubble removed; (○) no-till with stubble removed; (▼) tillage with stubble incorporated; (△) no-till with stubble retained. (■) Tillage with plastic film mulch and (□) no-till with plastic film mulch. Crop lower limit is 189 mm for spring wheat and 241 mm for field pea; drained upper limit is 554 mm.

film mulch treatments had a higher WUE than group 1 treatments for spring wheat ($P < 0.05$), but no difference between groups for field pea (Table 3).

There were no significant differences in ET between treatments although the NTS treatment tended to have a higher ET among treatments for both crops (data not shown). Spring wheat had a higher ET than field pea (270 mm vs. 168 mm) due to a longer growing season for spring wheat (130–138) compared with field pea (90–96 days). The in-crop (sowing–harvest) rainfall ranged from 120–176 mm for field pea to 178–282 for spring wheat (Table 2).

3.2. Agronomic performance

There was no significant difference in seedling density at establishment between treatments for either spring wheat or field pea, however there was significant variation between years ($P < 0.001$, Table 4). Spring wheat had the highest seedlings numbers in 2005 (286–329 plants/m^2) and the lowest in 2004 (128–187 plants/m^2). Field pea had an average of 57–111 plants/m^2 with the highest density in 2002 (data not shown). For field pea seedling DM, there was a significant difference between tillage treatments ($P < 0.05$, Table 4), but no difference between stubble treatments. There were large between year variations in seedling DM for both crops (data not shown).

There was significant interaction between tillage and stubble treatments for DM at anthesis ($P < 0.05$) and at maturity ($P < 0.001$) between treatments for both crops in group 1 (Table 4). However, no difference was detected between plastic film mulch treatments (Table 4). In general, crops in the NTS treatment had the highest DM production whereas crops in the NT treatment had the lowest DM at both anthesis and maturity for both crops and for all years in group 1 (data not shown). The exception was in 2002 where field pea had highest DM at anthesis in the T treatment and in 2003 where field pea had lowest DM in the TS treatment at maturity. In 2005 both crops had lowest DM in the T treatment at maturity.

There was a significant interaction between tillage and stubble treatments for grain yield for both crops ($P < 0.001$) in group 1, but no difference between plastic film mulch treatments (Table 4). There was significant year variation for both crops ($P < 0.001$). Grain yield was higher in the NTS treatment than the NT treatment in 3 of the 4 years (Table 5). Averaged over 4 years, yield of field pea under the NTS treatment was 0.3 t/ha (20%) higher than the conventional practice (T treatment). Similarly, yield of wheat under the NTS treatment was 0.3 t/ha (14%) higher than the T treatment. Averaged across years, field pea produced 1.6 t/ha of grain on group 1 and plastic film mulch treatments, whereas spring wheat produced 2.2 and 2.4 t/ha of grain on group 1 and plastic film mulch treatments, respectively (Table 5). The low grain yield of field pea in 2003 was due to a dry period around pea flowering time although annual rainfall in 2003 was high (Table 2).

3.3. Fallow efficiency

There was significant interaction between tillage and stubble treatments in soil water accumulation ($P < 0.001$) and fallow

Table 3
Water storage (mm) at sowing in 0–30 cm and water use efficiency during growing season in 2002–2005

Crop	Year	Group 1				Group 2		L.S.D.$_{0.05}$
		T	NT	TS	NTS	TP	NTP	
Water storage (mm) at sowing								
Field pea	2002	54	53	55	59	54	51	4.2
	2003	48	50	47	56	53	56	3.4
	2004	57	58	61	60	62	62	3.4
	2005	60	61	66	67	67	67	4.7
	Mean	55	56	57	60	59	59	2.1
Spring wheat	2002	52	52	52	58	52	51	6.4
	2003	46	50	45	55	51	57	6.0
	2004	55	58	58	60	60	63	4.7
	2005	58	61	63	66	66	68	3.8
	Mean	53	55	55	60	57	60	4.1
Water use efficiency (kg/ha mm)								
Field pea	2002	8.7	7.9	7.8	10.0	8.5	8.2	1.09
	2003	6.3	6.2	6.1	8.4	7.8	7.6	1.20
	2004	10.7	9.2	10.5	10.7	11.9	9.8	1.52
	2005	10.3	10.5	10.3	11.9	11.3	11.7	2.25
	Mean	9.0	8.4	8.7	10.2	9.9	9.3	0.95
Spring wheat	2002	7.1	6.4	6.7	7.8	6.9	7.1	1.56
	2003	4.7	4.7	5.0	6.1	6.2	6.6	1.09
	2004	9.1	7.7	9.4	8.5	10.3	8.7	1.41
	2005	8.8	9.0	9.3	9.7	9.7	10.7	2.17
	Mean	7.4	6.9	7.6	8.0	8.3	8.3	0.99

Field pea sown in early-April and harvested in mid-July; spring wheat sown in mid-March and harvested in early-August. T: conventional tillage with stubble removed; NT: no-till with stubble removed; TS: conventional tillage with stubble incorporated; NTS: no-till with stubble retained; TP: conventional tillage with plastic film mulch; NTP: no-till with plastic film mulch. Group 1 = T, NT, TS and NTS; Group 2 = TP and NTP. L.S.D.$_{0.05}$: Least significant difference for treatment comparison at $P < 0.05$.

efficiency ($P < 0.001$). Averaged across years, soil water accumulation during fallow was 33 mm on the NTS treatment, but only 16 mm on the NT treatment (Table 6). For plastic film mulch treatments, the NTP treatment accumulated an average of 4 mm more water than TP treatment. As a result, fallow efficiency was the highest on the NTS treatment (18.3%) and the lowest on the T treatment (8.3%). The fallow efficiencies on the treatments with plastic film mulch (TP and NTP) were similar to that on the NTS treatment (Table 6).

3.4. Nitrogen uptake and nitrogen use for spring wheat

Nitrate-N at sowing ranged from 93 to 138 kg N/ha, with no significant difference between treatments in any year (Table 7). There were, however, significant interactions between tillage and stubble for plant N uptake ($P < 0.01$) and NUE ($P < 0.001$) in group 1 treatments. Plant N uptake was the highest on the NTS treatment (46 kg/ha), and the lowest on the NT treatment (33 kg/ha, Table 7), reflecting differences in shoot biomass. Similarly, spring wheat had the highest NUE on the NTS treatment (24.5%) and lowest on the NT treatment (15.5%, Table 7). There was no difference in plant N uptake between tillage treatments under plastic film mulch. Nitrogen use efficiency was generally low, never exceeding 27%. There were significant year and tillage interactions in NUE under the plastic film mulch treatments ($P < 0.05$). The NUE was higher on the NTP treatment than TP treatment in 2003, but lower on the NTP treatment than TP treatment in 2004 where NUE in 2002 was similar for both treatments. There was no difference in NUE between groups with and without plastic film mulch.

3.5. Nitrogen balance

Treatments TS and NTS had an extra 30 kg/ha of N input from wheat straw (6.8 t/ha) in August 2001 when the experiment started. Two field pea crops were estimated to have fixed more than 25 kg/ha over 4 rotation years for NT, NTS, TP and NTP treatments, whereas the two conventional tillage treatments were estimated to have fixed only 8 (T) and 18 (TS) kg N/ha (Table 8). There were significant tillage and stubble interactions for N export ($P < 0.001$) and N balance ($P < 0.001$) in group 1 treatments (Table 8). There was no difference in N export and N balance between tillage treatments under plastic film mulch. The NTS treatment exported the greatest N from crop harvest, whereas NT treatment had the lowest over 4 years (Table 8). Over 4 years all treatments accumulated N in soils and had surplus N ranged from 119 kg N/ha for the T treatment to 175 kg N/ha for the TS treatment (Table 8).

4. Discussion

4.1. Grain yields

Between year variation in grain yield demonstrated the influence of rainfall variability on grain production on the western Loess Plateau. A recent survey of farmers in the area surrounding the experimental site found average grain yield was just 0.8 t/ha for field pea and 1.0 t/ha for spring wheat in the 2003 season (Nolan et al., in press). Corresponding results from the current study for the conventional practice (T) were 1.0 t/ha for field pea and 1.5 t/ha for spring wheat. This represents a potential significant improvement in grain yield through better agronomic practices of 25% for field pea and 50% for spring wheat. Clearly there is some scope for improving farmer crop yields using available technology within current production systems.

Grain yields were further improved in the experiment through adoption of conservation tillage practices. Continuing the 2003 season comparison, grain yields under the no-tillage with stubble retained system (NTS) were 1.4 t/ha for field pea and 2.0 t/ha for spring wheat, a 40% (field pea) and 33% (spring wheat) increase in grain yield over the conventional tillage (T) system and a 75 and 100% increase over local farmer yields under the same seasonal conditions. Over 4 years of experimental results, average wheat yields were 2.1 under conventional cultivation (T) and 2.4 t/ha under conservation tillage (NTS), and 1.6 (T) and 1.8 t/ha (NTS) for field pea. These results give local farmers and extension agents

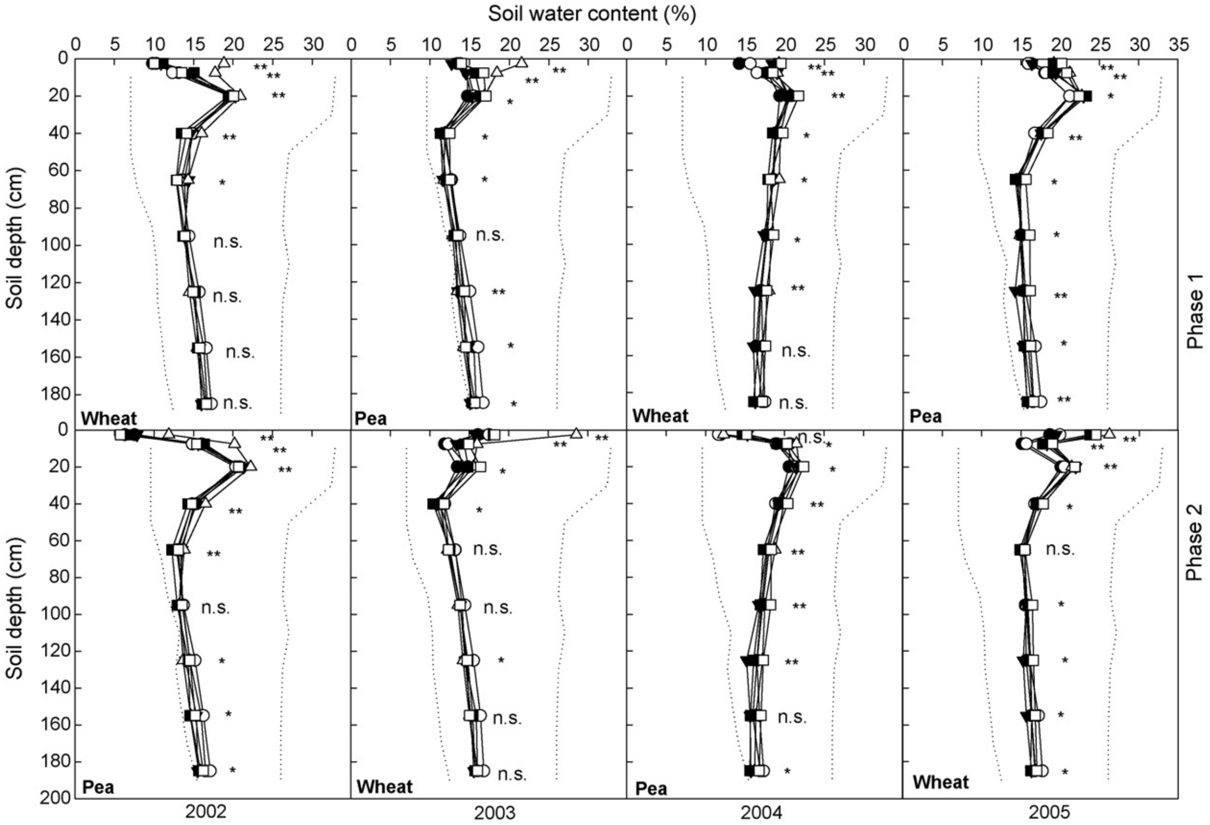

Fig. 2. Soil water profile at sowing in 2002–2005. Phase 1, wheat/pea/wheat/pea; phase 2 pea/wheat/pea/wheat. (●) Conventional tillage with stubble removed; (○) no-till with stubble removed; (▼) tillage with stubble incorporated; (△) no-till with stubble retained. (■) Tillage with plastic film mulch and (□) no-till with plastic film mulch. Dotted lines in each graph are crop lower limit on the left and drained upper limit on the right. Difference between treatments at that layer is significant at $^{*}P < 0.05$; $^{**}P < 0.01$; n.s., not significant.

Table 4
Wald statistics for main effects and their interactions for seedling establishment, dry matter at seedling establishment, anthesis and maturity, and grain yield

Terms in model	Effect	Establishment	Seedling DM	Anthesis DM	Maturity DM	Grain yield
Block.plot						
Phase	R	***	n.s.	n.s.	***	***
Group	F	0.79n.s.	3.65n.s.	0.88n.s.	8.93**	4.58*
(Group 1).tillage	F	0.06n.s.	7.09*	0.68n.s.	9.09**	3.03n.s.
(Group 1).stubble	F	1.64n.s.	0.00n.s.	3.6n.s.	21.19***	19.95***
(Group 1).stubble.tillage	F	0.05n.s.	0.13n.s.	6.76*	23.5***	33.43***
(Group 2).tillage	F	0.35n.s.	2.04n.s.	2.88n.s.	1.14n.s.	2.27n.s.
Residual	R					
Block.plot.year						
Year	F	21.75***	506.34***	34.63***	55.67***	77.8***
Group.year	F	5.43**	13.76***	6.62***	3.32*	1.79n.s.
(Group 1).year.tillage	F	0.56n.s.	1.97n.s.	1.41n.s.	0.85n.s.	2.81*
(Group 1).year.stubble	F	3.12*	7.43***	4.07**	2.43*	1.00n.s.
(Group 1).year.stubble.tillage	F	0.29n.s.	1.30n.s.	0.48n.s.	1.88n.s.	0.49n.s.
(Group 1).crop	F	663.4***	96.22***	219.63***	156.87***	97.52***
(Group 1).crop.tillage	F	1.35n.s.	3.34n.s.	0.25n.s.	0.36n.s.	0.01n.s.
(Group 1).crop.stubble	F	0.00n.s.	1.49n.s.	1.68n.s.	0.05n.s.	1.31n.s.
(Group 1).crop.stubble.tillage	F	0.00n.s.	1.68n.s.	4.98*	0.03n.s.	0.18n.s.
(Group 2).year.tillage	F	0.89n.s.	2.58n.s.	0.63n.s.	3.65*	1.74n.s.
(Group 2).crop	F	232.97***	57.90***	150.71***	139.37***	86.44***
(Group 2).crop.tillage	F	0.27n.s.	0.02n.s.	2.22n.s.	0.37n.s.	0.01n.s.
Residual	R					

Probability level is an approximate *F*-test for the fixed terms or a Chi-squared test based on the residual maximum likelihood ratio test for the random terms. n.s. not significant; F and R in Effect column represent fixed effect and random effect, respectively.

[*] $P < 0.05$.

[**] $P < 0.01$.

[***] $P < 0.001$.

Table 5
Grain yields for field pea and spring wheat under different treatments in 2002–2005

Crop	Year	Group 1				Group 2		L.S.D.$_{0.05}$
		T	NT	TS	NTS	TP	NTP	
Field pea	2002	1.5	1.3	1.4	1.7	1.5	1.4	0.18
	2003	1.0	0.9	0.9	1.4	1.2	1.2	0.18
	2004	1.7	1.3	1.6	1.7	1.8	1.4	0.30
	2005	2.0	2.2	2.1	2.4	2.2	2.4	0.48
	Mean	1.5	1.4	1.5	1.8	1.7	1.6	0.17
Spring wheat	2002	2.1	1.8	2.0	2.3	2.3	2.2	0.37
	2003	1.5	1.4	1.6	2.0	2.0	1.9	0.35
	2004	2.2	1.8	2.2	2.3	2.6	2.2	0.34
	2005	2.6	2.7	2.8	3.1	3.0	3.2	0.49
	Mean	2.1	1.9	2.2	2.4	2.5	2.4	0.29

Treatment notations are same as in Table 3.

Table 7
Soil nitrate N at sowing, plant N uptake and nitrogen use of spring wheat under different treatments in 2002–2004

Year	Group 1				Group 2		L.S.D.$_{0.05}$
	T	NT	TS	NTS	TP	NTP	
Soil nitrate N at sowing (kg N/ha, 0–140 cm)							
2002–2004	116	93	121	94	138	103	n.s.
Plant N uptake (kg/ha)							
2002	37	27	28	47	34	32	12.3
2003	41	36	41	44	49	49	5.8
2004	45	36	44	48	55	50	17.2
Mean	41	33	38	46	46	44	7.3
Nitrogen use efficiency (%)							
2002	18.9	17.0	13.0	27.0	17.1	17.2	6.87
2003	17.6	14.5	17.3	19.0	17.4	25.7	12.34
2004	22.6	14.9	18.3	27.4	26.3	15.7	4.82
Mean	19.7	15.5	16.2	24.5	20.3	19.5	4.97

Treatment notations are same as in Table 3.

confidence in the ability of conservation tillage systems to provide improvements in grain yield over current conventional systems.

The experimental design combined tillage and stubble treatments to allow their separate effects on grain yield to be assessed. Because of the high opportunity cost of crop stubbles in local farming systems, there may be a temptation to adopt a no-tillage system while persisting with removal of stubble for traditional uses. A comparison of grain yield from the NT and NTS treatments demonstrated that this would be an unproductive option. Wheat grain yields were generally high under the NTS treatment (2.0–3.1 t/ha) and low under the NT treatment (1.4–2.7 t/ha). Similar trends were observed for field pea. Furthermore, the NT treatment results in a massive crust formation that would exacerbate surface runoff and erosion and create difficulties for sowing crops using no-till machinery. These results highlight the degraded nature of the Loess soil after many years of traditional cropping practice and the important beneficial effects of retention of crop residue in terms of surface protection, moisture conservation and organic inputs. The important extension message from this study is that conservation tillage has to be adopted as a system, combining both no-tillage and retention of crop residues. Adoption of a no-till system with stubble removal will result in reductions in grain yields and a combination of soil degradation and erosion. Further research into stubble management, including the effects of machine harvested standing stubble on soil water and productivity, and exploring the options for sharing crop residues between conservation tillage and traditional uses is needed.

4.2. Soil water dynamics and water use efficiency

Soil water storage capacity is large in Loess soils with a drained upper limit of 554 mm in 0–200 cm, relative to annual rainfall (average 390 mm/year) in the present case, reducing the potential for losses due to deep drainage and runoff. In the current experiment the soil water content at depth never approached the drained upper limit (Fig. 1) and so it could be assumed there was no drainage or nitrate leaching. Surface soil

Table 6
Soil water accumulation (mm) and off-crop rainfall efficiency (%) during fallow from early-August after all crops were harvested to mid-March the following year before crops were sown

Year	Rainfall during fallow	Group 1				Group 2		L.S.D.$_{0.05}$
		T	NT	TS	NTS	TP	NTP	
Soil water accumulation (mm) during fallow								
2002–2003	112.5	10.7	19.2	17.7	28.6	27.2	27.9	41.06
2003–2004	302.0	31.4	21.1	29.4	45.9	34.3	43.5	12.13
2004–2005	174.5	8.7	8.5	12.5	24.7	19.7	20.8	9.72
Mean	196.3	16.9	16.3	19.9	33.1	27.1	30.7	14.63
Rainfall storage during fallow (%)								
2002–2003	112.5	9.5	17.1	15.7	25.5	24.2	24.8	37.11
2003–2004	302.0	10.4	7.0	9.7	15.2	11.4	14.4	3.82
2004–2005	174.5	5.0	4.9	7.2	14.2	11.3	11.9	5.50
Mean	196.3	8.3	9.6	10.9	18.3	15.6	17.0	12.57

Treatment notations are same as in Table 3.

Table 8
Nitrogen balance (kg N/ha) for the rotation system over 4 years (2001–2005) under different tillage and ground cover treatments

Nitrogen balance	Group 1				Group 2		L.S.D.$_{0.05}$
	T	NT	TS	NTS	TP	NTP	
Nitrogen input							
Fertiliser N	269	269	269	269	269	269	–
N in straw at year 1	–	–	30	30	–	–	–
Nitrogen fixation	8	26	18	25	26	25	5.9
Nitrogen export (N from grain and stubble)	158	125	142	179	164	156	15.0
Nitrogen balance	+119	+170	+175	+145	+130	+138	15.5

Each value is the sum of two crops of field pea and two crops of spring wheat over 4 years. Treatment notations are same as in Table 3.

water content did not reach the drained upper limit, even in the relatively wet year of 2003, rainfall intensity was generally less than 10 mm/h and saturated hydraulic conductivity of the soil at the site was generally >40 mm/h (Guosheng Zhang et al., personal communication), suggesting that runoff was unlikely to be a major pathway of water movement. This leaves evaporation from the soil surface as the most important pathway for unproductive loss of water from the system. Siddique et al. (1990) estimated that about 30–60% of total ET was via soil evaporation for wheat crops, which is not conducive to crop productivity (Xie et al., 2005). As such, there is a large gap between actual and attainable water use efficiency (Sadras and Angus, 2006). Results from the current study showed that the average WUE was 8.4–10.2 kg/ha mm for field pea and 7.4–8.3 kg/ha mm for spring wheat, which is similar to that in the dryland conditions in south-eastern Australia (Sadras and Angus, 2006). However, the estimated that the maximum water use efficiency (the water limited potential) was up to 22 kg/ha mm in the dryland conditions in south-eastern Australia (Sadras and Angus, 2006).

Soil surface cover in the form of crop residues or plastic film mulch can reduce evaporation losses, especially during the long fallow period (mid-August to mid-March) as shown by higher fallow efficiency (Table 6). In the current study, fallow efficiency was up to 18% on the no-till with stubble retained treatment compared to only 8% for the T treatment. Under traditional bare fallow in Australia, fallow efficiency on coarse texture soils can be as low as 3% and is usually in the range of 15–25% for fine textured soils (Felton et al., 1987). As a result, the no-till with stubble retained treatment preserved 16 mm more water in the soil profile compared with conventional tillage treatment.

Soil moisture in the 0–30 cm layer is critical for crop emergence and early crop growth in the semi-arid area in the western Loess Plateau where dry spring conditions is one of the major constraints for successful crop production. In the current study, there was more water storage at 0–30 cm under no-till with stubble retained (Table 6 and Fig. 2) than conventional tillage treatments. Considerable research on conservation tillage showed that soil water storage can be improved by retaining crop residues on the soil surface through reducing runoff, reducing evaporation and improving water infiltration (Gicheru, 1994; Barton et al., 2004; Lampurlanés and Cantero-Martínez, 2006). Al-Darby et al. (1987) found that the short-term crop growth yield advantage of conservation tillage came from the water conserving effect of crop residue retained on the surface of soil when drought stress was an issue in the semi-arid areas. Hemmat and Eskandari (2006) also found that the significant contribution of no-tillage with total residue to yield can be explained by greater water availability.

Our results demonstrate the effectiveness of conservation tillage in increasing water use and water use efficiency compared to the conventional system of intensive cultivation and complete stubble removal in the semi-arid area of the Loess Plateau. No-till on its own, however, did not have such effect. Retaining crop residues could capture and store more rainfall in soils during fallow and improve the WUE during growing season. This is of great benefit in this environment and results in significantly increased crop productivity.

4.3. Nitrogen use efficiency and nitrogen fixation

Results showed that the no-till with stubble retained treatment had the highest plant N uptake and nitrogen use efficiency, most probably due to higher soil available water in 0–30 cm, resulting in greatest grain production. A 15-year field experiment at the Changwu Ecological Station, Shaanxi Province in China also showed that soil available N can increase soil water use and improve WUE (Dang, 1999). However, over use of N fertiliser can reduce the efficiency of nitrogen use. Higher N inputs not only increased input costs, but also increased the risk of environmental contamination in the ground water systems. In the current research, there was up to 175 kg/ha surplus N accumulated after two rotation cycles under the current fertiliser regime over the 4 years. There appear to be excellent prospects for reducing current farmer fertiliser N inputs while maintaining spring wheat yields in all but the wettest seasons. This is a significant finding as it will directly increase farm profitability with little risk. Considerable savings are likely by adopting optimum fertiliser N rates.

Nitrogen fixation rates were low by international standards (Unkovich and Pate, 2000). It is likely that the main reason for low biological nitrogen fixation (BNF) was the relatively high soil inorganic nitrogen resulting from high fertiliser N application rates, both directly on field pea (20 kg N/ha) and on spring wheat (105 kg N/ha), and the low dry matter production of field pea. Reduced fertiliser N inputs will lead to lower inorganic N levels and create greater contributions of

N fixation to field pea. If dry matter production of field pea is increased, the demand for N by pea will be lifted, increasing potential N_2 fixation. Greater contributions from BNF can be expected as a secondary outcome of reduced fertiliser N use, especially if N_2 fixation can match increased legume productivity. Further research is needed to improve the contribution of BNF to the nitrogen economy of cropping systems in the region, including assessment of possible inoculant rhizobia. There appear to be no other reports on estimates of N fixation for the Loess Plateau.

4.4. Plastic film mulch use and concerns

Results from the current study showed that plastic film mulch can be effective for achieving high grain yields (Table 5) probably due to increased soil water storage during fallow and improved WUE, especially for spring wheat. This is probably one of the reasons that the local authorities have promoted the use of plastic film mulch in the region. However, plastic film mulch can potentially cause serious surface crusting and have detrimental effects on crop production should a heavy rainfall event occur between sowing and emergence. It was observed that grain yield was reduced by 15% for field pea and 6% for spring wheat in 2002 due to soil crusting compared to the NTS. In addition, plastic film mulch requires additional expense, creates a disposal problem of the used plastic film, and may further exacerbate soil infertility and erosion. The additional cost of plastic film was US$ 75/ha (2006 prices) and this is unlikely to be recovered by the slight increase in grain yield over the T treatment, and there was no grain yield advantage of TP and NTP treatments over the NTS treatment.

In the long-term, plastic film mulch does not have any beneficial effects on soil chemical and physical properties, unlike crop residues (Lal, 2007). In addition, use of non-biodegradable plastic film creates a disposal problem and contamination risk for soil and water resources. Crop residues can achieve the increased grain yield benefits of plastic film mulch while avoiding most of the limitations listed above. The cost of crop residues, like the cost of plastic film mulch, remains an issue. In local systems, crop residues represent a valuable farm resource, used for livestock feed and as an energy source for heating and cooking. Crop residues thus have high opportunity costs in local farming systems. The optimal allocation of crop residues to the competing demands of conservation agriculture, livestock feed and energy supply is a complex issue requiring a whole farm or farm livelihood analysis with close involvement of local farmers to develop local solutions.

4.5. Prospects for adoption of conservation tillage under local conditions

In the Dingxi district, local farmers are resource-poor, with average farm size just under one hectare, and most wheat is grown for household consumption (Nolan et al., in press). Under these conditions, maintenance or improvement in grain yield with a low risk of harvest failures due to new cropping technologies is imperative. Several studies have found that grain yields can initially decline before improving as farmers make the transition from conventional practice to conservation tillage (Kirkegaard, 1995). This possibility is of great concern in a farming system where farmers survive from year to year on the current season's harvest. Results from the current study provide strong support for the ongoing promotion of conservation tillage on the Loess Plateau, and also highlight some constraints requiring more detailed research.

Firstly, it is clear that crops can be successfully grown on conservation tillage with stubble retention on the western Loess Plateau. The grain yield increases achieved in the NTS treatment provide an incentive for growers to adopt these practices. Despite these results, there is still a strong belief among farmers, extension agents, and some researchers that cultivation is necessary for successful crop production on these soils. Ongoing demonstration and extension will be required for many years to overcome traditional beliefs and adapt conservation tillage to local conditions (Hobbs, 2007).

Secondly, the significant labour and cost savings (US$ 118/ha, traditional practice of ploughing three times at ¥20/mu per time using local costs in 2006), achieved by no longer cultivating the soil results in increased profitability (coupled with higher yields) and the freeing up of labour for other, hopefully more profitable, activities. Despite a high population density, there is a shortage of labour on many farms as young males seek more profitable employment off-farm (van den Berg et al., 2007), and the labour saving feature of conservation tillage is very attractive for the often elderly and/or female farmers that remain on the farm.

Thirdly, the expected environmental benefits of conservation tillage; reduced runoff and erosion, increased soil organic carbon, reduced pollution (in comparison to plastic film mulch); provide both off-farm benefits and potential for longer term increases in crop yields as soil fertility improves. These positive results support the Chinese government's current policy of extending conservation tillage across the country. However, there are a number of areas requiring further research and/or institutional support if these benefits are to be realised.

An obvious area for further research is to explore options for resolving the current conflict between the new use of crop residues for soil protection and fertility in conservation tillage, and the use of crop residues for livestock feed and/or fuel for cooking and heating. Potential research topics include determining the minimum amount and placement (standing or spread) of crop stubbles required to achieve conservation goals (increased infiltration, reduced evaporation, increased soil organic carbon, etc.) while leaving some residues available for traditional uses. Another research topic is to understand the current role of crop residues in the livestock feed supply with a view to identifying alternative feed sources so that crop residues can be used for conservation tillage without placing the livestock enterprise at risk.

A second area of concern is how to provide local farmers with access to appropriate no-till seeders. One aspect to this problem is the large proportion of farm land that is unsuitable for tractors because of difficult terrain limiting access or small terraces. Perhaps an animal drawn no-till seeder would have potential in these areas. A second aspect is the limited capital reserves of local farmers for investment in new machinery or technology. Options for addressing this constraint include government subsidies for the purchase of no-till seeders, purchase of communal no-till seeders by villages or other units, and development of a contract no-till sowing service along the lines of the existing contract machine harvest service that is very popular with local farmers. These are mainly policy and financing issues.

An important extension message from this research is the need for a systems analysis approach to improve farm management. This is illustrated by the need to consider conservation tillage as the combination of no-tillage and stubble retention. No-tillage by itself is likely to exacerbate problems of an already degraded cropping system. A further illustration is the need to recognise the competing demands on crop residues created by the introduction of conservation tillage. A focus on the crop enterprise in isolation will fail to appreciate legitimate farmer concerns over livestock feed supply and farm energy supply. Analysis of production systems at the farm scale, coupled with a strong focus on farmer needs and concerns, holds promise for realising the potential benefits of conservation tillage. Finally, performance of the new system needs to be monitored over a longer period of time as many of the changes, particularly soil quality and biology are still evolving.

Acknowledgments

Authors are grateful to land owners, Mr. Li Junqi, Mr. Zhang Feng, Mr. Guo Changlin and Mr. Wu Changqing, for allowing us to use their land and their cooperation, and to Mr. Jin Zhen who looked after the site. Special thanks to all postgraduate and undergraduates students from Gansu Agricultural University who were involved in this project for different periods. The project received financial support from the Australian Centre for International Agricultural Research (Project number: CIM/1999/094) in 2001–2006 and the Ministry of Science and Technology, China (Project number: 2006BAD15B06).

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11.3 Productivity, soil water dynamics, and water use efficiency of lucerne–wheat rotations on the Loess Plateau, north-west China. Field Crops Research

Shen, Y[1], Li, L[2], Chen, W[3], Robertson, MJ[4], Unkovich, MJ[5] and Bellotti, WD[6] (Submitted) Productivity, soil water and resource use efficiency of lucerne-wheat rotations on the Loess Plateau, north-west China. *Field Crops Research* (re-submitted April 2008).

Abstract

On the Loess Plateau in China, farmers have been encouraged to grow lucerne (Medicago sativa) to reduce soil erosion and improve soil fertility. Incorporating perennials into rotations with annual grain crops poses several challenges in relation to water and nutrient management. Lucerne-wheat rotation experiments were established at two locations in Gansu Province and examined the yield of lucerne and wheat along with changes in soil water and nitrogen (N). Lucerne proved to be well adapted to the high water holding capacity soils and summer dominant rainfall of the region with annual production of around 12 t ha^{-1} at the higher rainfall site (Qingyang). An old (30 years), sparse stand of lucerne growing in the drier location (Dingxi) was much less productive, being dependent on incident rainfall. Apparent water use efficiency of lucerne over individual harvest periods ranged from 4-56 kg ha^{-1} mm^{-1}at Qingyang. Lucerne was able to dry the soil to the crop lower limit to depths of 3 m and there was clear evidence that lucerne roots were extracting water below this depth.

Wheat following lucerne is subject to low plant available soil water at sowing, unless substantial rainfall occurs, but climate variability in this region makes this difficult to predict. Rain which falls during short fallow periods after lucerne termination provides opportunity for N fertiliser responses, which may be greater after large rainfall events that lead to N leaching. In drier environments such as Dingxi, deep drainage and leaching appear unlikely under rotations which incorporate lucerne, and here evaporative water loss from the soil surface presents a more significant management challenge. The overall variability in seasonal rainfall at both sites, even within the short period of this study, indicates that an adaptive management strategy may be required, rather than fixed rotations. Systems modelling may shed further light on the most useful strategies to manage crop rotations within this variability.

Keywords: dryland farming; rotation; water use, water use efficiency, soil nitrogen

Introduction

On the Loess Plateau in north-western China, cropping systems are dominated by dryland wheat, but extensive stubble removal, tillage and cultivation of sloping land contribute to severe soil erosion problems. The region has a continental monsoon climate (Hutchinson *et al.* 1992), experiencing cold dry winters and warm wet summers, with annual rainfall ranging from 600mm in the south east of the region to <100mm in the north-west. Rain falls sporadically over a short summer period but is highly variable from year to year. The combination of tillage with stubble removal, which reduces soil fertility and increases erosion on sloping land, and variable or low rainfall, results in low or uncertain cereal grain yields for many farmers (Liu 1999).

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To address problems of soil erosion, low soil fertility, and agricultural development, the central government introduced a revegetation campaign to encourage farmers to convert sloping cropland to forest or grassland, in exchange for cash and grain (Feng *et al.* 2003). Lucerne (*Medicago sativa*) is adapted to a wide range of environments in the western Loess Plateau and the forage is good for livestock production and cash income under this policy. In 2003 lucerne was grown on 1 million ha in China, a 31% increase compared to 2001 (Jia *et al.* 2006).

However, there are problems with both perennial lucerne pasture/forage systems and the continuous cropping systems they might replace. Continuous cereal cropping may reduce soil nitrogen content and soil fertility (Fan *et al.* 2005) and traditional tillage and stubble removal associated with cropping in this region leaves the soil exposed to erosion. Lucerne can deplete soil moisture, reducing both lucerne productivity and that of subsequent annual grain crops (McCallum *et al.* 2001). A key challenge for rain-fed cropping systems is thus to develop strategies that make optimal use of soil water and nutrients across rotations (Li *et al.* 2002; Connor 2004). However, in lower rainfall environments when lucerne is grown in rotation with wheat, it is important to terminate lucerne growth early enough to provide opportunity for soil water accumulation prior to cereal sowing, otherwise wheat yield after lucerne may be depressed (Liu *et al.* 2000; Hirth *et al.* 2001). Soil water recharge is affected by soil type, but more so by seasonal conditions in most regions (Tennant and Hall 2001; Li *et al.* 2002). In China, previous research showed soil water deficits after long-term lucerne reduced following crop yields but indicated that 5-6 years might be a suitable period for growing lucerne on slope-land in a 380mm rainfall environment (Zhang and Lu 1996).

Tackling the challenge of integrating perennial forages with subsistence cereal crops is particularly important on the Loess Plateau in Gansu, China's poorest rural Province (Nolan *et al.* 2007). In addressing this need, two field experiments were established in the western Loess Plateau, one in a winter wheat growing area (Qingyang) and one in a drier environment where spring wheat is grown (Dingxi). We hypothesised that earlier terminated lucerne should result in significantly more stored soil water and mineralised nitrogen, and a higher grain yield for following wheat crops. This experiment was also designed to generate a comprehensive (climate, soil water, soil nitrogen, plant growth and grain yield) dataset for use in testing the performance of the APSIM simulation model under local soil, climate and management conditions (Chen et al, 2007). As such, some treatments in the experimental design, for example, an extended period of fallow, were included to generate a wide range of soil conditions, rather than being seen as a practical option for local farmers. Measurements of soil water, pasture and crop biomass, water use efficiency, and grain yield of wheat were undertaken from 2000-2004. The implications of lucerne-wheat sequences for improvement of farming systems in two contrasting environments in the region are discussed.

Materials and Methods

Two localities, Qingyang and Dingxi, were chosen to represent the principal land systems and contrasting environments of Gansu Province. The areas differ in their position in the Loess landscape, with Qingyang (35^{o} 40'N, 107 ^{o} 51'E, elev. 1298m a.s.l.) on tableland in eastern Gansu, and Dingxi (35 ^{o} 28'N, 104 ^{o} 44'E, elev. 1971m a.s.l.) occupying loess hills in central Gansu. Winter wheat is grown in Qingyang but this is not possible in Dingxi where there is less snow cover and more severe radiation frosts in winter. Spring wheat is grown in Dingxi where it is considerably drier than in Qingyang. We first detail experimental protocols for Qingyang, and then highlight differences at the Dingxi experimental site. Field experiments were conducted at the two sites from 2001-2004.

Qingyang

Qingyang Experimental Station (35°40'N, 107°51'E; elevation, 1298 ml) Lanzhou University, is in the rain fed agricultural production zone of the western Loess Plateau.

Average annual long-term precipitation is 561mm, varying from 320 to 820 mm over the past 43 years. The mean number of frost-free days is 255, which approximates the length of the annual crop growing season. Daily rainfall, solar radiation and temperature were recorded during the period of study using an automatic weather station on site.

The soil at Qingyang is a Heilu soil (see Zhu *et al.* 1983) (Entisol of US classification), being an infertile sandy-loam with 70% silt, and represents the major cropping soil of the district. Soil properties (Table 1) show a uniform profile with high pH, and low organic carbon and low total nitrogen. Although total phosphorus is high (0.08% at the surface), available P (Olsen) was low at the start of the experiment. Soil bulk density, determined by inserting thin-walled cylinders horizontally into the wall of a soil pit, is moderate and constant down the profile at about 1.3 g/cm^3. Bulk density was used to convert gravimetric soil water to volumetric soil water, and inorganic nitrogen concentration to mass of inorganic nitrogen in each soil layer.

Experimental design

An existing lucerne ley (**Medicago sativa*****, local landrace Longdong) established in the spring of 1997 was used as the basis for the experiment at Qingyang. Plant density was 7-8 plants /m^2. In 2001 a completely randomised block design was imposed over the lucerne ley, with plot sizes of 20 by 4 m and four replicates of the following treatments (Tables***

Table 1 Soil properties in 2001 at Qingyang after four years of lucerne and Dingxi after ca 30 years lucerne, and prior to the imposition of fallow and crop treatments. Available N is NO_3^--N, and available P is Olsen P (Moody and Bolland 1999).

Depth (cm)	pH (CaCl2)	Organic carbon (%)	Total N (%)	Available N (mg/kg)	Available P (mg/kg)	Available K (mg/kg)	Bulk density (g/cm3)
Qingyang							
0-10	8.7	0.688	0.065	38.9	6.6	130.7	1.3
10-30	8.7	0.611	0.061	40.2	3.2	94.4	1.2
30-60	8.7	0.587	0.056	34.3	2.1	90.1	1.4
60-90	8.6	0.602	0.060	29.2	2.1	81.8	1.3
90-120	8.7	0.456	0.058	23.2	2.6	80.1	1.2
120-150	8.8	0.356	0.058	26.1	2.3	72.1	1.3
150-200	8.9	0.298	0.058	21.0	2.9	69.9	1.3
200-250	8.9	0.260	0.057	17.2	2.0	66.7	1.3
250-300	9.0	0.243	0.056	19.6	2.0	69.5	1.3
Dingxi							
0-10	8.3	0.836	0.105	22.9	7.0	195.4	1.25
10-30	8.4	0.691	0.079	28.1	5.9	124.3	1.20
30-60	8.4	0.572	0.063	16.9	2.8	115.9	1.21
60-90	8.4	0.693	0.072	19.3	3.0	135.4	1.25
90-120	8.4	0.749	0.082	16.1	3.6	132.9	1.11
120-150	8.5	0.702	0.075	14.9	2.8	106.4	1.13
150-200	8.4	0.776	0.086	15.2	2.8	91.8	1.18
200-250	8.4	0.881	0.098	13.9	3.7	103.6	1.09
250-300	8.3	0.675	0.071	15.5	2.8	101.8	1.13

Table 2 Lucerne dry matter production, changes in soil water (0-300 cm), and and water use efficiency of lucerne for sequential forage harvests in each growing season in Qingyang. (± values are s.e.m. with n=4). 'Start' for the first harvest each year is soil water

content at lucerne regreening in the spring (March), and 'end' is soil water content at each harvest date, which then becomes the 'start' for the next harvest. ∆SWC is the change in stored soil water between start and end. Rainfall is for the period between the start and end for each harvest.

Year	**Harvest date**	**DM production (± s.e.m.) (t/ha)**	**Soil water (0-300cm)**			**Rainfall (mm)**	**"apparent" water use efficiency (± s.e.m.) kg ha-1 mm-1**
			Start (mm)	End (mm)	∆SWC (mm)		
2002	30-May	7.96 ±1.13	534	474	60	167	35.0
	21-Aug	3.37 ±0.16	474	411	63	100	20.7
	23-Oct	0.44 ± 0.09	411	447	-36	142	4.2
annual total		11.77 ±0.69	534 ±10.5	447 ± 2.5	88 ± 8.2	409	23.7± 1.4
2003	30-May	7.10 ± 0.64	444	428	16	110	56.4
	21-Jul	3.34 ± 0.37	428	492	-64	181	28.5
	15-Sep	2.46 ± 0.24	492	693	-201	274	33.6
annual total		12.90 ± 0.63	444 ± 1.9	693 ± 14.1	-249 ±12.4	565	40.8± 1.6
2004	1-Jun	7.47	704	523	181	62	30.7

Table 3 Dry matter (DM) production, grain yield, harvest index, water use between sowing and harvest (∆ SWC + in crop rainfall) and water use efficiency (WUE) of consecutive winter wheat crops, harvested in 2002- 2004 following removal of lucerne in May (4fW) or August 2001 (W) and receiving 0 or 138 kg N ha^{-1}, and for winter wheat harvested in 2004 following a two year fallow (FW) and receiving 0, 75 or 150 kg N ha^{-1} at Qingyang. WUE is calculated on the asumption that ∆ SWC is constant within rotations.

Treatment	**Dry matter (t ha-1)**	**Grain yield (t ha-1)**	**Harvest index**	**Water use (mm)**	**WUE in DM (kg ha-1 mm-1)**	**WUE in grain (kg ha-1 mm-1)**
Harvested 2002 (in crop rainfall 519mm)						
W	9.00a	3.15a	0.35	496	18.1	6.3
W138	10.83ab	3.71ab	0.35		21.8	7.5
4fW	8.93a	3.34a	0.37	511	17.5	6.5
4fW138	12.61b	4.43b	0.37		24.6	8.7
LSD	3.07	1.23	nsd	nsd	nsd	nsd
Harvested 2003 (in crop rainfall 484mm)						
WW	8.68ab	3.35	0.39	559	15.5	6.0ab
WW138	10.2ab	3.98	0.39		18.3	7.1b
4fWW	8.07a	3.12	0.39	574	14.1	5.4a
4fWW138	10.21b	3.95	0.39		17.8	6.9b
LSD	1.97	0.97	nsd	3	nsd	1.2
Harvested 2004 (in crop rainfall 159mm)						
WWW	10.51a	3.72a	0.35	376a	28.1ab	9.9a
WWW138	15.32b	5.89b	0.38		41.1d	15.8b
4fWWW	10.71a	4.23a	0.39	447b	24.1a	9.5a
4fWWW138	14.54b	5.55b	0.38		32.7cd	12.5c
LSD	0.87	0.54		57		2.2
FW	16.26	5.11x	0.31	615	26.5	8.3

FW75	17.52	6.28y	0.36		28.5	10.2
FW150	17.05	5.8xy	0.34		24.1	9.5
LSD	2.41	1.08	nsd		nsd	nsd

Table 4 Dry matter production of lucerne and weeds, and water use efficiency (WUE) system in thirty year old lucerne at Dingxi in 2002 and 2004. (s.d. for n=2)

	Dry matter production (t ha-1)			**WUE (kg ha-1mm-1)**
Year	Lucerne	Weeds	Total	
2002	0.95 (0.236)	0.01 (0.003)	0.96 (0.233)	4.0
2004	0.50 (0.284)	0.73 (0.162)	1.23 (0.126)	6.4

Table 5 Crop dry matter (DM), grain yield, harvest index, and water use efficiency (WUE) of consecutive spring wheats sown nine (9f) or four (4f) following the termination of a 30 year old lucerne stand in Dingxi, and receiving 0 or 15 kg N ha^{-1}.

Treatment code	**DM (t ha-1)**	**Grain yield (t ha-1)**	**Harvest index**	**∆ SWC (mm) sowing - harvest**	**WUE (DM) (kg ha-1mm-1)**	**WUE (Grain) (kg ha-1mm-1)**
	2002 (in crop rain 211mm)					
9fW	5.00±0.489	1.78±0.082	0.36±0.05	-49	19.3	6.9
9fW15	4.69±0.417	1.80±0.123	0.38±0.04	-45	18.4	7.0
4fW	4.08±0.436	1.62±0.096	0.40±0.05	-38	16.2	6.4
4fW15	4.89±0.359	1.49±0.077	0.30±0.04	-30	20.4	6.2
	2003 (in crop rain 210mm)					
9fWW	4.07±192	0.358±0.011	0.09±0.00	41	23.9	1.9
9fWW15	4.38±44	0.381±0.056	0.09±0.01	39	25.0	2.1
4fWW	3.29±655	0.603±0.034	0.18±0.03	48	20.3	3.2
4fWW15	4.45±503	0.512±0.043	0.12±0.02	46	27.7	2.8
	2004 (in crop rain 127mm)					
9fWWW	4.9±9	1.89±0.077	0.38±0.01	-94	22.6	8.6
9fWWW15	5.18±92	1.92±0.113	0.37±0.04	-92	23.0	8.5
4fWWW	4.24±169	1.90±0.074	0.45±0.05	-98	19.2	8.6
4fWWW15	4.76±166	1.94±0.002	0.41±0.04	-84	22.8	9.3

Figures

Figure 1):

- continuation of the established lucerne stand (L)
- winter wheat cropping phase initiated after 4 months of fallow following lucerne removal in May 2001 (4fW)
- winter wheat cropping phase initiated after 1 month of fallow following lucerne removal in August 2001 (W)
- 2 year fallow initiated in May 2001 which was not sown to winter wheat until Aug 2003 (FW).

Wheat plots were split for N as detailed in Tables

Table 1 Soil properties in 2001 at Qingyang after four years of lucerne and Dingxi after ca 30 years lucerne, and prior to the imposition of fallow and crop treatments. Available N is NO_3^-*-N, and available P is Olsen P (Moody and Bolland 1999).*

Depth (cm)	**pH (CaCl2)**	**Organic carbon (%)**	**Total N (%)**	**Available N (mg/kg)**	**Available P (mg/kg)**	**Available K (mg/kg)**	**Bulk density (g/cm3)**
Qingyang							
0-10	8.7	0.688	0.065	38.9	6.6	130.7	1.3
10-30	8.7	0.611	0.061	40.2	3.2	94.4	1.2
30-60	8.7	0.587	0.056	34.3	2.1	90.1	1.4
60-90	8.6	0.602	0.060	29.2	2.1	81.8	1.3
90-120	8.7	0.456	0.058	23.2	2.6	80.1	1.2
120-150	8.8	0.356	0.058	26.1	2.3	72.1	1.3
150-200	8.9	0.298	0.058	21.0	2.9	69.9	1.3
200-250	8.9	0.260	0.057	17.2	2.0	66.7	1.3
250-300	9.0	0.243	0.056	19.6	2.0	69.5	1.3
Dingxi							
0-10	8.3	0.836	0.105	22.9	7.0	195.4	1.25
10-30	8.4	0.691	0.079	28.1	5.9	124.3	1.20
30-60	8.4	0.572	0.063	16.9	2.8	115.9	1.21
60-90	8.4	0.693	0.072	19.3	3.0	135.4	1.25
90-120	8.4	0.749	0.082	16.1	3.6	132.9	1.11
120-150	8.5	0.702	0.075	14.9	2.8	106.4	1.13
150-200	8.4	0.776	0.086	15.2	2.8	91.8	1.18
200-250	8.4	0.881	0.098	13.9	3.7	103.6	1.09
250-300	8.3	0.675	0.071	15.5	2.8	101.8	1.13

Table 2 Lucerne dry matter production, changes in soil water (0-300 cm), and and water use efficiency of lucerne for sequential forage harvests in each growing season in Qingyang. (± values are s.e.m. with n=4). 'Start' for the first harvest each year is soil water content at lucerne regreening in the spring (March), and 'end' is soil water content at each harvest date, which then becomes the 'start' for the next harvest. ∆SWC is the change in stored soil water between start and end. Rainfall is for the period between the start and end for each harvest.

Year	**Harvest**	**DM production**	**Soil water (0-300cm)**	**Rainfall**	**"apparent" water use**

	date	**(± s.e.m.) (t/ha)**	Start (mm)	End (mm)	∆SWC (mm)	**(mm)**	**efficiency (± s.e.m.) kg ha-1 mm-1**
2002	30-May	7.96 ±1.13	534	474	60	167	35.0
	21-Aug	3.37 ±0.16	474	411	63	100	20.7
	23-Oct	0.44 ± 0.09	411	447	-36	142	4.2
annual total		11.77 ±0.69	534 ±10.5	447 ± 2.5	88 ± 8.2	409	23.7± 1.4
2003	30-May	7.10 ± 0.64	444	428	16	110	56.4
	21-Jul	3.34 ± 0.37	428	492	-64	181	28.5
	15-Sep	2.46 ± 0.24	492	693	-201	274	33.6
annual total		12.90 ± 0.63	444 ± 1.9	693 ± 14.1	-249 ±12.4	565	40.8± 1.6
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Treatment	**Dry matter (t ha-1)**	**Grain yield (t ha-1)**	**Harvest index**	**Water use (mm)**	**WUE in DM (kg ha-1 mm-1)**	**WUE in grain (kg ha-1 mm-1)**
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Figures

Figure 1, with di-ammonium phosphate being used in the first year of wheat and urea fertiliser thereafter. All winter wheat (cv Xifeng No.24) was sown under conventional tillage (one working before sowing and one after harvest), at a rate of 187 kg/ha, a depth of 2.5cm and in rows 15 cm apart. Sowing dates were 14th September 2001, 17 September 2002, and 24 September 2003. Phosphate was applied at sowing of each wheat crop at 46 kg P/ha. There were no significant pests or diseases evident and weeds were controlled by hand in both the lucerne, wheat and fallow plots. Lucerne removal was achieved by hand hoeing.

Soil water and nitrate measurement

The volumetric soil water content was measured using a neutron moisture meter (NMM, Campbell Pacific, CPN 503). In early May 2001, a 2 m aluminium access tube was set in the centre of each plot, but these were replaced by 3 m tubes on 17th August. Soil moisture was measured by NMM at 14 day intervals at the following depths: 15, 45, 75, 95, 110, 135, 175, 225, and 275 cm. Water content of the surface 0-10 cm was determined gravimetrically on 11 occasions. In September 2001 and April 2002, the neutron moisture meter was calibrated following Greacen and Hignett (1979). Neutron readings expressed as the count ratio (reading over reference count) were regressed against averaged volumetric water content obtained from 16 intact cores sampled from each plot at each depth increment.

The plant available water capacity (PAWC) was estimated as the difference between the drained upper limit (DUL) of the soil and the crop lower limit of soil water extraction (CLL). The DUL is the soil water content of a soil after drainage has practically ceased (principally a soil property), and the CLL is the soil water content after a water-limited crop has extracted all of the water from soil that it can (cultivar x soil property). The DUL was estimated using the pond method, and the CLL was defined for both lucerne and wheat using rain-out shelters (see Dagliesh and Foale 2000). The PAWC was calculated as follows:

$$PAWC(mm) = \sum_{0}^{\max depth} (DUL - CLL)$$

$$\text{PAWC (mm)} = \Sigma\ \text{(DUL – CLL)(mm/mm)} \times \text{layer depth (mm)}$$

where the summation is carried out over the whole rooting depth.

Soil nitrate was measured in all plots at the time of sowing and harvest of each crop, in the same depth increments as the soil water measurements. Soils were dried at 35 °C before extraction with 1M KCl. Nitrate-N was measured on extracts using the ultra-violet colorimetric method (Norman *et al.* 1985).

Dry matter and grain yield assessment

Lucerne growth was measured at three times per year by determining dry matter (DM) from three 1 m^2 quadrat cuts/plot. Cuts were taken by hand at ground level. At each time the quadrat samples were taken, the whole lucerne plot was also cut by hand, and all shoot material removed from the plot as per normal farmer practice in the district. Winter wheat grain yield was estimated from three 0.3 m^2 quadrat samples in each plot and grain threshed by hand. Fresh material was oven-dried at 85 ^{o}C for 48 hour prior to weighing.

Dingxi

Dingxi is *ca* 450 km west of Qingyang. Average annual rainfall at Dingxi over the last 35 years is 391mm, although this has varied from 115mm in 1982 to mm 417mm in 1979. On average, 54% of annual rainfall is received between July and September. The summer is thus warm and moist, with temperatures of up to 35^{o}C (Jul 2000), but winter is cold and dry with temperatures dropping to -30 ^{o}C (Dec 1991). Dingxi provides a drier and slightly colder environment compared to Qingyang. The soil at the Dingxi site is similar to Qingyang, but being a Huangmian soil (Entisol of US classification), has a slightly lower pH, higher and more uniform organic C, and a lower bulk density (Table 1).

Experimental design

The experiment at Dingxi was established on an existing >30 year old lucerne (L) stand. Lucerne density was low (ca 2 plants/m^2), and there was considerable weed invasion. Eight treatments (Table 2) were arranged in a split-plot design with a lucerne-spring wheat rotation as the main plot, and N rate (0 and 15 kg ha^{-1}) as sub-plots. Each plot measured 4m×10m. Due to space limitations only two replicates per treatment were possible. Lucerne was removed from plots by manual weeding with a hoe in either May or October 2001, producing either a nine (9f) or five (5f) month fallow prior to spring wheat sowing in April 2002. Spring wheat (cv. Dingxi No.35) (W) was then sown on to these wheat plots in the subsequent two years (2003 and 2004). Wheat was sown on 17 March 2002, 15 March 2003, and 18 March 2004.

Soil water and nitrogen measurements

At the beginning the experiment (May 2001) soil chemical and physical properties (Table 1) and soil water were assessed across the whole lucerne stand to 3m depth, in the same increments as at Qingyang. Soil water content was then measured every two weeks, gravimetrically for 0-10cm, and by neutron moisture meter for 10-300 cm as per the Qingyang site. Each year before wheat sowing and after wheat harvest, each plot was also sampled for assessment of nitrate nitrogen (Maynard and Kalra 1993). The same depth increments were used for both soil water and N measurements. Determination of DUL and CLL and PAWC at Dingxi were as for Qingyang, except that for lucerne the soil at Dingxi was determined to be at the CLL at the start of this work.

Dry matter accumulation and grain yield

Lucerne and weed dry matter were measured once each year in three 0.5 m × 0.5 m quadrats in each lucerne plot. For spring wheat, dry matter production in each plot was assessed by cuts of three 1m rows at maturity. At spring wheat maturity, 0.5m from the margins of every wheat plot were discarded, and grain yield assessed by bulk hand harvest of the remaining whole plot area.

Water use efficiency (WUE) calculation

Accumulated water use or evapotranspiration (ET) was calculated using the water balance equation:

$$ET\ (\text{mm}) = P - \Delta S$$

where P is the precipitation for the period of interest, and ΔS is the change in soil water storage to 3m depth. This equation assumes that there is no drainage or run-off and thus represents *"apparent"* crop water use. The validity of the drainage assumption might be strengthened by the growing deep rooted lucerne, and the experimental sites were on flat ground. Water use efficiency for grain yield (kg ha^{-1}) and biomass (kg ha^{-1}) were calculated by the following equation:

$$WUE\ (\text{kg mm}^{-1}\ \text{ha}^{-1}) = \text{grain yield (or biomass)}/ET$$

Statistical analysis

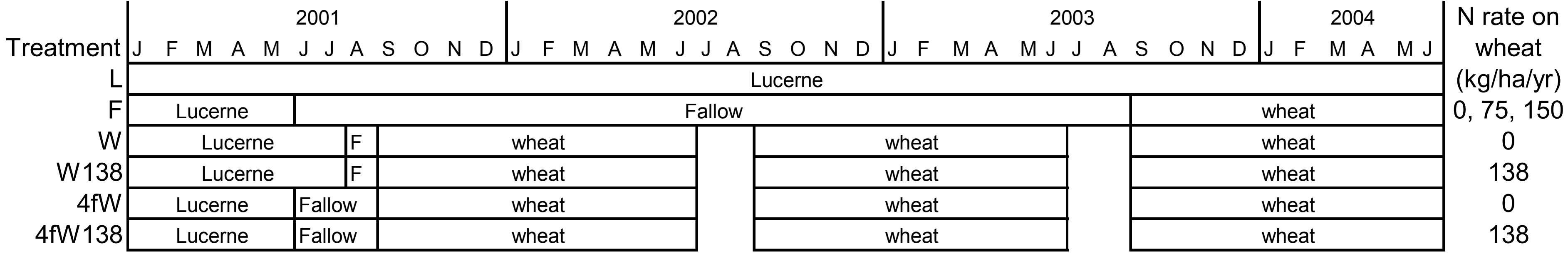
One way ANOVA was used to compare the soil water content between treatments at various times and depths using Genstat (GenStatCommittee 2000). Paired F tests were used to determine the differences in grain yield and HI and N content of grain between treatments. Difference between treatments with confidence interval of 5% were considered significant.

Results

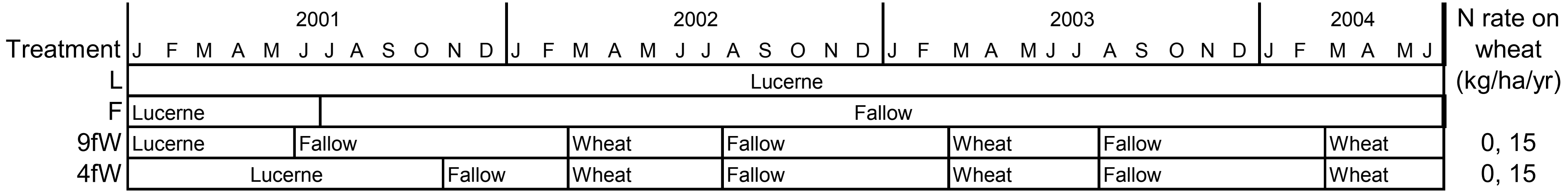
Qingyang

Annual rainfall ranged from 794mm in 2003, well above average (548mm), to well below average in 2004 (421mm). The large seasonal variability of rainfall is highlighted in data for the month of August

Lucerne/Fallow/Winter wheat sequences at Qingyang



Lucerne/Fallow/Spring wheat sequences at Dingxi



(

Figure 2) where rainfall was 34mm in 2002 and 238mm in 2003. In September 2001, 102mm fell over four days (including 55mm in one day). Early in 2002 (April and May) there was above-average rainfall, while below-average rainfall occurred for the remainder of that year. A dry spring and summer were experienced in 2003, but this was followed by a relatively wet autumn, with a total of 626 mm rainfall from 1st July to 31st October.

Plant available water capacity

Both lucerne and winter wheat were able to extract water to the 300 cm depth of the NMM access tubes. When grown under rainout shelters, *ca* 427 mm of water (CLL) remained in the soil, indicating this amount was unavailable (held too tightly) for crop uptake. The drained upper limit for the soil was 827 mm within the top 300 cm, giving a potential storage capacity of 400 mm plant available water. Water extraction below the 300 cm measurement depth was likely, especially for lucerne, as indicated by DUL and CLL profiles not converging at 300cm.

Soil water content over time

Significant differences in soil water content were observed between fallow and non-fallow treatments, and between years (Figure 3). Generally, soil water under the fallow was recharged episodically (Sept. 2001, Apr 2002, Aug-Sept 2003) and reached the DUL (828 mm water) in the top 300 cm in late 2003, coinciding with the sowing of winter wheat on the long-term fallow plots (Sep. 2003). After the fallow plots were sown with winter wheat in 2003, soil water was depleted by 448mm of (extraction + drainage) during growth of the wheat crop such that by harvest in June 2004, soil water was again close to the crop lower limit. Significant differences ($P<0.05$) in SWC under lucerne and wheat crops were only apparent for the first wheat crop sown on to the four-month fallow in September 2001. This wheat crop had *ca* 65 mm more water within 0-300 cm profile until the end of the first spring. After this time there were no significant differences in the soil water content under lucerne and wheat. A small but consistent difference in SWC between the 4f and W treatments was not statistically significant.

Water content down the soil profile

Figure 4 shows differences in soil water content with depth at sowing of each winter wheat crop, and at final wheat harvest in June 2004 in Qingyang. Here it can be seen that (i) in the first two years, the soil water content at sowing of wheat was close to the lower limit of extraction below 75cm depth (ii) the soil profile to 300cm under continuous fallow filled to the DUL in September 2003 (sowing), that (iii) both wheat and lucerne extracted most of the plant available water to 300 cm depth each year, (iv) the wheat crops sown in the wet 2003 had extracted most of the plant available water (DUL-CLL) to 300cm by harvest in 2004, and finally (v) drainage is indicated at sowing in 2003 where the SWC>DUL in the F and 4fW plots.

Lucerne DM production and water use efficiency

Annual DM production of lucerne at Qingyang was 11.8-12.9 t ha^{-1}, with the first harvest usually accounting for >50 % of the total annual DM production, and with DM yields declining for the subsequent two harvests each year (Table 2). Dry matter production from the first harvest each year (end May) was remarkably similar (7.10 - 7.96 t ha^{-1}) given the differences in stored soil water at regreening (end March, 417-712 mm, Table 2), perhaps indicative of low temperature rather than water limiting growth at this time of the year, and/or remobilisation of C reserves.

Apparent WUE ranged from 4-56 kg ha^{-1} mm^{-1} (Table 2), with the first harvest each year having the highest WUE. Minimal regrowth after cutting in August 2002 resulted in a very low WUE (4 kg ha^{-1} mm^{-1}), associated with a period of low rainfall and then cold temperatures.

Growth, yield and water use efficiency of wheat following lucerne and fallow.

For the first crop after lucerne (2002) there were no significant differences in dry matter, grain yield, harvest index or water use efficiency for wheat grown on one or four month fallows (Table 3). However, the combination of di-ammonimum phosphate fertiliser and a four month fallow (4fW$_{138}$) increased crop dry matter and yield above that of the W and 4fW crops.

Heavy rain in Aug-Sept 2003 refilled the soil profile under all rotations, effectively eliminating differences in soil water storage between the long fallow (F) and all other rotations at wheat sowing. Nevertheless, dry matter production of wheat following the long fallow (16.3 - 17.5 t ha^{-1}) was higher than following two years of winter wheat (10.5 - 15.3 t ha^{-1}).

The addition of fertiliser N increased WUE for both DM and grain yield above that of unfertilised treatments in all years, although the differences were not always statistically significant (Table 3). Water use efficiency for grain yields were all below 10 kg ha^{-1} mm^{-1}, excepting in 2004 when they were >10 kg ha^{-1} mm^{-1} for most crops receiving N fertiliser. Nitrogen fertiliser on the third consecutive wheat crop substantially increased growth (5 t/ha), yield (1-2 t/ha) and water use efficiency for grain by 3-5 kg ha^{-1} mm^{-1} above the nil fertiliser crops.

Soil nitrate at Qingyang

At sowing of the first wheat crop in 2001, soil NO_3^--N concentrations ranged from 30-35 mg kg^{-1} at the soil surface (0-30cm) to *ca* 1 mg kg^{-1} at 300 cm. There were no significant differences (P>0.05) in soil NO_3^--N concentrations resulting from the earlier termination of lucerne, although the total amount of NO_3^--N was slightly higher following the four month fallow (239-250 kg N ha^{-1}, 0-300cm) than directly following lucerne (205 kg N ha^{-1}). By sowing in 2003 the soil under the continuing fallow (F) treatment had accumulated some 369 kg NO_3^--N (269 kg N 0-125cm of soil and 100kg 125-300cm) compared to 167-180 kg NO_3^--N in the previously cropped soils (Figure 5). After cropping of this fallow in 2003-04, soil NO_3^--N was some 236 kg less, with a high concentration of NO_3^- (24 mg kg^{-1}) observed below 250cm depth (Figure 5). For fallow plots that were cropped in 2003-04 and receiving fertiliser N, NO_3^--N below 250cm was even higher, being 35 (FW$_{75}$)- 46 (FW$_{150}$) mg kg^{-1}.

Dingxi

Annual rainfall in 2003 (564mm) was 200mm above the long term average, but close to it in the other two years of the study (345-351mm). Rainfall in Dingxi in August 2003 (149 mm) was well above average (84mm), and spring (March-May) rainfall (86) in 2004 below average (125mm).

Plant available water capacity

The DUL (800mm) and CLL (345mm) for lucerne at Dingxi were similar to those measured at Qingyang, giving a potential plant available water capacity for lucerne of 455 mm. For wheat at Dingxi the crop lower limit (CLL$_w$) was some 188mm less at 321 mm, due to the shallower rooting depth of wheat. The DUL for wheat to 3m depth was 426mm, giving a potential plant available water capacity of the soil of 455 mm for lucerne but only 269 mm for wheat.

Soil water content over time

In contrast to Qingyang, (lucerne) plant available soil water storage averaged only 13mm from September 2001 until the autumn of 2003 when soil water increased to 434mm (16 October), producing 89 mm of plant available water storage for lucerne at this point (Figure 6). By the following summer, lucerne had used all of this water and soil water down the profile was close to the lower limit of extraction. For the first wheat crop in 2001, sown four months after lucerne termination (4fW), the sum of the soil water content to

1.5m was just below the crop lower limit of extraction, and following the slightly longer fallow (9fW) it was just 16mm above the CLL. Indeed, for the first two years after lucerne removal, the soil water content barely exceeded the CLL, except for the near surface layers. Prior to crop harvest in August 2003 there had been no significant differences in soil water content under fallow, lucerne or crop treatments (Figure 6). Rainfall at the end of the 2003 growing season, which contributed a small amount of stored soil water, was all extracted or evaporated in the subsequent growing season. It was not until the summer of 2004, three years after establishment, that any significant difference in soil water storage developed between the fallow and crop treatments (Figure 6).

Water content down the soil profile

We did not observe any wetting above the CLL below 150cm depth at Dingxi during the course of this study, except for a small amount of water in the fallow treatment at crop sowing time in 2004 (Figure 7). By the first crop harvest in 2002 the upper soil profile was well below the crop lower limit, especially for wheat, and at sowing of the 2003 crop there was still a small deficit (ca 6 mm) in the top 150 cm of soil. This was presumably a result of evaporation. For wheat, PAWC was not increased until the first substantive rains which occurred around harvest in 2003, which resulted in 87mm of PAW at wheat sowing in 2004 (Figure 7), the only time we observed any stored soil water which might contribute to crop growth. However, by crop harvest in 2004 there was again a deficit below the $\mathrm{CLL}_{\mathrm{wheat}}$, of 29mm, mostly due to near surface evaporation. Water stored in the fallow moved slowly down the soil profile but not further than 150cm by the end of this study, one year after the single recharge period.

Lucerne growth and water use

Dry matter production by lucerne at Dingxi (Table 4) was modest in the two years of measurement (0.95 and 0.5 t ha^{-1}). Productivity of companion weeds was similar to that of lucerne in 2002, but much lower than that of lucerne in 2004. Water use efficiencies for the lucerne-weed system were low.

Wheat growth, yield and water use

Crop dry matter production at Dingxi (Table 5) was about one half to one third of that at Qingyang, and relatively consistent between years at 3-5 t ha^{-1}. There were no significant responses to fertiliser N, either in dry matter production or grain yield. Harvested grain yields were 1.7 t ha^{-1} in 2002, 0.46 t ha^{-1} in 2003 and 1.9 t ha^{-1} in 2004. The soil water deficit at the beginning of the 2003 growing season, and a lack of rain until the end of this growing season resulted in a very low yield and harvest index (0.12) in 2003 compared to the other years (0.30 - 0.45). Corresponding WUE values for grain were 6.6 (2002), 2.5 (2003) and 8.8 kg ha^{-1} mm^{-1} (2004). Water use efficiencies for crop dry matter (Table 5) were more similar between years, averaging 18.6 in 2002, 24.2 in 2003 and 21.9 kg ha^{-1} mm^{-1} in 2004.

Discussion

Lucerne Productivity

The productivity of the lucerne at Qingyang was high (*ca* 12 t ha^{-1} per year), and close to the average productivity of (mostly irrigated) lucerne in the USA (15.7 t ha^{-1} Schaeffer *et al.* 1988). In Australia Hirth *et al.* (2001) found productivity of dryland lucerne to range from 3.1 - 11.6 t/ha over a 6 year period when annual rainfall varied from 407 - 786mm. This local Longdong lucerne landrace thus remains comparatively productive, even after seven years of forage harvest. However, for the thirty-year old lucerne at Dingxi, productivity was very much limited by the very low soil water status and low rainfall and competition from weeds; given a more favourable water status, the stand density would also limit productivity. Productivity there was substantially sub-optimal and renovation or removal would probably be recommended. It should also be noted that very low rainfall years were recorded just prior to this experiment, with seasonal rainfall being just 162mm in 2000 and

167mm in 2001. Working in Ansai, Shaanxi (520mm annual rainfall), Lu *et al.* (2003) suggested that lucerne can remain productive for 8-9 years, with peak production in the fourth year. They recommended a 3 - 5 year growing period for lucerne prior to rotation with another crop, and in the work of Li and Hao (2007) productivity of lucerne declined after eight years. There is no evidence from our study at Qingyang that lucerne productivity declined over the period of study. The length of the lucerne phase will very much depend on soil water storage and rainfall, the intended following land use, and other management objectives (see e.g. Latta *et al.* 2002). For farmers in Dingxi the primary objective is subsistence agriculture, while in Qingyang cash cropping is becoming increasingly important (Nolan *et al.* 2007). In most dryland agricultural systems, soil water storage is likely to be a key rotational consideration. In dry environments like Dingxi, short-term lucerne phases after soil water recharge might be the most rational option.

Lucerne water use

At both of our study sites lucerne was able to extract water at, or near to, the lower limit of extraction all the way to the 3m measurement depth. It was also likely to have extracted water from below this depth at both sites. At Qingyang we have observed roots of lucerne at 7m depth after just two years. Elsewhere in China lucerne has been shown to root to >5m in two years (Jia *et al.* 2006) and >10m after just five years (Li and Hao 2007). Lucerne has been reported to root to >34m (Schaeffer *et al.* 1988) and thus clearly has capacity to use up considerable stored soil water. Where long-term lucerne dries the soil profile to the lower limit of extraction, such as at Dingxi, it then becomes dependent on precipitation, resulting in lower productivity.

The apparent WUE of lucerne at Qingyang (4 - 56 kg ha^{-1} mm^{-1}) was much greater than that at Dingxi (4 - 6 kg ha^{-1} mm^{-1}), partly due to the low density of lucerne at Dingxi. The very high value at Qingyang of 56 kg ha^{-1} mm^{-1} (April-May 2003) may have resulted from water extraction below the 300cm measurement depth, since soil water extraction in the 0-300cm zone during this growth period was only 17mm due to the very low soil water content throughout the measured profile (Table 3 and Figure 3). Mobilisation of stored C from roots during this regreening period would also provide additional shoot C for relatively little transpiration cost, resulting in high apparent WUE. The value of 40 kg ha^{-1} mm^{-1} calculated for July-September the same year, under very favourable soil water and rainfall conditions may represent the upper limit of WUE for a well-managed lucerne stand. If we assume that this is correct, then from Table 3 we calculate that for the April-May period in 2003 lucerne may have extracted at least 50mm of water from below 300cm depth. WUE of lucerne growing in environments similar to Dingxi on the Gansu Loess Plateau increased from 2.9 through 8.4 to 14 kg ha^{-1} mm^{-1} in the three years after sowing (Jia *et al.* 2006). In Australia WUE for lucerne ranged from 6.7 - 17.1 kg ha^{-1} mm^{-1}, averaging 12.8 kg ha^{-1} mm^{-1} (Hirth *et al.* 2001). In the USA, WUE for mostly irrigated lucerne is said to be 14.8 kg ha^{-1} mm^{-1} (Schaeffer *et al.* 1988).

At Qingyang the earlier termination of lucerne prior to cropping resulted in the storage of an additional 30mm of water in the top 200 cm of the soil profile by sowing, an 11% fallow storage efficiency for the four month period. At Changwu (Gansu) the storage efficiency of a 2.5 month (July-early September) fallow was 40% in a continuous wheat rotation, but only 13% for a rotation including a nine month fallow (Huang *et al.* 2003). At Dingxi earlier termination of the lucerne made no difference to the stored soil water at sowing of subsequent wheat because the soil profile was so dry and there was no significant rain during the short fallow period. Furthermore by November 2003, near surface evaporation reduced soil water content 15mm below the lower limit of extraction for lucerne, such that small amounts of rain (<20mm) were unlikely to be of any benefit to lucerne at Dingxi.

Crop production after lucerne

In the first year of cropping at Qingyang the combination of short fallow plus di-ammonimum phosphate fertiliser increased dry matter production and grain yield of wheat

above the nil N fertiliser treatments. This suggests that deficits in both soil water and soil N or P might need to be overcome in order to increase wheat grain yield. Such co-limitation has also been observed in some regions of Australia (Sadras *et al.* 2004). We suspect that P rather than N may have been limiting as the available P at the site was near critically low at the initial sampling. In the subsequent years there was no significant difference in soil water at sowing or in crop growth or grain yield between the previously four and one month fallow treatments, although the third successive wheat crops responded positively and significantly to fertiliser N, indicating that any soil reserves built up after lucerne had been exhausted, and/or that leaching of N had occurred. Extensive studies of grazed lucerne in Australia have indicated that earlier termination of lucerne prior to cereal cropping can increase soil water storage at cereal sowing (Holford and Doyle 1978; Angus *et al.* 2000), but that this may not always lead to increased yield since in-crop rainfall may or may not be the principal factor limiting yield (McCallum *et al.* 2001). Working in Gansu Huang *et al.* (2003) showed that for winter wheat, on average, in-crop rainfall contributed some 68% of crop water needs and stored soil water 32%. The value of accumulated soil water for winter crop growth is well established in the region (Gao et al., 1995; Zhang & Lu, 1996; Long, 1997; Li & Shao, 2001), even from below 200 cm depth (Shao et al., 1999; Yang & Shao, 2000) .The 300cm rooting depth of winter wheat in this environment results from benign soils and a long growing season (270 days, 3 m depth), compared to that of spring wheat at Dingxi (120 days), providing considerable opportunity for retrieving deep nutrients or water at Qingyang.
The extended three-year fallow at Qingyang had accumulated some 369 kg ha^{-1} NO_3^--N and a full soil water profile when wheat was sown into it in 2003. Despite this accumulation of N, there was a significant grain yield response to 75 kg ha^{-1} of fertiliser N, but not to 150 kg ha^{-1} fertiliser N, perhaps due to "haying off" (van Herwaarden *et al.* 1998). Typical N fertiliser application rates for winter wheat in the region are quite high, averaging ca 160 kg N ha^{-1}, plus animal manures (Nolan *et al.* 2007). This responsiveness to N at Qingyang in 2004 in an apparently N rich environment may have been due to leaching of much NO_3^--N past 300cm. Although another study in a very similar environment in Shaanxi (Lu *et al.* 2003) suggested that NO_3^- leaching was unlikely, we present here strong evidence that it was very likely to have occurred in late 2003 when heavy rain pushed the soil profile over the DUL, and the soil NO_3^--N concentration at 300cm depth increased from 4 mg kg^{-1} in September 2003 to 28 mg kg^{-1} by July 2004.

Wheat growth and grain yield responses to water and N at Qingyang came through improved water use efficiencies in each case. WUE of winter wheat also increased from 1.2 kg ha^{-1} mm^{-1} for unfertilised wheat to 14.4 kg ha^{-1} mm^{-1} under high fertilisation over a 21 year period at Pingliang in Gansu (Fan *et al.* 2005). Maximum WUE_{grain} at Qingyang of 15.8 kg ha^{-1} mm^{-1} was recorded for the 2004 harvested crop which had received N. The higher WUE recorded for the 2004 harvested crop probably resulted from having a lower fraction of total available soil water lost as evaporation since the soil profile was at DUL at sowing. The WUE of winter wheat was similar in the studies of Huang *et al.* (2003) (7.5 - 9.1 kg ha^{-1} mm^{-1}) and Su *et al.* (2006) (9.9 - 13.7 kg ha^{-1} mm^{-1}), close to the values recorded here in Qingyang and in the third year in Dingxi. Low WUE's recorded in Dingxi in 2003 were a result of a very low harvest index (<0.2). This season started with the lowest soil water at sowing and while in-crop rainfall was 210mm much of it fell too late in the growing season to be effective. The annual means of 7.2 (2002), 6.4 (2003) and 10.8 kg ha^{-1} mm^{-1} (2004) at Qingyang were well below potential (Passioura 2006), although similar to elswehere in Gansu and in other comparable environments (Sadras and Angus 2006). These authors also highlighted that gains in crop WUE might be made in such environments through reducing soil evaporation. The substantial contribution of evaporation to the soil water balance in Loess soils is well recognised in China, to the extent that the efficacy of straw (Huang *et al.* 2005), plastic (Li *et al.* 1999; Li *et al.* 2004) and pebble (Li *et al.* 2005) mulches to reduce evaporation have been investigated, and indeed plastic mulches are widely used in cropping systems. Plastic mulches have also been investigated for lucerne (Jia, 2006). Improved practices to reduce soil evaporation are likely to have a significant impact on crop productivity in this environment.

Conclusions

Lucerne is well adapted to the high water holding capacity soils and summer dominant rainfall of the Loess Plateau. A wide range of WUE for lucerne reflected the complex relationships between supply of soil water and lucerne demand for water that results in lucerne accessing stored soil water during the spring. Lucerne is able to dry the soil to depths of at least 3 m depth. There was also evidence of deep drainage and nitrate leaching below 3 m at Qingyang. In contrast, there was only a relatively small amount of water storage under fallow at Dingxi, and no evidence of deep drainage or nitrate leaching. Loss of water through evaporation represented the greatest pathway of loss at Dingxi. Lucerne productivity can be maintained for several years in the higher rainfall environment at Qingyang, but not in the lower rainfall environment of Dingxi.

Present results indicate that there are some yield penalty risks associated with the first wheat crop after lucerne, but these risks appear small and manageable. Nitrogen built up after a lucerne phase may be exhausted after three subsequent cereal crops. Interactions between soil water, available N and crop yield in lucerne-wheat rotations are affected by the idiosyncratic nature of climate variability. This can usefully be studied through simulation modelling and is the focus of a related paper (Chen *et al.* 2007). Winter wheat is able to root to 300cm depth, considerably more than spring wheat in a drier environment, probably due to a longer growing season. Results indicate potential for deep drainage and nitrate leaching at Qingyang. These results demonstrate the potential for developing productive and sustainable rotations based on lucerne and wheat in higher rainfall regions on the Loess Plateau.

Acknowledgements

Funding for this research was jointly provided by the Australian Centre for International Agricultural Research (ACIAR project LWR2/1999/094) and the National Key Basic Research Special Funding Project of China (2007CB106800-4, G2000018602). Lanzhou University are grateful for continuing funding at Xifeng from 2007CB106800-4. The authors are very grateful to Miss Sheng-Qiang Zhang and You-Zhong Li for technical support.

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Tables

Table 1 Soil properties in 2001 at Qingyang after four years of lucerne and Dingxi after ca 30 years lucerne, and prior to the imposition of fallow and crop treatments. Available N is NO_3^--N, and available P is Olsen P (Moody and Bolland 1999).

Depth (cm)	pH (CaCl2)	Organic carbon (%)	Total N (%)	Available N (mg/kg)	Available P (mg/kg)	Available K (mg/kg)	Bulk density (g/cm3)
Qingyang							
0-10	8.7	0.688	0.065	38.9	6.6	130.7	1.3
10-30	8.7	0.611	0.061	40.2	3.2	94.4	1.2
30-60	8.7	0.587	0.056	34.3	2.1	90.1	1.4
60-90	8.6	0.602	0.060	29.2	2.1	81.8	1.3
90-120	8.7	0.456	0.058	23.2	2.6	80.1	1.2
120-150	8.8	0.356	0.058	26.1	2.3	72.1	1.3
150-200	8.9	0.298	0.058	21.0	2.9	69.9	1.3
200-250	8.9	0.260	0.057	17.2	2.0	66.7	1.3
250-300	9.0	0.243	0.056	19.6	2.0	69.5	1.3
Dingxi							
0-10	8.3	0.836	0.105	22.9	7.0	195.4	1.25
10-30	8.4	0.691	0.079	28.1	5.9	124.3	1.20
30-60	8.4	0.572	0.063	16.9	2.8	115.9	1.21
60-90	8.4	0.693	0.072	19.3	3.0	135.4	1.25
90-120	8.4	0.749	0.082	16.1	3.6	132.9	1.11
120-150	8.5	0.702	0.075	14.9	2.8	106.4	1.13
150-200	8.4	0.776	0.086	15.2	2.8	91.8	1.18
200-250	8.4	0.881	0.098	13.9	3.7	103.6	1.09
250-300	8.3	0.675	0.071	15.5	2.8	101.8	1.13

Table 2 Lucerne dry matter production, changes in soil water (0-300 cm), and and water use efficiency of lucerne for sequential forage harvests in each growing season in Qingyang. (± values are s.e.m. with n=4). 'Start' for the first harvest each year is soil water content at lucerne regreening in the spring (March), and 'end' is soil water content at each harvest date, which then becomes the 'start' for the next harvest. ΔSWC is the change in stored soil water between start and end. Rainfall is for the period between the start and end for each harvest.

Year	Harvest date	DM production (± s.e.m.) (t/ha)	Soil water (0-300cm)			Rainfall (mm)	"apparent" water use efficiency (± s.e.m.) kg ha-1 mm-1
			Start (mm)	End (mm)	ΔSWC (mm)		
2002	30-May	7.96 ±1.13	534	474	60	167	35.0
	21-Aug	3.37 ±0.16	474	411	63	100	20.7
	23-Oct	0.44 ± 0.09	411	447	-36	142	4.2
annual total		11.77 ±0.69	534 ±10.5	447 ± 2.5	88 ± 8.2	409	23.7± 1.4
2003	30-May	7.10 ± 0.64	444	428	16	110	56.4
	21-Jul	3.34 ± 0.37	428	492	-64	181	28.5

	15-Sep	2.46 ± 0.24	492	693	-201	274	33.6
annual total		12.90 ± 0.63	444 ± 1.9	693 ± 14.1	-249 ±12.4	565	40.8± 1.6
2004	1-Jun	7.47	704	523	181	62	30.7

Table 3 Dry matter (DM) production, grain yield, harvest index, water use between sowing and harvest (∆ SWC + in crop rainfall) and water use efficiency (WUE) of consecutive winter wheat crops, harvested in 2002- 2004 following removal of lucerne in May (4fW) or August 2001 (W) and receiving 0 or 138 kg N ha^{-1}, and for winter wheat harvested in 2004 following a two year fallow (FW) and receiving 0, 75 or 150 kg N ha^{-1} at Qingyang. WUE is calculated on the asumption that ∆ SWC is constant within rotations.

Treatment	**Dry matter (t ha-1)**	**Grain yield (t ha-1)**	**Harvest index**	**Water use (mm)**	**WUE in DM (kg ha-1 mm-1)**	**WUE in grain (kg ha-1 mm-1)**
Harvested 2002 (in crop rainfall 519mm)						
W	9.00a	3.15a	0.35	496	18.1	6.3
W138	10.83ab	3.71ab	0.35		21.8	7.5
4fW	8.93a	3.34a	0.37	511	17.5	6.5
4fW138	12.61b	4.43b	0.37		24.6	8.7
LSD	3.07	1.23	nsd	nsd	nsd	nsd
Harvested 2003 (in crop rainfall 484mm)						
WW	8.68ab	3.35	0.39	559	15.5	6.0ab
WW138	10.2ab	3.98	0.39		18.3	7.1b
4fWW	8.07a	3.12	0.39	574	14.1	5.4a
4fWW138	10.21b	3.95	0.39		17.8	6.9b
LSD	1.97	0.97	nsd	3	nsd	1.2
Harvested 2004 (in crop rainfall 159mm)						
WWW	10.51a	3.72a	0.35	376a	28.1ab	9.9a
WWW138	15.32b	5.89b	0.38		41.1d	15.8b
4fWWW	10.71a	4.23a	0.39	447b	24.1a	9.5a
4fWWW138	14.54b	5.55b	0.38		32.7cd	12.5c
LSD	0.87	0.54		57		2.2
FW	16.26	5.11x	0.31	615	26.5	8.3
FW75	17.52	6.28y	0.36		28.5	10.2
FW150	17.05	5.8xy	0.34		24.1	9.5
LSD	2.41	1.08	nsd		nsd	nsd

Table 4 Dry matter production of lucerne and weeds, and water use efficiency (WUE) system in thirty year old lucerne at Dingxi in 2002 and 2004. (s.d. for n=2)

	Dry matter production (t ha-1)			**WUE (kg ha-1mm-1)**
Year	Lucerne	Weeds	Total	
2002	0.95 (0.236)	0.01 (0.003)	0.96 (0.233)	4.0
2004	0.50 (0.284)	0.73 (0.162)	1.23 (0.126)	6.4

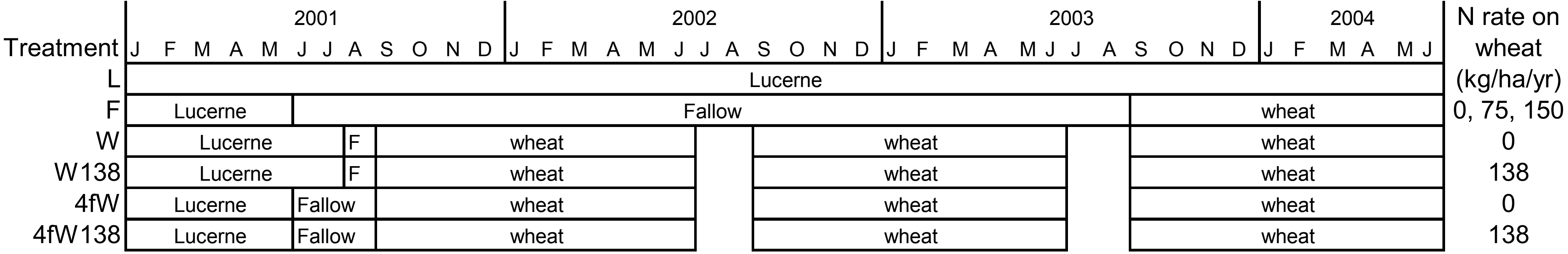
Table 5 Crop dry matter (DM), grain yield, harvest index, and water use efficiency (WUE) of consecutive spring wheats sown nine (9f) or four (4f) following the termination of a 30 year old lucerne stand in Dingxi, and receiving 0 or 15 kg N ha^{-1}.

Treatment code	**DM (t ha-1)**	**Grain yield (t ha-1)**	**Harvest index**	**∆ SWC (mm) sowing - harvest**	**WUE (DM) (kg ha-1mm-1)**	**WUE (Grain) (kg ha-1mm-1)**
	2002 (in crop rain 211mm)					
9fW	5.00±0.489	1.78±0.082	0.36±0.05	-49	19.3	6.9
9fW15	4.69±0.417	1.80±0.123	0.38±0.04	-45	18.4	7.0
4fW	4.08±0.436	1.62±0.096	0.40±0.05	-38	16.2	6.4
4fW15	4.89±0.359	1.49±0.077	0.30±0.04	-30	20.4	6.2
	2003 (in crop rain 210mm)					
9fWW	4.07±192	0.358±0.011	0.09±0.00	41	23.9	1.9
9fWW15	4.38±44	0.381±0.056	0.09±0.01	39	25.0	2.1
4fWW	3.29±655	0.603±0.034	0.18±0.03	48	20.3	3.2
4fWW15	4.45±503	0.512±0.043	0.12±0.02	46	27.7	2.8
	2004 (in crop rain 127mm)					
9fWWW	4.9±9	1.89±0.077	0.38±0.01	-94	22.6	8.6
9fWWW15	5.18±92	1.92±0.113	0.37±0.04	-92	23.0	8.5
4fWWW	4.24±169	1.90±0.074	0.45±0.05	-98	19.2	8.6
4fWWW15	4.76±166	1.94±0.002	0.41±0.04	-84	22.8	9.3

Figures

Figure 1 Lucerne-crop sequences at Qingyang and Dingxi field sites

Lucerne/Fallow/Winter wheat sequences at Qingyang



Lucerne/Fallow/Spring wheat sequences at Dingxi

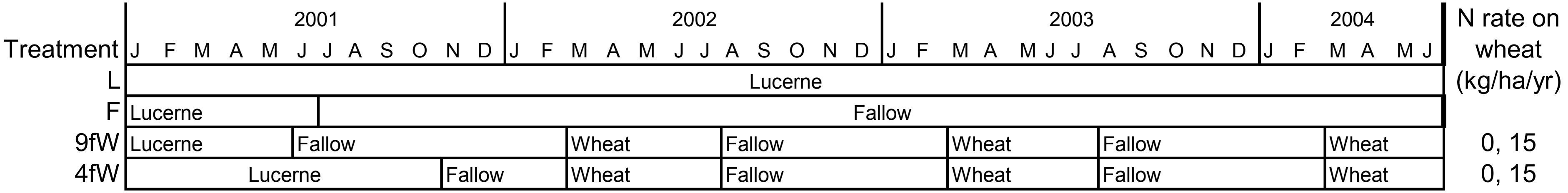


Figure 2 Long-term average (LTA) monthly rainfall, and rainfall for the experimental period (values in brackets are annual rainfall) and long-term average daily maximum and minimum temperature for Qingyang and Dingxi.

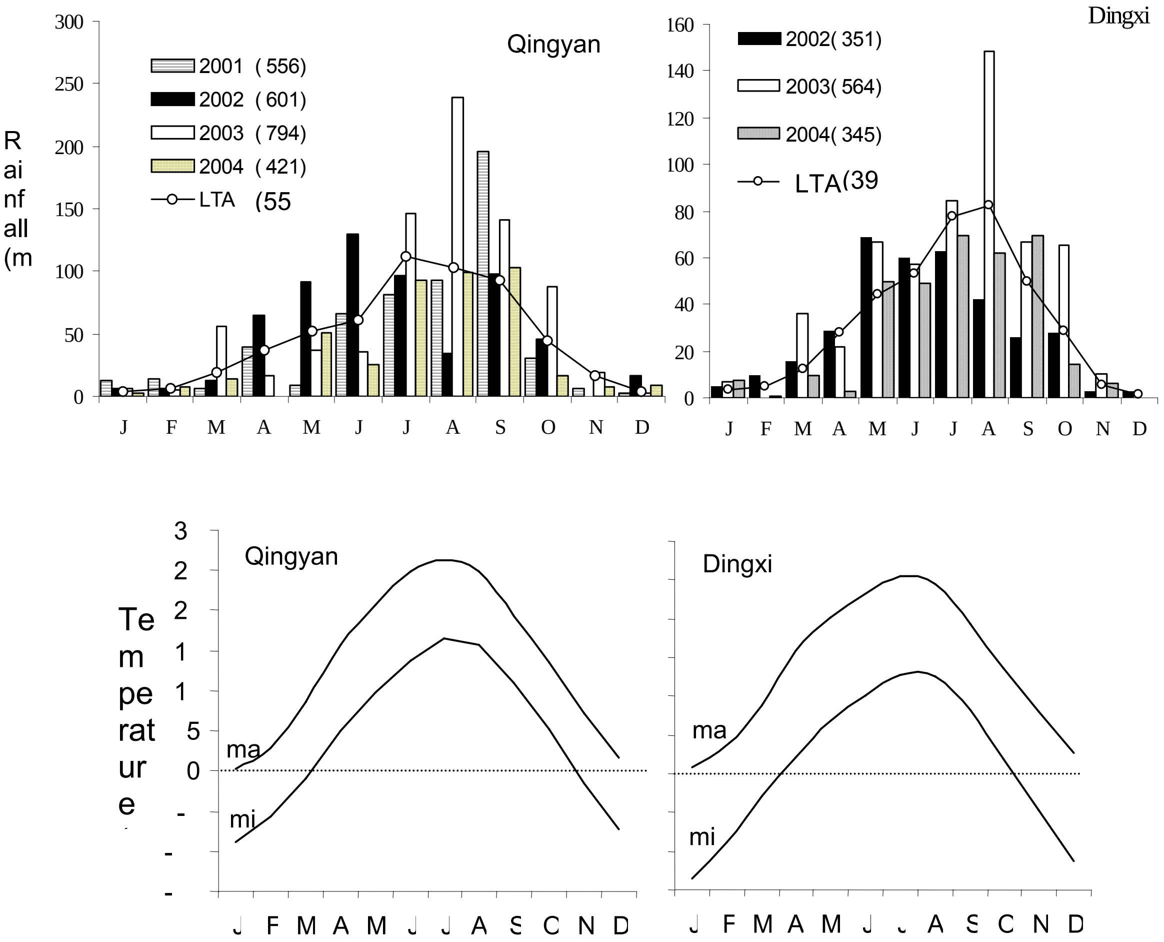


Figure 3 Total soil water content to 3m depth from September 2001 to July 2004 under lucerne and fallow, and under three consecutive winter wheat crops after lucerne terminated four months (4f) or immediately prior to sowing of the first wheat. Qingyang. Sowing S and harvest H times for wheat are indicated. Wheat was also sown onto the previously Fallow plots in September 2003. The drained upper limit (DUL) of the soil and crop lower limit (CLL) of water extraction are indicated.

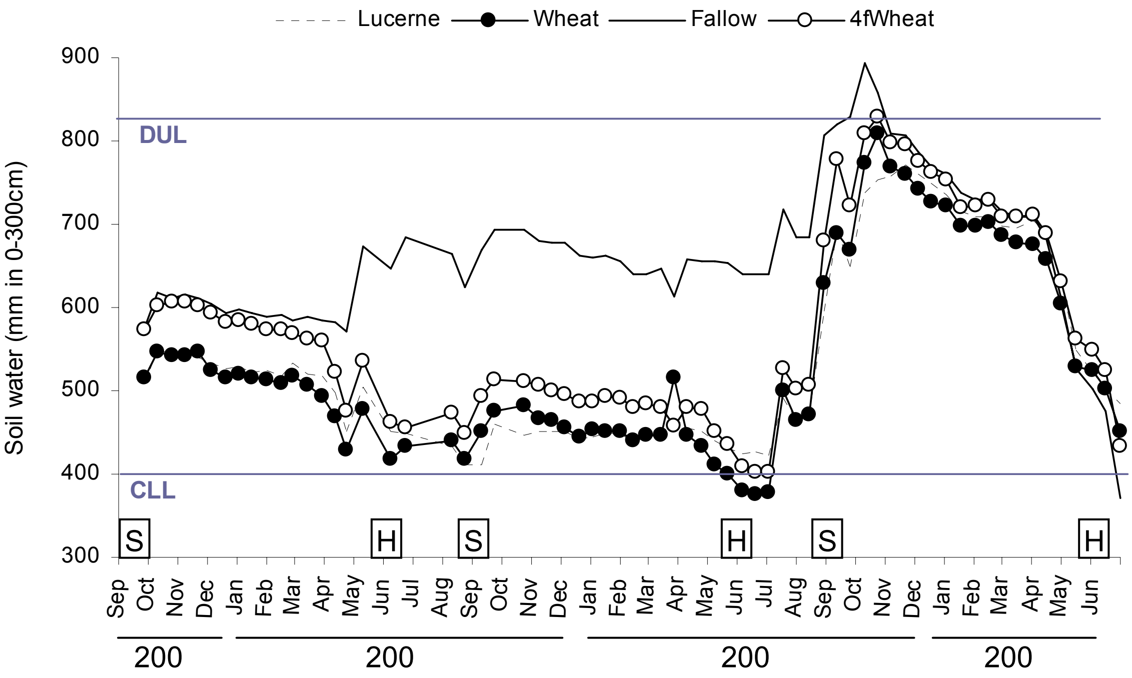


Figure 4 Soil water content to 3m depth under lucerne, fallow and a series of consecutive winter wheat crops following lucerne or a four month fallow (4f), at sowing of the wheat 2001-2003 and harvest of the 2004 wheat crop at Qingyang. The "Fallow" treatment was sown to wheat in 2003. The crop lower limit (CLL) of water extraction and the drained upper limit (DUL) for the soil are also indicated.

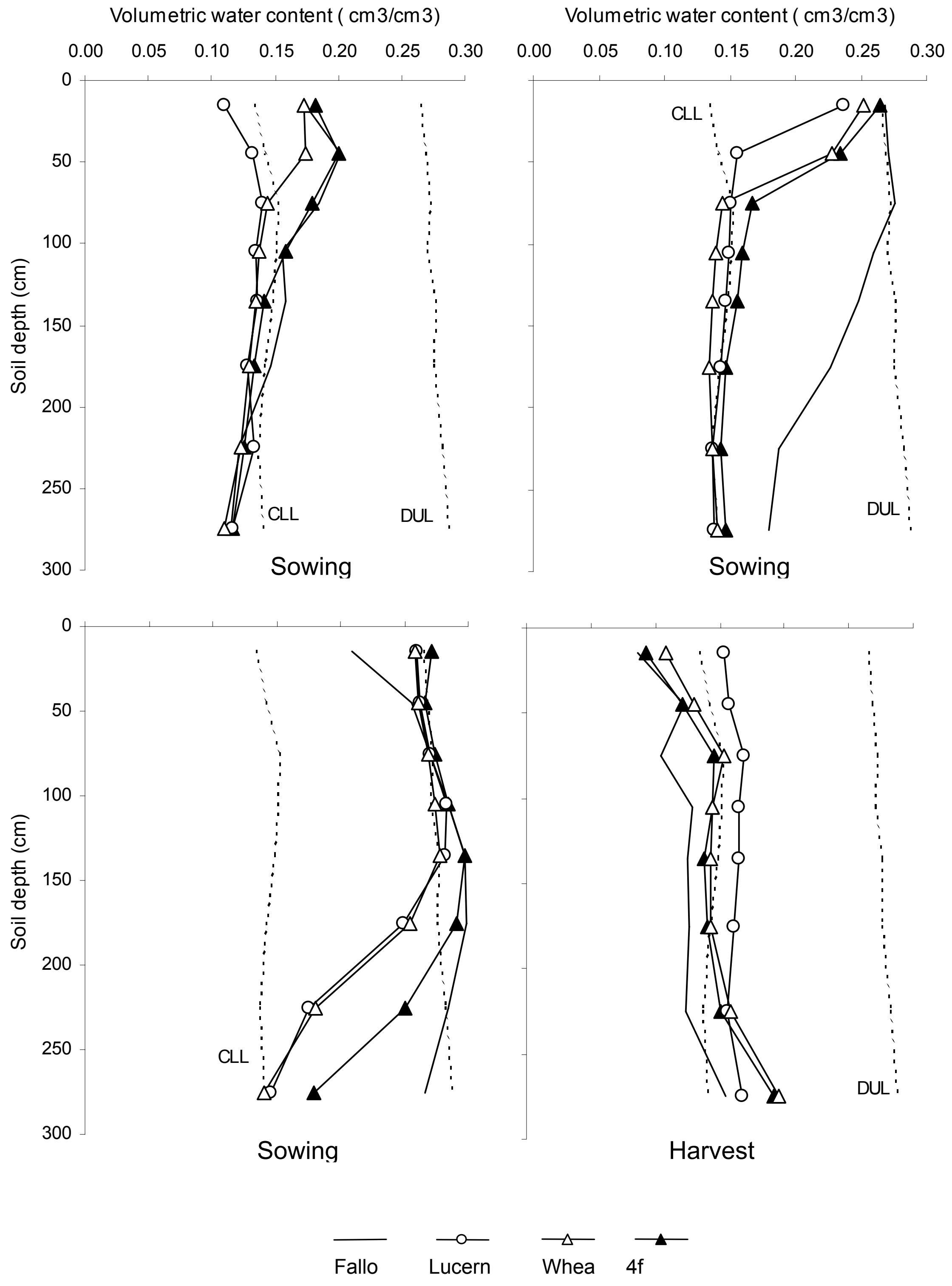


Figure 5 Soil nitrate-N (mg kg^{-1}) at Qingyang to 3m depth at sowing under fallow and the second (2002) and third (2003) consecutive winter wheats following lucerne or a four month fallow (4f), and at harvest of the wheat in 2004 after the long fallow had also been cropped to wheat.

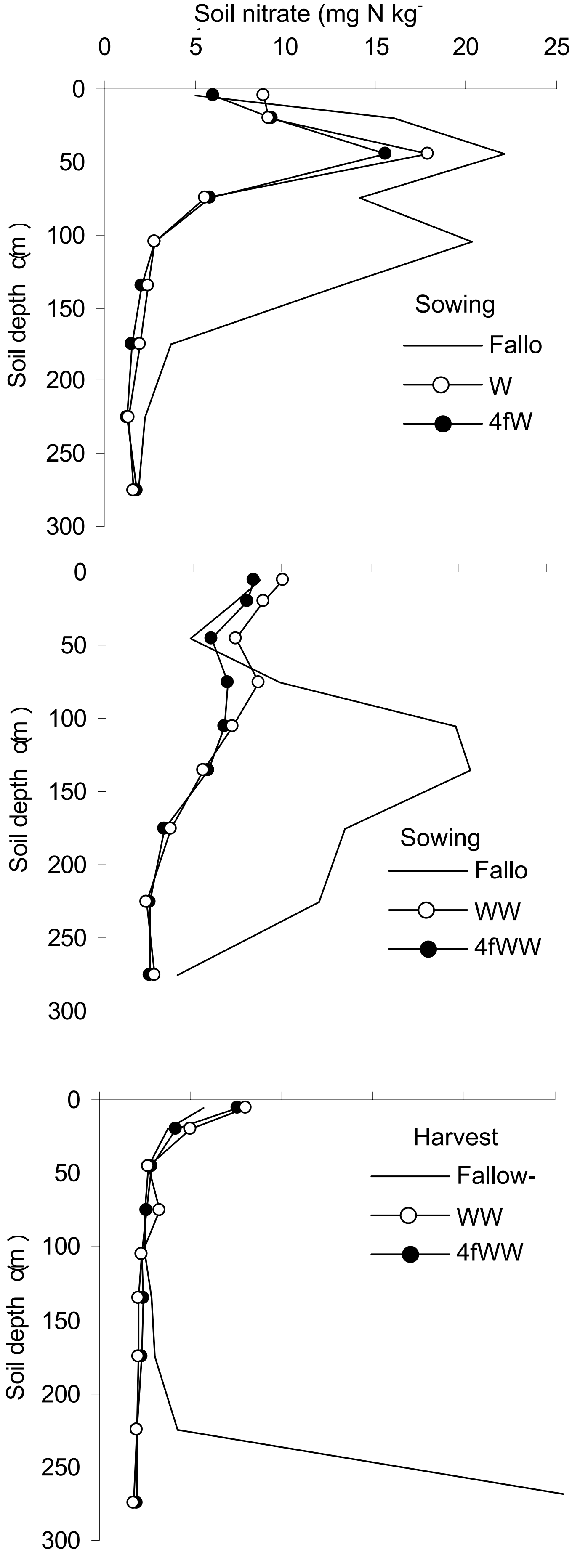


Figure 6 Soil water content (0-300cm depth) at Dingxi under lucerne and fallow, and under three consecutive spring wheat crops sown nine (9f) or four (4f) months fter termination of lucerne in 2001, and the drained upper limit (DUL). Sowing S and harvest H times for spring wheat are indicated.

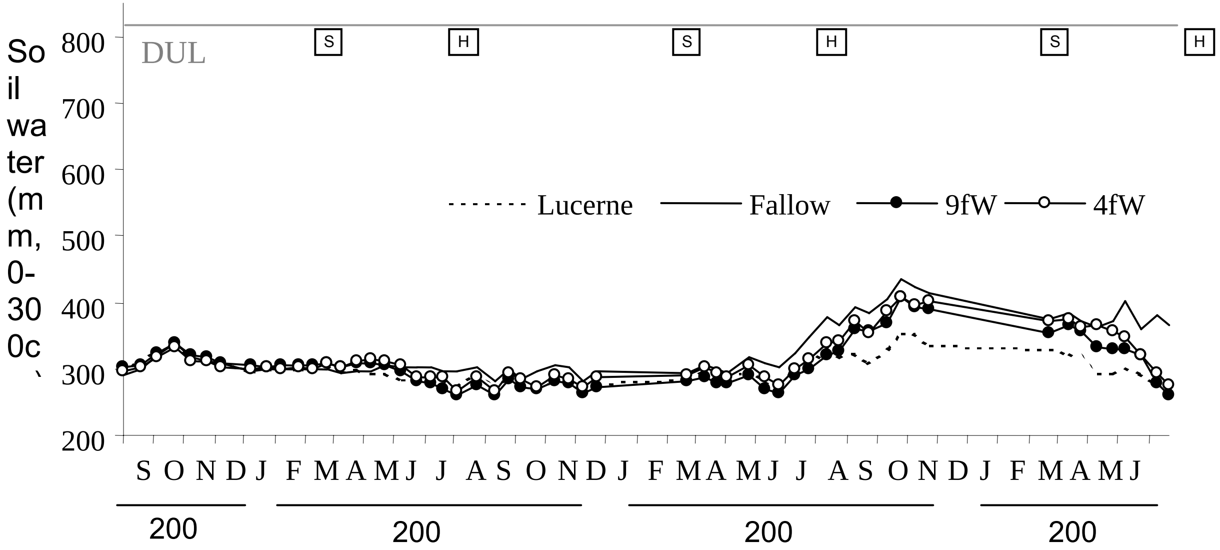
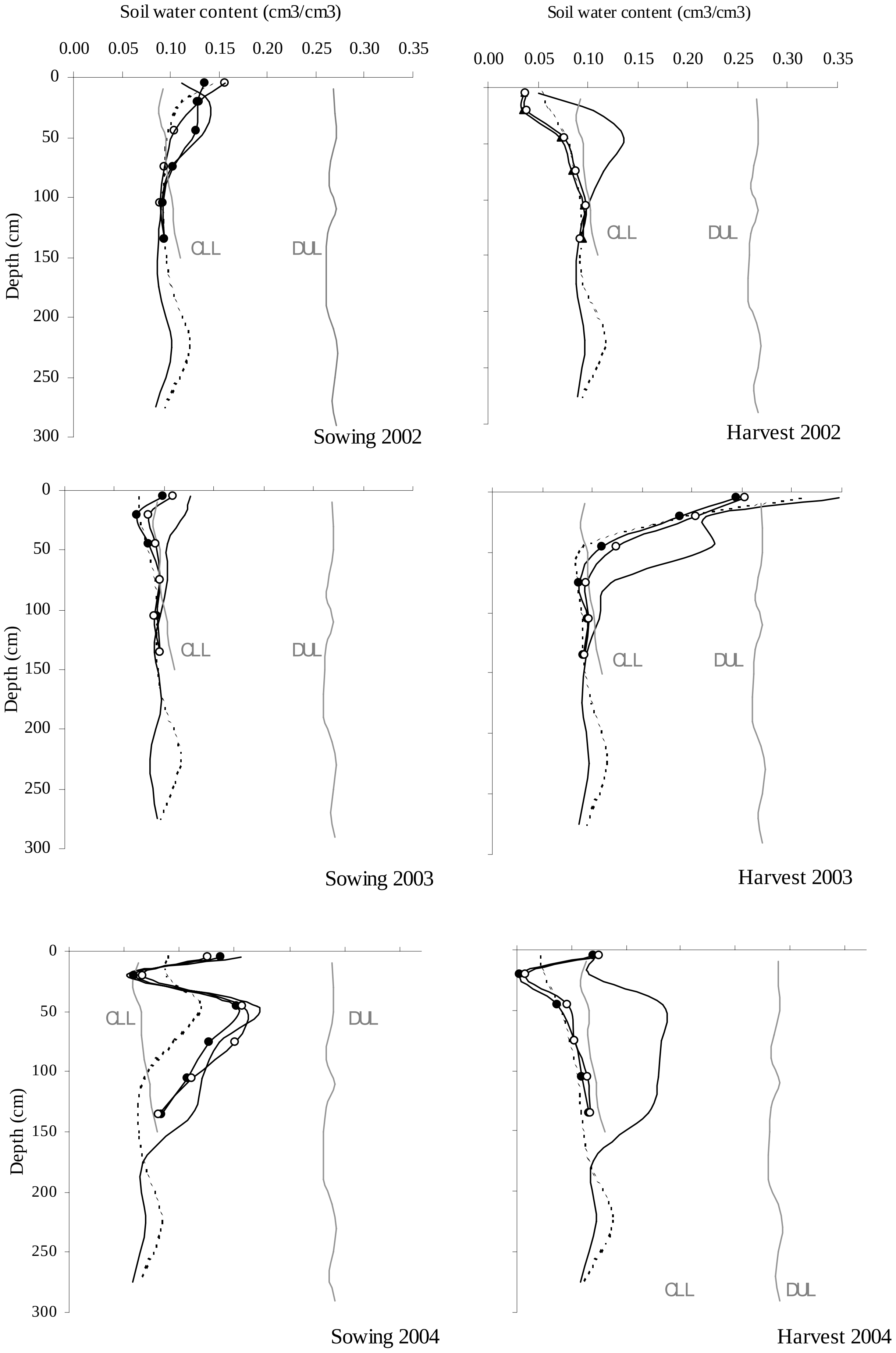


Figure 7 Soil water content under lucerne and fallow, and under three consecutive spring wheats first sown nine (9f) or four (4f) months after lucerne termination, and measured at sowing and harvest of spring wheat at Dingxi. CLL is for wheat (158mm), the lower limit for lucerne approximates the lucerne line.



Sowing 2002

Harvest 2002

Sowing 2003

Harvest 2003

Sowing 2004

Harvest 2004

11.4 Simulation analysis of lucerne–wheat crop rotation on the Loess Plateau of north-west China. Field Crops Research

Chen, W[7], Shen YY[8], Robertson, MJ[9], Probert, ME[10], and Bellotti, WD[11]. (2008) Simulation of lucerne – wheat crop rotation on the Loess plateau of northwest China. *Field Crops Research* (accepted April 2008).

Abstract

The Agricultural Production System Simulator (APSIM) was parameterised and validated against data sets from two field experiments being conducted on Heilu soil at the Qingyang Research Station, Gansu, China as to investigate long-term lucerne productivity and management options of reducing impact of lucerne on winter wheat yield in a lucerne-wheat rotation system. With minimal parameterisation and configuration of the APSIM-Lucerne module, APSIM was able to successfully simulate phenological development and seasonal growth of winter-dormant lucerne cultivar, Longdong compared with the observed data. Flowering date was well simulated using the established relationship between accumulated thermal time and mean photoperiod. After the APSIM-Lucerne module was configured for the seasonal variation in RUE, the model accurately simulated lucerne seasonal biomass production over three growing seasons in the continuous lucerne treatment with RSMD of 1132 kg/ha (30% of the mean observed biomass). In the treatment where lucerne was removed in August 2001 and two winter wheat crops were sown and harvested in 2001/2002 and 2002/2003 growing seasons, APSIM simulated winter wheat crop biomass in both growing seasons well with RSMD of 1420 kg/ha (20% of the mean observed crop biomass). Wheat grain yield was also simulated reasonably well with RSMD of 918 kg/ha (27% of the mean observed grain yield). Using measurements of DUL and LL, and standard soil evaporation and runoff parameters, the model was able to simulate soil water dynamics and water use by lucerne in the lucerne-fallow, continuous lucerne and lucerne-wheat treatments.

The long-term simulation suggested that under local climatic conditions, lucerne could produce 11000 kg/ha biomass annually. The simulation also indicated that integrating lucerne with annual cropping could potentially reduce runoff and early removal improved soil water storage prior to sowing winter wheat and optimise wheat yield following lucerne in a lucerne-wheat rotation system. The findings from these long-term simulations suggest there is need to develop management strategies when lucerne is integrated with annual cropping system to improve soil water use and reduce runoff. There is also need to consider a balance between sustaining wheat yield and providing feed for livestock when developing management strategies for timing of lucerne removal and cropping option in lucerne-based rotation systems. The successful validation of APSIM will give local researchers confident to use the tool exploring cropping system issues in Northern China.

Keywords: APSIM, Simulation, Lucerne, Rotation, Runoff.

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Introduction

The Loess Plateau is situated in northwest China between 34 and 40^0N, and 102 and 112^0E with an altitude ranging from 700 to 2200m (The region consists of parts of Gansu, Qinghai, Ningxia, Shannxi and inner Mongolia provinces with a total area of 620 000km^2, approximately 6% of the Chinese territory). It has a temperate continental climate with cold winters, a windy and dry spring, and a warm and rainy summer followed by a short, cool autumn. Dryland cropping occupies 80% of the cultivated land (Shan 1993). Predominant winter wheat cropping together with the summer fallow after the wheat harvest between July and September and extensive stubble removal and cultivation, leads to the lower soil water use and water erosion, which is the major threat to sustainable crop production on the loosely structured sandy loams of Loess origin (Li *et al*. 2002). Developing cropping systems with increased soil cover and higher water use is the key to sustain crop yields in this region.

The inclusion of perennial forages such as lucerne (*Medicago sativa*) in crop rotations could improve overall rainfall use efficiency (Gao *et al*. 1994), by synchronising seasonal water demand by crops with rainfall, thus improving rainfall utilization and potentially reducing runoff and soil erosion (Gao 1994, Gao *et al*. 1994). Lucerne (*Medicago sativa*) was introduced into China from Iran (Persia) and has been grown as a cultivated crop for more than 2000 years. It has been one of the important perennial legumes used in the Loess Plateau for increasing livestock production, improving rainfall use efficiency in a rotation with annual crops, and soil fertility through crop rotation or by transferring nutrients (via livestock manure) from lucerne-based pasture on sloping land to annual cropping flat uplands (Chen 1992). Although benefits of including lucerne in cropping systems to improve rainfall use efficiency and soil fertility have been documented, farmers are still unsure about the risks and benefits to crop yield following lucerne, and the climate risk associated with changing from current to forage legume-based cropping systems. For example, an unresolved issue is that in rainfed cropping systems, where lucerne is grown in rotation with annual crops such as wheat, it is important to terminate lucerne growth early enough to allow soil water storage prior to sowing crops, and minimise the detrimental effects of dry soil profiles to subsequent crops.

Previous international studies on the water use and forage production of dryland lucerne and impact on crops in rotation have been largely restricted to southern and western Australia (Angus et al. 2000, 2001; Dolling *et al*. 2005a,b; Dunin *et al*. 2001; Hirth *et al*. 2001; Latta *et al*. 2001; McCallum *et al*. 2001; Ridley *et al*. 2001; Ward *et al*. 2005) where seasonal rainfall patterns, soil types and cropping systems are markedly different to those on the Loess Plateau. With the proposed wider adoption of lucerne on the deep loam-textured soils of the Loess Plateau with a summer-dominant rainfall pattern, there is a need to evaluate the impact of lucerne on the crop-soil water balance and explore the consequent management implications. Simulation modelling is an ideal tool to conduct such investigations as it integrates climate, soil, crop and management interactions and can highlight possible management interventions. The Agricultural Production Systems Simulator (APSIM) has been used in dryland environments of Australia to explore issues of crop-soil water balance and management in lucerne-crop rotations (Dolling *et al*. 2007, Verberg *et al*. 2007a,b). However, APSIM has not been used for analysing cropping system issues in the temperate cold environment such as the Loess Plateau of China, where changes in crop parameterisation are needed to deal with strongly winter-dormant lucerne, and soil parameterisation to deal with deep loess soils. This study will build upon the experimental dataset of Shen *et al*. (2007) and use simulation modelling with APSIM to quantify the processes underlying forage production and the crop-soil water balance in lucerne-wheat dryland systems, and compare and contrast this with the more established understanding developed in dryland environments of Australia. The validated model parameterisation will then be used to evaluate a pertinent management issue, that is the long-term impact of early (May) vs. late (August) lucerne termination date on soil water content at the time when winter wheat is usually sown and its subsequent impact on wheat grain yield.

Materials and methods

APSIM model

The Agricultural Production Systems Simulator (APSIM) has been developed in Australia to facilitate analysis of complex production and sustainability issues of agricultural systems (McCown *et al*. 1996; Keating *et al*. 2003). APSIM simulates cropping systems at the point-scale, accounting for soil chemical, physical and crop physiological growth processes on a daily time step. In this study, crop (lucerne and wheat), soil water (SOILWAT2), soil N (SOILN2) and crop residue (RESIDUE2) modules have been linked within the APSIM framework. Input parameters or crop and soil modules are described below.

Location of studies and data sets

Two long-term experiments were established at the Qingyang Research Station (35^0 40’N, $107^0$5’E; elev. 1298 m above sea level), Gansu, China and used for parameterising and validating the model. Both experiments were conducted under dryland conditions on the well-fertilized Heilu soil (a sandy loam of loess deposits or the Los-Orthic Entisols based on the FAO soil classification). Rainfall at Xifeng (in the central part of the Qingyang county) averages 561mm per annum with a marked summer dominance i.e. July to September (55% of the total annual rainfall). Temperature is above 15^0C from May to September but winters (November to March) are cold and dry (the rainfall in the winter is only 6% of the total) with temperature below 0^0C from December to February (Chen 1993).

The first data set from a published experiment (Liu 1992) was used to parameterise the APSIM-Lucerne module for phenology and biomass accumulation. The experiment consisted of three different cutting regimes for lucerne (*Medicago sativa* cv Longdong) (cutting at bud, early flowering, and late flowering), and was conducted during 1985-1987. Plot size was 5m x 2.25m. Lucerne was cut to residual height of 3cm and total fresh weight of lucerne in the harvest area was recorded. A subsample of 200g fresh material was taken from each plot, oven-dried and re-weighed to determine dry matter yield.

The second data set from a recent field experiment was used to validate the APSIM model. The experiment was established at the same site, where lucerne was established in the spring of 1997 and managed for hay production since. In 2001, some lucerne stands were terminated to create fallow and winter wheat cropping treatments. Winter wheat was sown in September and harvested in June/July each year. The treatments are described in Table 1. Experimental plot size was 20m by 4m, and plots were arranged in a completed randomized block design with 4 replicates. The volumetric soil water content was measured using a Neutron Moisture Meter (NMM, Campbell Pacific, CPN503). In early May 2001, a 3 m aluminium access tube was installed in the centre of each plot. Soil water measurement, neutron moisture calibration and other experimental details were described in Shen *et al*. (2007).

APSIM model parameterisation

Initial runs with APSIM indicated that new phenology parameters were required for the local lucerne cultivars. The relationship between thermal time from cutting to flowering and photoperiod for cultivar Longdong was established using the cardinal temperatures of base (5^0C), optimum (30^0C), and maximum (40^0C) (Moot *et al*. 2001) (Figure 1).

The APSIM-Lucerne module does not explicitly deal with winter dormancy as seen in north-west China. Hence, the model was configured to reflect seasonal changes of lucerne growth and development in this cold temperate environment. For a period in the autumn, RUE (radiation use efficiency, g/MJ) was reduced from the standard values of 1.3, 1.3 and 0.7 (Robertson *et al*. 2002) to 0.6, 0.6 and 0.5 g/MJ, for juvenile, flower_initiation and flowering stages, respectively to simulate reduced shoot growth coincident with increased partitioning of biomass to roots at this time of year (Brown *et al*. 2006), followed by a termination of growth due to frost and then a dormant period where phenological development, and hence leaf area development ceased. After the parameterisation described above, the model simulated well the observed seasonal variation in lucerne above-ground biomass production of each cut at early and late flowering dates (Figure 2). Observed above-ground biomass values (n=12) ranged from 1200 to 6670 kg/ha. This wide range of the seasonal biomass values was simulated with RMSD (root mean squared deviation) of 392 kg/ha, which was 11% of the mean observed biomass (r^2=0.98). During the parameterisation, the possibility that declining temperature in the autumn could be linked to the reduced RUE was also examined. We found that the seasonal variation in RUE from the summer to autumn was not directly related to temperature as shown in Figure 2 and is more than likely a consequence of increased partitioning of photosynthate from shoots to roots.

In order to simulate crop-soil water dynamics it is necessary to parameterise the soil for plant available water capacity. The drained upper limit (DUL) and lower limits (CLL) of soil plant available water capacity (Figure 3) was derived using the methodology of Dalgliesh and Foale (1998). DUL was measured by wetting a bare area of soil, covering with black plastic, allowing to drain, and then sampling for gravimetric soil water content with a hand-held auger. Volumetric water content was calculated from gravimetric water content using bulk density, which was measured as 1.3 g cm^{-3} down the soil profile at the same site. CLL was measured under a small clear plastic tent covering an area of crop at maximum canopy development and allowing transpiration to dry soil until maturity or when crops stop growing (Shen *et al*. 2007). The DUL and CLL were further refined using soil water data from the second experiment. In summary, plant available water capacity to 3m was 400 and 380 mm for lucerne and winter wheat, respectively.

Other soil parameters were based on site-specific measurements of organic carbon and pH (Shen *et al*. 2007). In the water balance module of APSIM, simulation of soil evaporation is based on the concept of first and second stage evaporation (Probert *et al*. 1998). The evaporation parameters of *U* and *cona* were set to 5 and 4.5. Runoff was simulated using the USDA curve number of 75. Standard values were chosen for the model constants in SOILN2 and RESIDUE2 (Probert *et al*. 1998). The simulations were initialised for soil water (plant available water of 66mm down to 3m) and nitrogen (96 kg N/ha as nitrate down to 3m) based on the measurement at the beginning of each experiment, and no resetting was done after the model initialisation except for the time of sowing winter wheat in September 02 when the soil water was reset to observed value due to the discrepancy between observed and simulated soil water over the June-September 02 fallow period.

Daily rainfall, minimum and maximum air temperature and solar radiation for Xifeng from 1963 to 2001 were accessed from the local met office and then at the experimental site for the duration (2002 and 2003) of experiment 2 with single-channel data-loggers that recorded air temperature and solar radiation and a manual rain gauge for rainfall.

Scenario analysis

Simulation experiments were conducted to evaluate the impact of early vs. late lucerne stand termination on soil water content at sowing winter wheat and subsequent impact on wheat crop yield in a lucerne-wheat rotation system. In the simulation of lucerne-wheat rotation system, lucerne was established in the first year and managed as hay until the fourth year when lucerne hay stands were either terminated in May or August prior to sowing the wheat crop in September. At seeding, 90 kg N/ha was applied to prevent N limitations on crop growth. A series of four offset simulations were run to ensure that lucerne was terminated in every year of the climate record (1961 to 2003).

Results

Validation

Lucerne phenology and biomass production

The relationship between the thermal time accumulation between cutting and flowering and day-length is critical in determining the timing of phonological events in lucerne. After using the established relationship in Figure 1, the model adequately simulated against datasets of the flowering dates over the 8 harvest cycles. The observed flowering dates were obtained in the field in 2001, 2002 and 2003 with about 5-7 days differences between observed and simulated flowering date at each harvest cycle except for the 5th harvest cycle (Figure 4). There was close agreement between simulated and observed data for lucerne above-ground biomass production after the model was modified to use reduced RUE. Observed lucerne above-ground biomass values ranged from 2159 to 9064 kg/ha under three harvests each year over three growing seasons (2001-2003). The observed data were well simulated with a RSMD of 1058 kg/ha, which was 27% of the mean observed biomass (r^2=0.79). The exception was in 2003 where the model tended to under-predict biomass production at the first and second harvests (Figure 5a).

Soil water dynamics in the lucerne-fallow (LF) and continuous lucerne (LC) treatments

Soil water accumulation (through rainfall in the lucerne-fallow) and drying (by lucerne in the continuous lucerne) processes were well simulated (Figure 5b and 6). In the lucerne-fallow treatment, soil water content was continuously increased from the time when lucerne stands were terminated in May 2001, and by October 2003 total soil water was close to DUL, due to significant rainfall in July-September 2003 (Figure 5b). In the lucerne-fallow treatment, the simulated water balance components were examined in detail for selected periods. The autumn/winter period (14th October 01 to 3rd April 02 and 31st October 02 to 3rd April 03) when there is low rainfall (46-85 mm) and little runoff, was selected to evaluate if the soil evaporation was simulated accurately with the model as it is the predominant factor driving soil water content (Table 2). The observed soil water change (ΔSW) was -37 and 7mm for 01-02 and 02-03 respectively, and was in agreement with the simulated ΔSW values in Table 2. The spring/summer/autumn periods in both 2002 (4th April 02 to 30th Oct. 02) and 2003 (4th April 03 to 24th Oct. 03) were also selected to evaluate if the runoff/infiltration partitioning process was accurately simulated with or without deep drainage events (Table 2). In 2002, runoff occurred as result of summer rainfall but no deep drainage occurred, but in 2003, both runoff and deep drainage occurred due to significant rainfall over the period of July-October when the soil profile was close to DUL (Table 2 and Figure 5b). Compared with the simulated ΔSW values in Table 2, the ΔSW calculated from observed soil water content were 123 and 130mm in these two periods, suggesting the runoff/infiltration partitioning process was reasonably well simulated with the model during the runoff events.

In the continuous lucerne treatment, lucerne maintained a dry soil profile close to the crop lower limit from May 2002 to June 2003. From June 2003 there was significant refilling of the profile (Figure 5b). The observed and simulated changes in soil water (evapotranspiration (ET)) were compared during the periods when runoff and drainage were unlikely (based on the simulations) (Table 3). The observed ET values were closely related to simulated ones with RSMD of 9.1 mm, which was only 5% of the mean observed. Soil water dynamics at three soil layers (0-60, 60-200 and 200-300cm) in the continuous lucerne treatment (Figure 6) indicated that lucerne maintained dry soil down to 3m and there seemed to be no deep drainage occurring even after significant rainfall events in the summer-autumn periods of 2003 (Figure 5b and 6).

Wheat biomass, grain yield and associated soil water dynamics in the lucerne-wheat rotation (LFW)

In the treatment where lucerne was removed in August 2001 and two winter wheat crops were sown and harvested in 2001/2002 and 2002/2003 growing seasons, observed wheat crop biomass, grain yield and soil water dynamics were well simulated. APSIM simulated winter wheat crop biomass in both growing seasons well with RSMD of 1420 kg/ha, which was 20% of the mean observed crop biomass (Figure 7a). The linear regression between observed and simulated crop biomass (r^2 = 0.86, slope = 0.71 and intercept = 2770 kg/ha) suggested that model simulated crop biomass accurately. The observed and simulated wheat biomass values at harvest were 10164 and 9095 kg/ha in 2001/2002 growing season, and 8675 and 10417 kg/ha in 2002/2003 growing season. Wheat grain yield was also simulated reasonably well with RSMD of 918 kg/ha which was 27% of the mean observed grain yield. The observed and simulated wheat grain yields were 3271 and 3721 kg/ha in 2001/2002 growing season, and 3351 and 4567 kg/ha in 2002/2003 growing season (Figure 7a).

Soil water dynamics under winter wheat cropping in 2001/2002 and 2002/2003 following the removal of lucerne in August 2001 was well simulated compared with observed soil water data. The exception was the fallow period between June and September 2002. After 4 years continuous lucerne, the total soil water was 366mm at the time when lucerne was removed in August in 2001 due to the high water use by deep-rooted lucerne, but since then a significant amount of soil water accumulated from rain falling over the August-October period in 2001. During the wheat growing periods, the soil was maintained dry in both 2002 and 2003 due to water use by wheat crop. However, after wheat harvest in June 2003, soil water was refilled significantly (400mm) as result of significant rain from July to October in 2003 (Figure 7b).

Scenario analysis

Long-term lucerne biomass production and impact of lucerne removal date on plant available water at sowing of winter wheat and wheat yield

The simulated total seasonal above-ground lucerne biomass over the historical climate record varied significantly between years, ranging from 975 to 20441 kg/ha with a median value of 11327 kg/ha (Figure 8). There was also a general decline in mean biomass from the first harvest (5920 kg/ha) to the second (3124 kg/ha) and third harvest (2283 kg/ha) with the first harvest biomass making up about 50% of the total seasonal biomass production. This simulated seasonal trend in lucerne biomass production was consistent with the field observed data presented in Figure 2 and 5a.

The long-term simulation of the lucerne-wheat rotation indicated that late removal of lucerne in August had lower plant available water at the time of sowing wheat in September compared to an early removal of lucerne in May. On average about 80mm more plant available water could be stored at sowing if the removal was implemented early (May) rather than late (August) (Figure 9). Furthermore, when lucerne was removed in August, soil water content at sowing was at the lower limit for about 10% of the years simulated (Figure 9). Wheat yield was reduced when lucerne was removed late, and in general, the yield was reduced from an average of 4166 kg/ha in the early termination treatment to 2944 kg/ha in the late termination treatment (Figure 10).

Discussion

Model performance

Lucerne phenology and seasonal biomass production

With minimal parameterisation and configuration of the APSIM-Lucerne module, APSIM was able to successfully simulate phenological development and seasonal growth of winter-dormant lucerne cultivar, Londong in a contrasting environment to where it had been previously tested (Figure 4 and 5a). After adjustment to the relationship between thermal time and daylength, flowering date was accurately simulated (Figure 4). Furthermore, seasonal biomass production of lucerne was also well predicted after the crop radiation use efficiency (RUE) was adjusted to simulate increased partitioning of biomass to roots from the summer to autumn, followed by termination of growth due to frost and then a dormant period of no phenological development until spring (Figure 4 or 5a). In a Mediterranean-type environment of Western Australia, Dolling *et al*. (2005a) found that lucerne seasonal biomass simulation was also improved when reduced RUE was used for the autumn/winter period in the APSIM-Lucerne module. The above results suggest that the proper parameterisation for crop phenology and RUE is important when the model is used in cold temperate environments. It also suggests that adjustments to only a few key physiological parameters are required to re-parameterise the model to a new environment. This test adds to those already conducted for APSIM-Lucerne in a range of Australian environments (Dolling *et al*. 2007, Verberg *et al*. 2007a, b) and builds confidence in its portability.

There was close agreement between simulated and observed total lucerne biomass production (Figure 5a), and the production values were consistent with the long-term lucerne variety evaluation experiment of Chen (1993) who found that local lucerne cultivar, Londong produced about 10000 kg/ha biomass in the first and second year after establishment. The model also accurately captured seasonal biomass production as observed in the field except in 2003 where the model tended to under-predict biomass production at the first and second harvest (Figure 5a). In field studies, where 59 lucerne cultivars were evaluated over 4 years, Chen (1993) reported that biomass production declined in successive harvests within a growing season for all cultivars. The decline could have some association with shorter growth intervals and faster phenological development in the summer as the number of days to flowering after first harvest was decreased greatly. However, decline from the second to third harvest could be related to declining solar radiation receipts and reduced RUE due to the increased biomass partitioning to roots and this statement is supported by the studies of Khaiti and Lemaire (1992) and Brown *et al*. (2006) who reported that there were seasonal variation in above-ground biomass radiation use efficiency in lucerne and seasonal variation in potential production of lucerne was determined by the pattern of the assimilate partitioning between roots and shoots.

The under-prediction of biomass production at the first and second harvest in 2003 (Figure 5a) could be due to assumptions for lucerne rooting depth. In the simulation, rooting depth was set as 3m as soil water content in the field experiment was measured only to this depth. Lucerne maintained total soil water content close to the crop lower limit most of the time between December 2002 and June 2003 when biomass was over-predicted (Figure 5b and 6). Thus to simulate the observed biomass of 7104, 3337 kg/ha, respectively for the first and second harvest in 2003, lucerne had to extract soil water stored below 3m. Soil water extraction below 3m by lucerne on the Loess Plateau was observed by Liu *et al*. (2000). They observed that lucerne could extract soil water down to 10m and growing lucerne for an extended period could create a ‘dry’ soil layer at certain depths, which would be difficult to re-wet with rainfall, and this could have a significant impact on winter wheat yield following the termination of lucerne stands, particularly in a prolonged drought year. The above results also indicate that ‘old’ stands of lucerne still seem to be increasing their depth of water extraction, and thus the rooting depth may not be static. On deep soils such as Loess soils, simulating ‘old’ lucerne stands can not assume static root system.

Soil water dynamics in the lucerne-fallow and continuous lucerne treatments

Using measurements of DUL and CLL, and standard soil evaporation and runoff parameters, soil water dynamics in the lucerne-fallow and continuous lucerne treatments were well simulated with the model (Figure 5b and 6). Plant available water capacity determined through measurements of DUL and CLL and reported here (Figure 3) was consistent with the values measured by Huang *et al*. (2003) on a Heilu soil. Dolling *et al*. (2005b) found that plant available water changes over time under lucerne were accurately simulated with APSIM-Lucerne module when critical soil parameters such as DUL and

CLL were derived from the soil water content measurements. The detailed analysis of water balance components (Table 2) with the comparison between the simulated and observed soil water change (∆SW) suggested that the model accurately simulated soil evaporation and runoff/infiltration processes in this wet summer and dry/cold winter temperate environment. For the lucerne-fallow treatment, 126mm and 95mm water were refilled over the spring-summer-autumn (April-October) periods, respectively in 2002 and 2003, and these represent a fallow efficiency of 23% and 14%. Fallow efficiency declined from 23% in 2002 to 14% in 2003 because soil water content was at DUL resulting in significant runoff and deep drainage in October 03 (Table 2). In contrast to this, lucerne in the continuous lucerne treatment maintained a dry soil profile most of the time until June 03 (Figure 5b). The detailed analysis of simulated and observed evapotranspiration (ET) (Table 3) suggested the model was able to accurately simulate soil water use by lucerne. The observations of the large difference in soil water dynamics between two contrasting land use systems (Figure 5b and 6, Table 2 and 3) indicated that integrating lucerne with cropping systems and minimising the fallow could significantly increase soil water use and reduce runoff, and these observations are consistent with local research experience (Gao 1994, Gao *et al*. 1994). Furthermore, growing lucerne also could potentially eliminate deep drainage as deep-rooted lucerne can extract soil water and create a ‘dry soil profile’ that can hold more water. In summary, our results show an ability to simulate soil water dynamics and biomass production of lucerne on deep silt loam soils in a cold temperate climate with minimal model modifications. Such conditions are in contrast to the Mediterranean climate and texture-contrast soils where previous model tests had been conducted in Australia.

Wheat biomass, grain yield and associated soil water dynamics in the lucerne-wheat rotation

The APSIM model satisfactorily simulated winter wheat growth, grain yield and associated soil water dynamics. The exception was soil water content during the fallow period between June and September 02 (Figure 7). Like lucerne, winter wheat could extract soil water down to 3m and thus maintain a dry profile. Possible reasons for the discrepancy between observed and simulated soil water over the fallow period were explored such as poor simulation of late crop water use, runoff following wheat harvest and error in soil water measurement, but we did not find a legitimate reason to explain the discrepancy.

Model application

The long-term lucerne simulation suggested that under local climatic conditions, lucerne could produce about 11000 kg/ha of harvested biomass annually (Figure 8), and this is in agreement with local knowledge (Chen 1993). When lucerne is grown in rotation with crops, timing of lucerne removal can have a significant impact on soil water availability at sowing and subsequent crop yield. In the field studies in NSW, Australia, Angus *et al*. (2000) reported a decrease in total soil water content prior to sowing wheat, when lucerne was removed monthly from November to April. They also found that delaying lucerne removal from November to April reduced grain yield and protein content of following wheat crops. The long-term simulation conducted in this study suggested that overall, a delay in lucerne removal from May to August reduced plant available water at sowing from 156mm to 70mm, and more importantly, in 10% of the years simulated, the delay removal could lead to no plant available water at sowing (Figure 9). The reduced plant available water at sowing of wheat crop in a lucerne-based phase cropping system due to a delay in lucerne removal from the summer to the autumn, is commonly observed in a Mediterranean-type environment of southern and western Australia where rainfall is winter dominant and variable (Angus et al. 2000, 2001; Dolling *et al*. 2005a,b; Dunin *et al*. 2001; Hirth *et al*. 2001; Latta *et al*. 2001; McCallum *et al*. 2001; Ridley *et al*. 2001; Ward *et al*. 2005). This simulation studies suggest that in high rainfall and summer dominant temperate environment, the delay in lucerne removal could also affect plant available water at sowing.

The simulation also suggested that the difference in soil water content at sowing between May and August lucerne termination reduced wheat grain yield by 30% (decrease from 4166 to 2924 kg/ha) (Figure 10). In the simulation, because 90 kg N/ha was applied at sowing and plus soil mineral N was derived from lucerne roots through mineralization, simulated average wheat yield could be slightly higher than what might occur if N deficit following lucerne removal was also accounted for. A wide range of winter wheat grain yield simulated in the long-term runs (Figure 10) was consistent with the field studies of Shen *et al*. (2007) who reported winter wheat grain yield ranging from 3100 to 6300 t/ha under different soil water and fertilization conditions at this site. The results from this simulation studies suggest that when lucerne is grown in rotation with annual crops, there is need to develop management strategies for timing of lucerne removal as to sustain crop yield following the termination. The developed management strategies also need to consider a balance between sustaining wheat yield and providing enough feed for livestock in the winter. In this environment, the removal of lucerne stands after the first harvest (usually in May) not only could provide an opportunity for soil to store more water prior to sowing winter wheat and thus sustain wheat yield but also it does not affect annual lucerne hay production significantly because the first harvest is usually made up 50% of the total annual production. However, there is often a shortage of feed in the winter and early spring for livestock. If the delay in lucerne removal (till August) is required to produce more feed for the winter, alternative cropping options could also be considered, for example lucerne stands could be removed in August and followed by sowing maize in the following spring.

Acknowledgements

The research reported in this paper was funded by the Australian Centre for International Agricultural Research (ACIAR, SMCN/1999/094). The technical support in crop and soil data collection by the staff at the Qingyang Research Station of the Lanzhou University was greatly acknowledged.

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Tables and Figures

Table 1. Treatment description, cropping and fertilization details of the experiment being simulated in Xifeng.

Treatment code1	**Lucerne removed date**	**Subsequent land use**	**Crop sowing and harvest date**	
			Sowing	**Harvest**
LC	Lucerne	Lucerne	-	-
LF	13th May 2001	Fallow	-	-
LFW	17th August 2001	Winter wheat	14th September 01 17th September 02	29th June 02 9th July 03

[1.] LC: Continuous lucerne. LF: Lucerne terminated in May 2001 after 4 years lucerne and remained as fallow since. LFW: Lucerne removed one month (August) before winter wheat sowing in 2001. P fertilizer at 45.6 kg/ha was applied in LFW treatment plots, and no N was added.

Table 2. Summary of simulated water balance components of the lucerne-fallow treatment (LF).

Period	**Rain (mm)**	**Runoff (mm)**	**Soil evaporation (mm)**	**Drainage (mm)**	**ΔSW (mm)**
14 Oct 01. to 3 April 02	46	0	89	0	-44
4 April 02 to 30 Oct. 02	559	81	353	0	126
31 Oct. 02 to 3 April 03	85	5	79.1	0	0.7
4 April 03 to 24 Oct. 03	701	163	291	152	95

Table 3. Summary of rain, observed soil water change and ET and simulated ET in four different periods in the continuous lucerne treatment.

Period	**Rain (mm)**	**Observed ΔSW (mm)**	**Observed ET1 (mm)**	**Simulated ET2 (mm)**
28 Feb. to 8 June 02	205	-62	267	273
9 June to 26 July. 02	184	-16	200	188
27 July to 24 Oct. 02	180	5	175	186
28 Feb. to 6 June 03	113	-14	127	121

[1] Observed ET was calculated based on rain and measured soil water change of each period.
[2] Simulated ET was calculated based on simulated soil evaporation and transpiration of each period.

Fig. 1. Relationship between accumulated thermal time from cutting to early flowering and mean photoperiod (y = 1835-69.9x, r2 = 0.89).

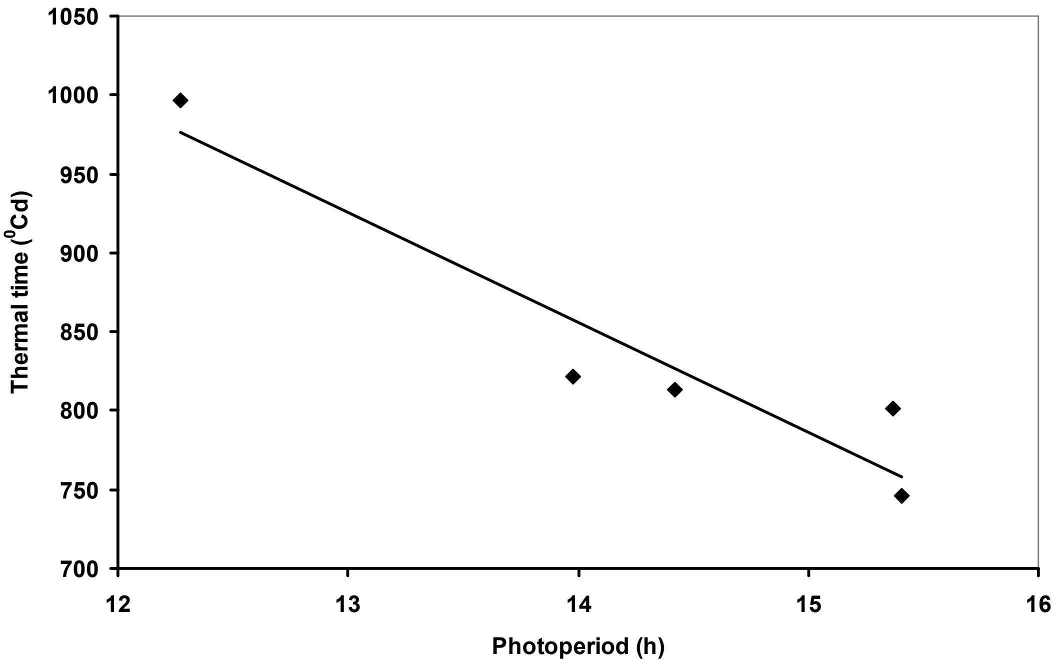
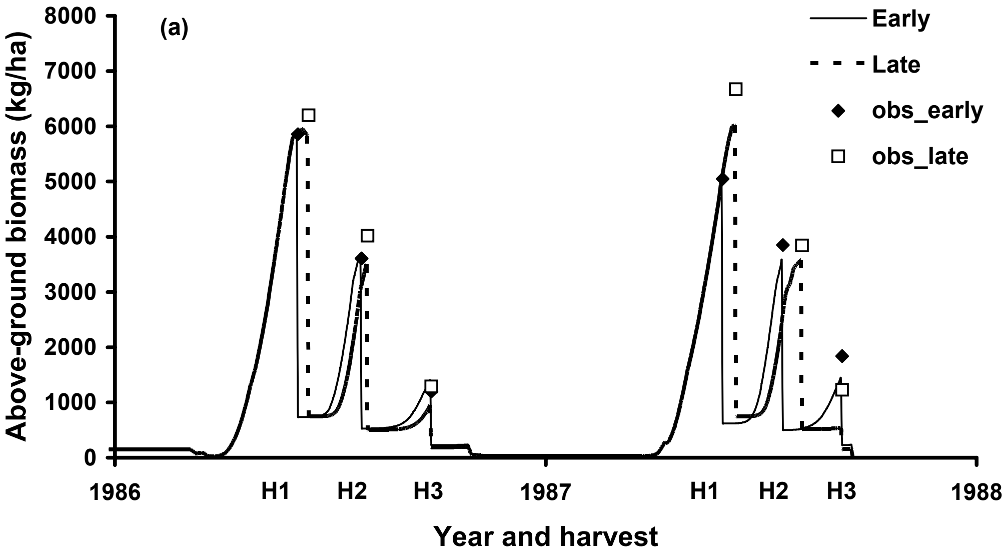


Fig. 2. (a) Observed and simulated lucerne biomass of each cut at early and late flowering dates in 1986 and 1987 after the model configuration of using the reduced RUE in the autumn period; (b) maximum and minimum temperature over the experimental period. Vertical lines indicate the timing of harvests 1 and 3.



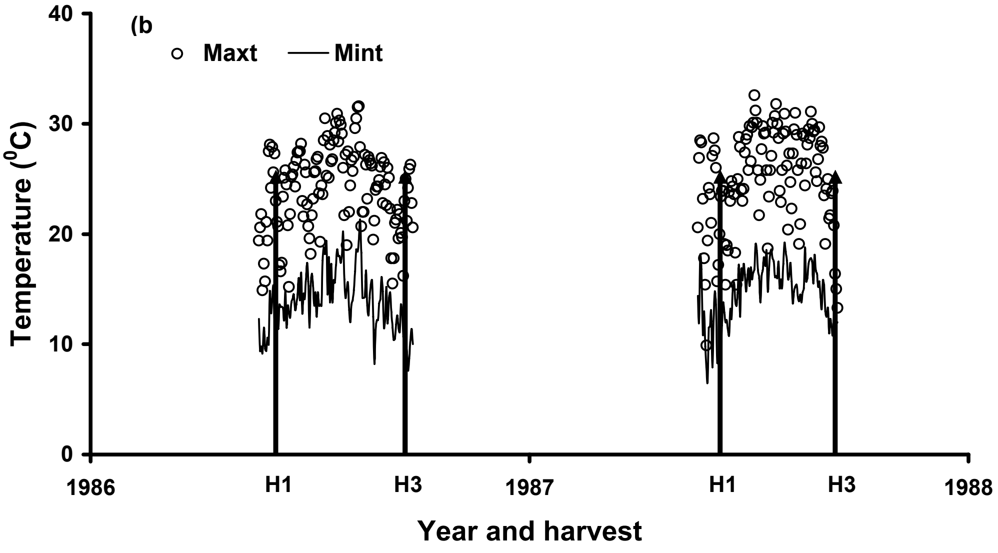


Fig. 3. Drained upper limit (DUL) and crop lower limit (LL) used in the APSIM simulations for lucerne and wheat.

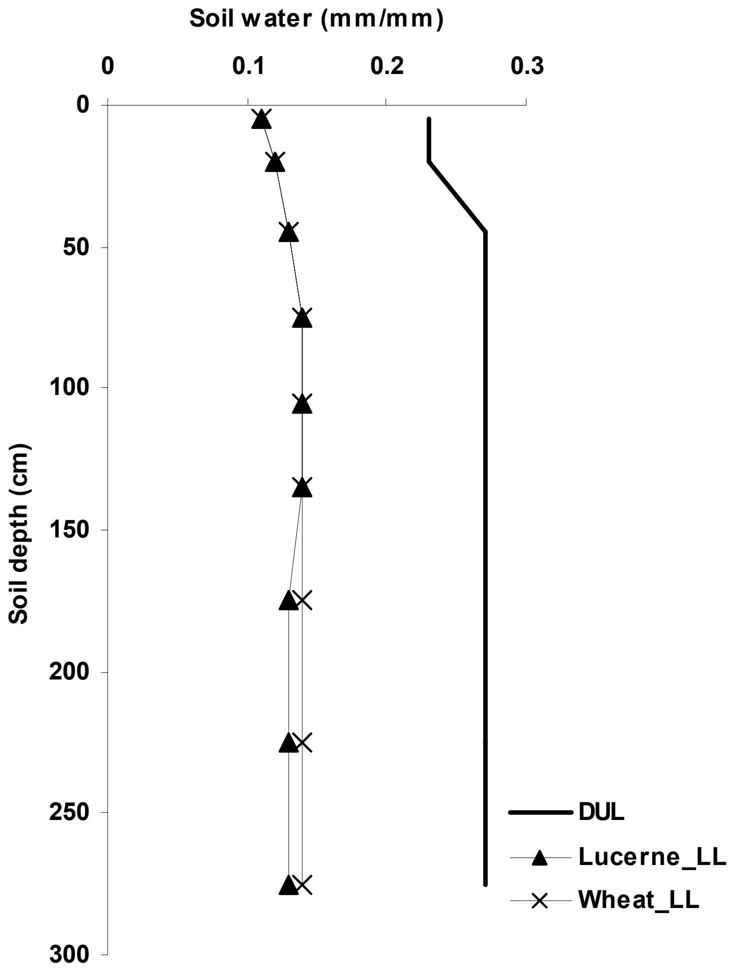


Fig. 4. Observed and simulated flowering dates of lucerne for the 8 harvest cycles from 2001 to 2003.

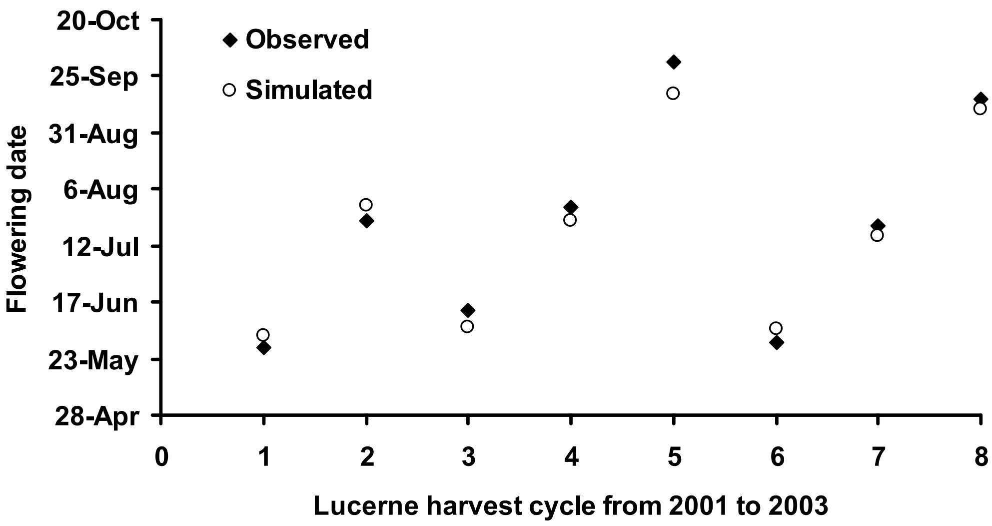


Fig. 5. (a) Observed (point) and simulated (line) lucerne above-ground biomass at each cut in 2001, 2002 and 2003; (b) Observed (point) and simulated (line) soil water content (0 to 3m) in the fallow (lucerne stands terminated in May 2001 and remained as fallow since) and continuous lucerne treatments, and daily rainfall during the experimental period.

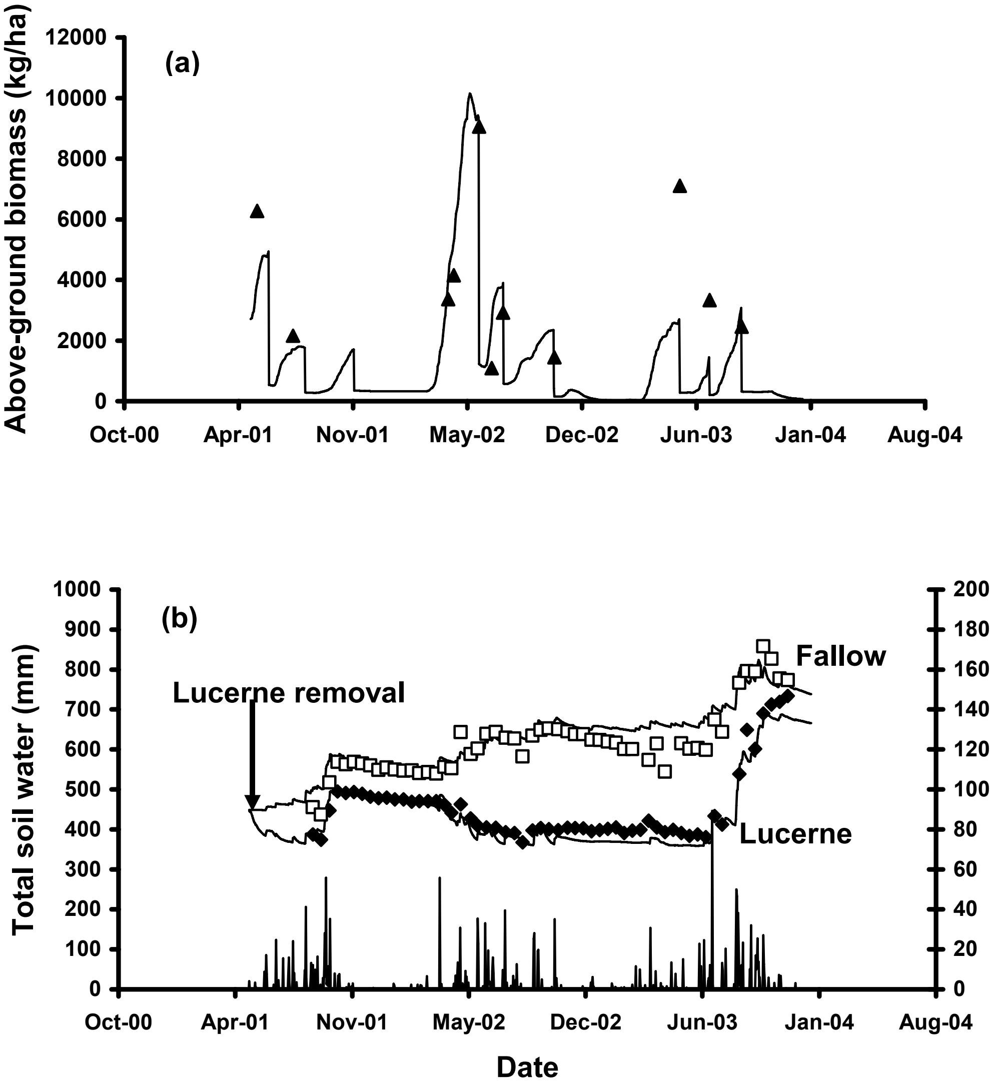


Fig. 6. Soil water content at the different soil layers in the continuous lucerne treatment.

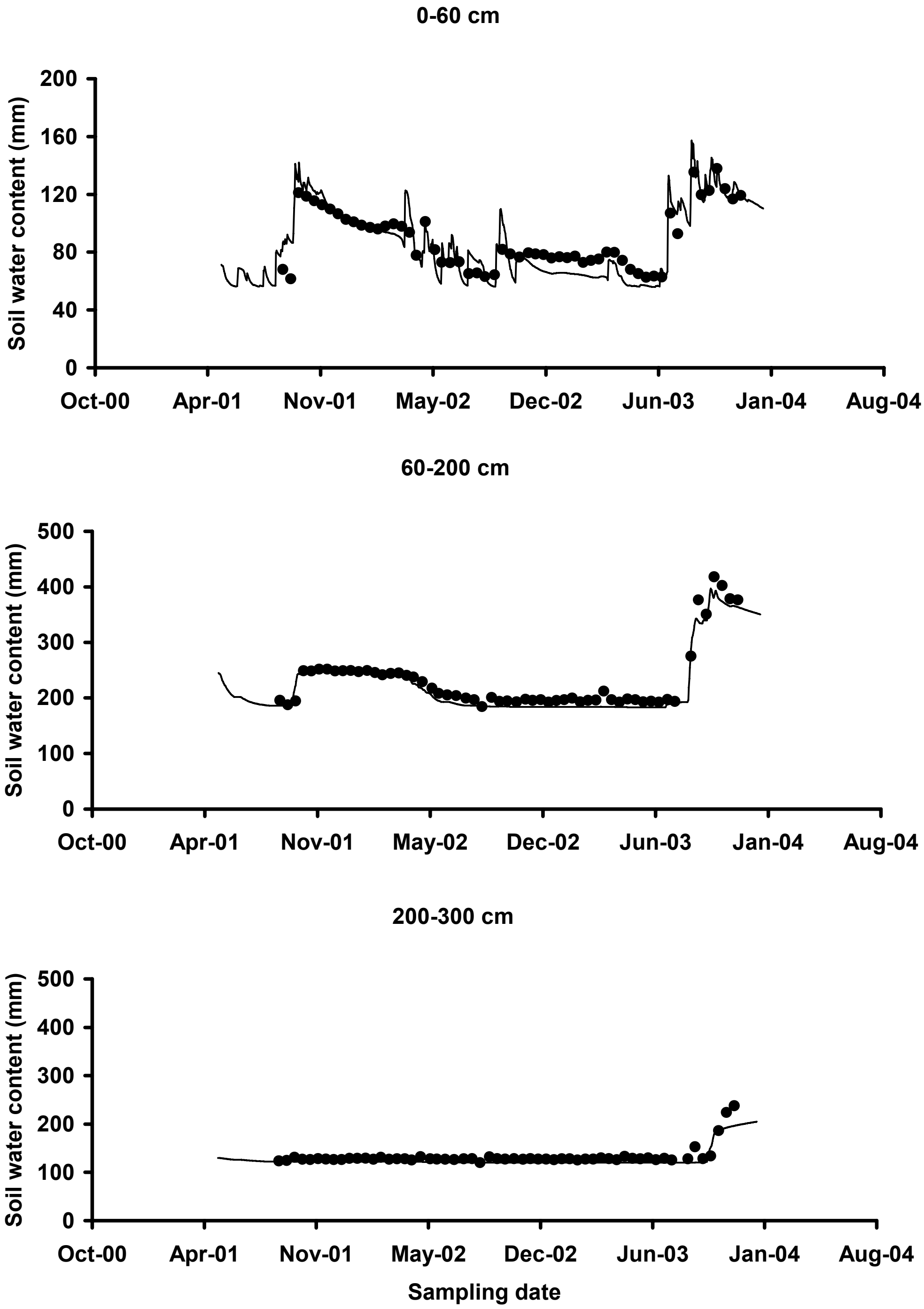


Fig. 7. (a) Observed (point) and simulated (line) crop biomass and grain yield of winter wheat when they were sown in September of 2001 and 2002, respectively following the termination of lucerne stands in August 200; (b) Observed (point) and simulated (line) soil water content (0 to 3m) during the two winter wheat growing periods in 2001/2002 and 2002/2003 following the lucerne removal in 2001 and daily rainfall during the experimental period.

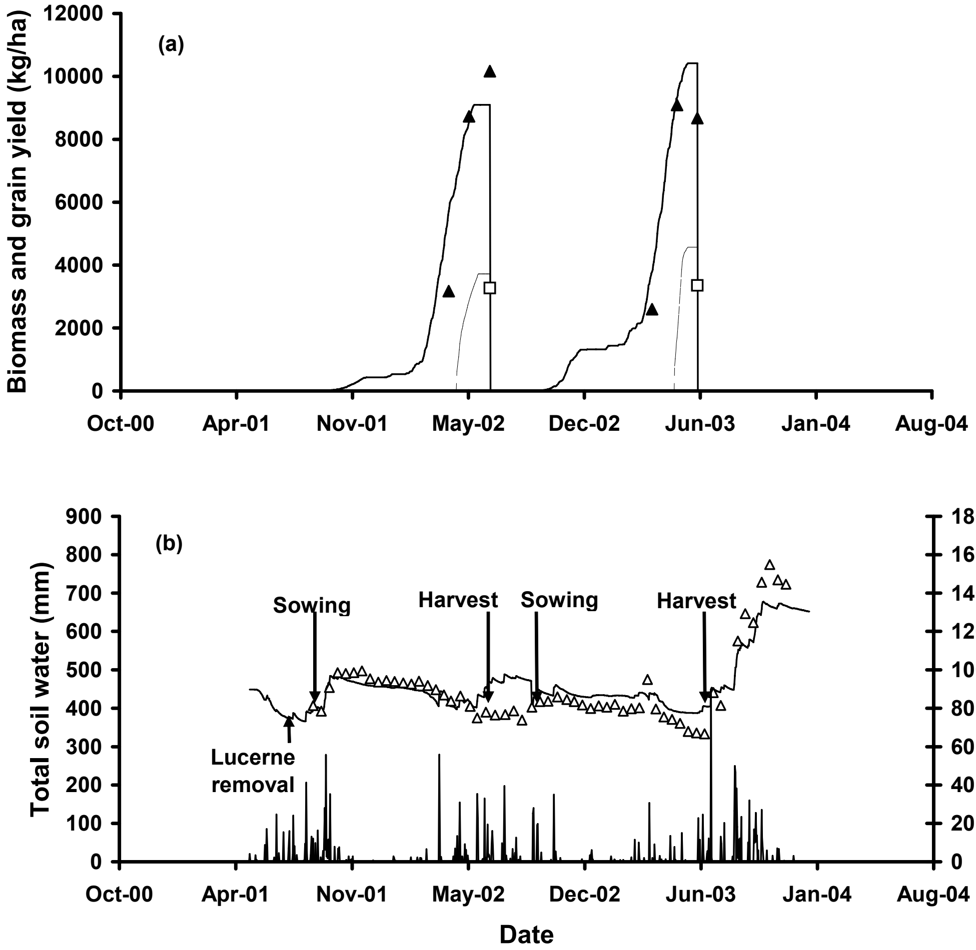


Fig. 8. Simulated lucerne above-ground biomass at each harvest at flowering from 1961 to 2003.

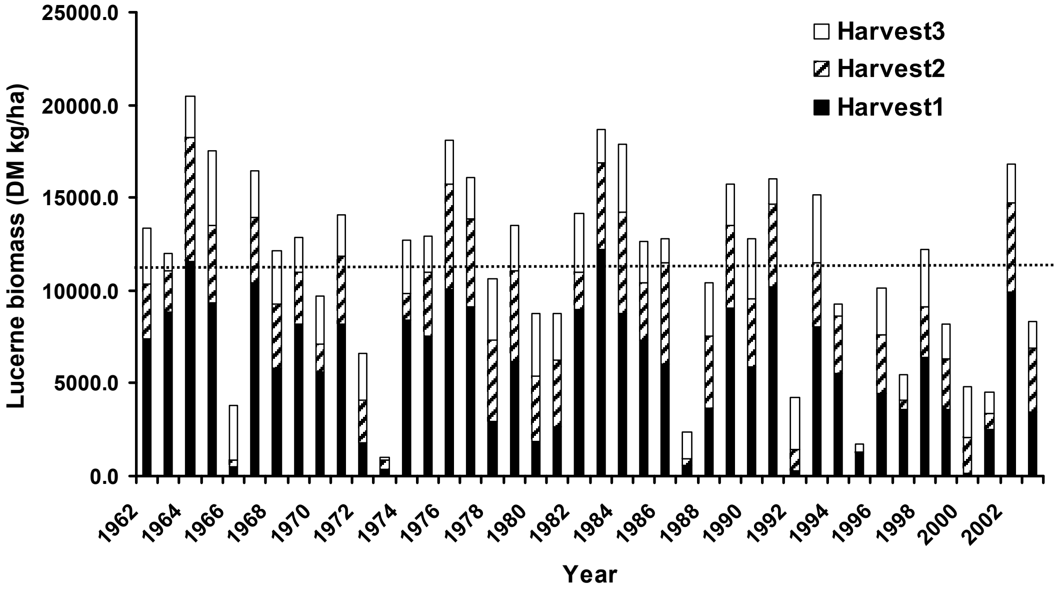


Fig. 9. Impact of different lucerne termination dates (May vs. August) on plant available water (0 to 3m) at sowing of winter wheat on 15th September simulated from 1961 to 2003.

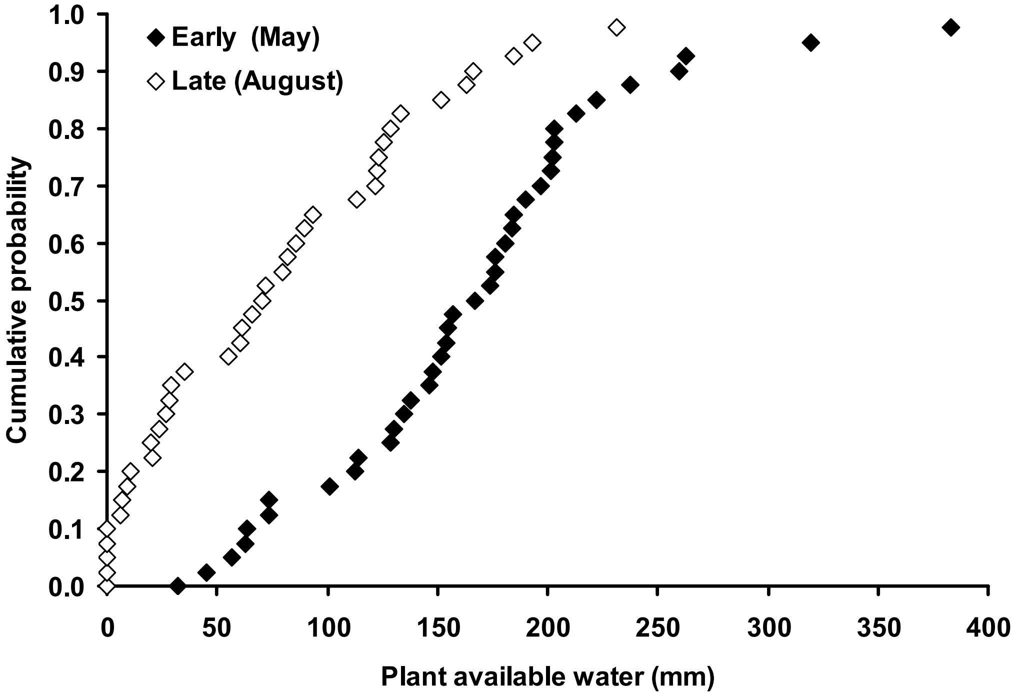
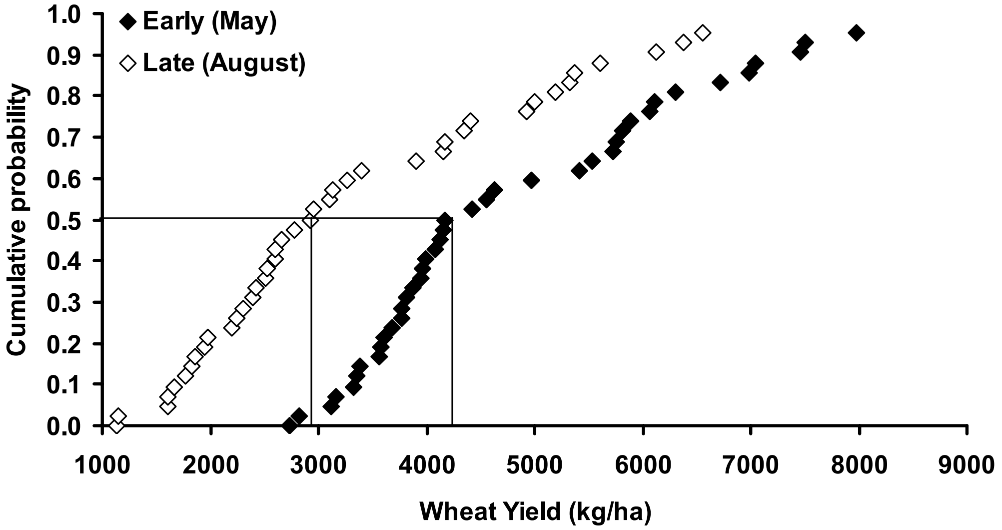


Fig. 10. Impact of different lucerne termination dates (May vs. August) on subsequent winter wheat yield simulated from 1961 to 2003.



11.5 The importance of in-crop lucerne suppression and nitrogen for cereal companion crops in south-eastern Australia. Field Crops Research

Harris RH, Clune TS, Peoples MB, Swan AD, Bellotti WD, Chen W, Norng S. (2007) The importance of in-crop lucerne suppression and nitrogen for cereal companion crops in south-eastern Australia. *Field Crops Research*, 104, 31-43.

Available online at www.sciencedirect.com
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Field Crops Research 104 (2007) 31–43

Field Crops Research
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The importance of in-crop lucerne suppression and nitrogen for cereal companion crops in south-eastern Australia☆

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Received 20 October 2006; accepted 25 May 2007

Abstract

Five field experiments located at four sites across south-eastern Australia found cereal grain yields were less in the presence of lucerne (companion cropping) than in the absence of lucerne (cereal monoculture). Top-dressed nitrogen (N) and in-crop lucerne suppression, generally did not enhance cereal crop yields in the presence of lucerne compared with cereals growing in monoculture. Grain yield reductions from cereals growing with lucerne were found at four of the five sites, with reductions ranging from 16 to 26% compared with cereals growing in monoculture. In regard to cereal production, there was no main treatment by top-dressed N interaction at all sites, indicating that applying N to cereals irrespective of whether they were growing with or without lucerne, resulted in the same yield responses. With favourable growing seasons (decile > 6) and low available soil N levels, top-dressing N resulted in a 31% and a 0.8 unit increase in grain yield and grain protein, respectively, across all cereal crops and years. However, the absence of a grain yield response to top-dressed N at one site was due to excessive cereal biomass production from N application, causing extensive crop lodging in 2003, and decile 2 growing season rainfall in 2004. At another site, high available soil N levels and low growing season rainfall (decile 3) resulted in a 12% decline in grain yield across all cereal crops and years in response to top-dressing N. We therefore conclude that N application to cereals growing with lucerne can increase cereal grain yields, but only when accompanied by favourable growing season rainfall and low available soil N levels. In-crop lucerne suppression was effective at reducing cereal grain contamination by lucerne pods and flowers in companion crops, but was less effective under dry seasonal conditions, demonstrating that soil moisture will affect herbicide efficacy and the effectiveness of this practice. Economic analyses of companion cropping based on grain yields alone, will not be adequate without an assessment of summer lucerne production, until such data exists across a range of environments, it would be premature to conclude whether and or where this practice has commercial merit.

Keywords: Inter-cropping; Companion cropping; Grain yield reduction; In-crop lucerne suppression; Top-dressed nitrogen; Lucerne; Wheat; Barley

1. Introduction

Lucerne (*Medicago sativa*) companion-cropping (also known as inter-cropping or over-cropping) involves sowing an annual crop directly into an existing lucerne stand (Willey, 1979; Harris et al., 2003; Robertson et al., 2004). In comparison with conventional cropping systems, companion cropping promotes greater use of rainfall by maintaining a perennial plant throughout the year, and therefore reduces the risk of excess rainfall leaking below the root zone and contributing to the harmful effects of dryland salinity (Crawford and Macfarlane, 1995; Angus et al., 2001; Dunin et al., 2001; Latta et al., 2001; Ward et al., 2002).

While lucerne's ability to dry soil profiles to depth is beneficial for reducing dryland salinity (Ridley et al., 2001), the

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☆ The herbicide clopyralid used in our study for in-crop lucerne suppression was used for research purposes only, and is not currently registered for the suppression of lucerne. The authors and the organisations we represent do not endorse the use of this product for lucerne suppression.

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doi:10.1016/j.fcr.2007.05.013

implications for crop performance are generally not favourable. Growing annual crops with lucerne exposes the crop to direct competition for essential resources such as sunlight, soil water and nutrients, often penalising the yield of the annual crop. Egan and Ransom (1996) reported companion-cropping cereals into young lucerne stands resulted in grain yield reductions of 6–62% compared with cereal monocultures in north-central Victoria. Humphries et al. (2004) reported similar grain yield reductions of 13–63% where wheat was sown into lucerne compared with wheat monoculture over two seasons in southern Australia. Although grain yield reductions from companion cropping can be large, there is evidence in the literature that agronomic intervention could minimise these reductions. Angus et al. (2000) concluded that top-dressed N in wet environments might reduce the grain yield gap between companion crops and crop monoculture. In addition, research in the United States has shown that corn growing in chemically suppressed lucerne yielded significantly more than corn growing in unsuppressed lucerne (Eberlein et al., 1992).

If companion cropping is to become a more reliable cropping system for managing excess soil water and reducing the threat of dryland salinity, then the grain yield reductions commonly associated with this practice need to be better managed. In this paper we attempt to answer three fundamental questions across a range of cropping environments throughout south-eastern Australia. Firstly, are cereal responses to the presence of lucerne consistent across a range of environments? Secondly, can in-crop lucerne suppression increase cereal productivity? Thirdly, can top-dressed N application increase cereal productivity in the presence of lucerne?

2. Materials and methods

2.1. Experimental sites

Five replicated field experiments located at four sites across the high rainfall-cropping zone of south-eastern Australia were established over a range of soil types (Table 1). The Roseworthy site involved two separate but adjacent field experiments (Roseworthy A and Roseworthy B). At all sites except North Boorhaman, there was at least 3 years of lucerne prior to the commencement of the experiments.

2.2. Experimental designs

Treatments included a cereal monoculture at all sites; a lucerne monoculture at Burraja and North Boorhaman; cereals growing in the presence of unsuppressed lucerne (cereal/lucerne) at Burraja, North Boorhaman and Roseworthy A and B and cereals growing in the presence of in-crop suppressed lucerne (cereal/supp lucerne) at Burraja, Grogan and Roseworthy A and B. Treatments were imposed on the same plots through time, and were replicated two times at Grogan, three times at Burraja, Roseworthy and North Boorhaman in 2003 and four times at North Boorhaman in 2005, in fully randomised block designs. The main treatments at Burraja, North Boorhaman and Grogan were divided into two subplots, with one subplot randomly allocated top-dressed N, although dry seasonal conditions at Burraja in 2002 meant no top-dressed N was applied.

2.3. Lucerne removal, crop establishment and management

At all sites, plots allocated to cereal monoculture treatments involved chemical removal of lucerne (glyphosate from 450 to 675 g of active ingredients (ai), ai/ha, in combination with either clopyralid at 150 g of ai/ha or 2,4-D at 450–900 g of ai/ha) although at Burraja and North Boorhaman mechanical cultivation was also used to kill lucerne. Lucerne was largely removed by the 20 May 2002 at Burraja; 17 October 2002 at Grogan; 10 April 2003 in replicates 1–3 and 5 May 2004 in replicate 4 at North Boorhaman and 11 June 2004 and 4 July 2005 at Roseworthy A and Roseworthy B, respectively.

Shortly after the seasonal break, all treatments (including the lucerne monoculture) at all sites, received a knockdown herbicide of paraquat and diquat (203–338 and 173–288 g of ai/ha,

Table 1
Site location, soil type, lucerne cultivar, lucerne population density and neutron probe calibration equations

	Burraja	Grogan	North Boorhaman	Roseworthy A	Roseworthy B
Longitude and latitude	146°37′E, 35°87′S	147°47′E, 34°15′S	146°23′E, 36°10′S	138°69′E, 34°53′S	138°69′E, 34°53′S
Soil type classification	Eutrophic, Red Chromosol[a]	Brown Vertosol[a]	Calcic, Mottled-Subnatric, Red Sodosol[a]	Calic, Hypernatic, Brown Sodosol[a]	Calic, Hypernatic, Brown Sodosol[a]
Field history					
1999	Lucerne	Lucerne	Annual pasture	Wheat	Wheat
2000	Lucerne	Lucerne	Annual pasture	Barley	Canola
2001	Lucerne	Lucerne	Wheat	Lucerne	Barley
2002	Experiment	Lucerne	Lucerne	Lucerne	Lucerne
2003	Experiment	Experiment	Experiment	Lucerne	Lucerne
2004	Experiment	Experiment	Experiment	Experiment	Lucerne
2005			Experiment	Experiment	Experiment
Lucerne cultivar	Aquarius	Aquarius	Pioneer 54Q53	Eureka	Eureka
Lucerne population[b] (plants/m^2)	11	15	11	7	8

[a] Isbell (1996).

[b] At the commencement of the experiment.

respectively) except at Grogan in 2004, when chlorosulfuron (11.25 g ai/ha) and trifluralin (384 g of ai/ha) was applied before sowing cereals (Table 2). In-crop herbicides applied to all treatments, were used at recommended rates at Burraja and Grogan to control germinating annual grasses (*Lolium rigidum*, *Avena fatua*, *Hordeum leporinum* and *Bromus diandrus*) and capeweed (*Arctotheca calendula*) at North Boorhaman in 2003 and 2004, which temporarily suppressed lucerne growth in the cereal/lucerne and lucerne monoculture treatments. All treatments sown to wheat at Grogan and North Boorhaman received propiconazole (125 g of ai/ha) in 2003, 2004 and 2005 to control outbreaks of stripe rust (*Puccinia striiformis*).

In-crop lucerne suppression was applied to plots at Burraja, Grogan and the two Roseworthy experiments. Suppression of lucerne involved the application of a Group I selective herbicide containing the active constituent clopyralid at varying rates and times (Table 2).

Treatments involving top-dressed N received between 40 and 100 kg N/ha in the form of urea at the first node (Zadok 31) of cereal crop growth at Burraja, Grogan and North Boorhaman in 2003, and at the second leaf stage (Z22) at North Boorhaman in 2005 (Table 2).

2.4. Soil water measurements

Soil water content was measured with a calibrated neutron moisture meter (CPN Corporation Martinez, CA, USA) (Greacen, 1981) around the seasonal break at all sites. Soil water was measured under the cereal monoculture at all sites, the lucerne monoculture at Burraja and North Boorhaman, the cereal/suppressed lucerne treatment at Grogan, and under the cereal/lucerne treatment at all remaining sites. One access tube with the lower end sealed was placed in each plot. The first measurement was taken at 0.2 m then at 0.2 m increments thereafter to 1.6 m depth.

At each site, neutron moisture meters were calibrated over wet and dry soil conditions for each depth increment. Access tubes located close to the field experiments were used for calibration against gravimetric measurements (Greacen, 1981). At each site one equation was sufficient, as the calibration did not vary with soil depth.

2.5. Soil N measurements

Soil mineral N (NH_4^+ and NO_3^-) was measured before the seasonal break at all sites. Three soil cores (internal diameter 42 mm) were collected from randomly selected positions within each plot to 1.2 m depth at Burraja, Grogan and North Boorhaman and to 0.6 m depth at Roseworthy. At all sites, cores were divided into 0.1 m increments to 0.2 m depth and 0.2 m increments thereafter, and bulked for each depth in each plot. Soils were oven dried at 40 °C for 24 h, and passed through a 2 mm sieve prior to extraction with 2 M KCl and determination of mineral N.

2.6. Biomass measurements

Cereal and lucerne biomass was collected at Burraja, North Boorhaman and Roseworthy when cereals reached maturity, but at Grogan only cereal biomass was sampled. For each sampling date at Burraja, North Boorhaman and Roseworthy 0.5 m^2 quadrats were randomly placed at six, four and four locations, respectively, within each plot, while at Grogan 0.4 m^2 quadrats were randomly placed at two locations within each plot. At all sites biomass was cut to within 2 cm of the ground level and bulked. Samples taken from the cereal/lucerne and cereal/supp lucerne treatments were sorted into cereal and lucerne biomass, and all samples were oven dried at 65 °C for 48 h and then weighed.

Table 2
Sowing details, top-dressed N management and in-crop lucerne suppression at Burraja, Grogan, North Boorhaman and Roseworthy A and B sites

Year	Sowing date	Crop and cultivar	Sowing rate (kg/ha)	Fertiliser rate at sowing			Top-dressed N management		In-crop lucerne suppression	
				N (kg/ha)	P (kg/ha)	S (kg/ha)	Time applied	Quantity applied (kg N/ha)	Time applied	Quantity applied (g ai/ha)
Burraja										
2002	23 May	Wheat[a] and Galaxy H45	100	18	20	0	NA	NA	21 August	30
2003	23 May	Barley[b] and Schooner	100	18	20	0	28 August	60	4 September	45
2004	28 May	Wheat and Diamondbird	100	18	20	0	31 August	60	31 August	36
Grogan										
2003	6 June	Wheat and Diamondbird	80	0	22	27	28 August	72	1 August	27
2004	28 May	Wheat and Drysdale	80	0	22	27	26 August	82	8 July	27
North Boorhaman										
2003	27 April	Wheat and Galaxy H45	100	18	20	0	23 July	60	NA	NA
2005	2 June	Wheat and Diamondbird	100	18	20	0	12 August	100	NA	NA
Roseworthy A and B										
2004	15 June	Wheat and Wyalkatchem	75	16	18	0	NA	NA	22 July	36
2005	9 July	Barley and Keel	70	16	18	0	NA	NA	16 August	36

[a] *Triticum aestivum*.

[b] *Hordeum sativum*.

2.7. Grain harvest measurements

Grain yield was measured by mechanical harvesting at all sites. A sub-sample of grain was retained to assess grain quality. Grain protein was calculated by multiplying grain N by 5.7. The contamination of cereal grain by lucerne pods and flowers was measured by counting their presence in a hectolitre (hL) of grain sample at Burraja. At Roseworthy, grain contamination was measured by weighing a representative sub-samples collected from the harvested grain, then sieving to separate lucerne pods and flowers before reweighing the sub-sample.

2.8. Chemical analysis

Soil mineral N concentrations were determined using the method of Rayment and Higginson (1992) via an automated colorimetric procedure and dual-channel auto analyser. The mean bulk density of soils collected when calibrating the neutron probe was used to calculate mineral N per unit volume. Grain N concentrations were measured using a LECO CNS2000 analyser apparatus.

2.9. Statistical analysis

Initially cross-site statistical analyses were performed by fitting a linear mixed model using the restricted maximum likelihood (REML) method, as experimental designs were different between sites and data sets were unbalanced. The REML analyses showed site-specific interactions, and so independent analyses for each site using analysis of variance (ANOVA) appropriate for completely randomised block designs were conducted to assess the effect of year, main treatment and top-dressed N on cereal and lucerne productivity. ANOVA was also used to assess the effect of year and main treatment on soil water content and available soil N at sowing of cereal crops at all sites. All statistical analyses were performed using GENSTAT 8.1 (Genstat, 2005).

3. Results

3.1. Rainfall

At Burraja, growing season rainfall (GSR, April to October rainfall) was 174 mm (decile 1) and 103 mm (decile 2) below the long-term mean in 2002 and 2004, respectively, and 65 mm (decile 7) above the long-term mean in 2003 (Fig. 1). In both 2003 and 2004 Grogan received 71 mm (decile 3) and 79 mm (decile 3), less GSR than the long-term mean, respectively. In contrast North Boorhaman received 57 mm (decile 7) and 25 mm (decile 6) above the long-term mean GSR in 2003 and 2005, respectively. Roseworthy GSR was 167 mm (decile 1) below the long-term mean in 2004, and 60 mm (decile 6) above the long-term mean in 2005. Annual rainfall was below the long-term mean at Burraja in 2002 and 2004, in all years at Grogan and at Roseworthy in 2004 (Fig. 1). While above average annual rainfall fell at Burraja in 2003, in all years at North Boorhaman, and Roseworthy in 2005.

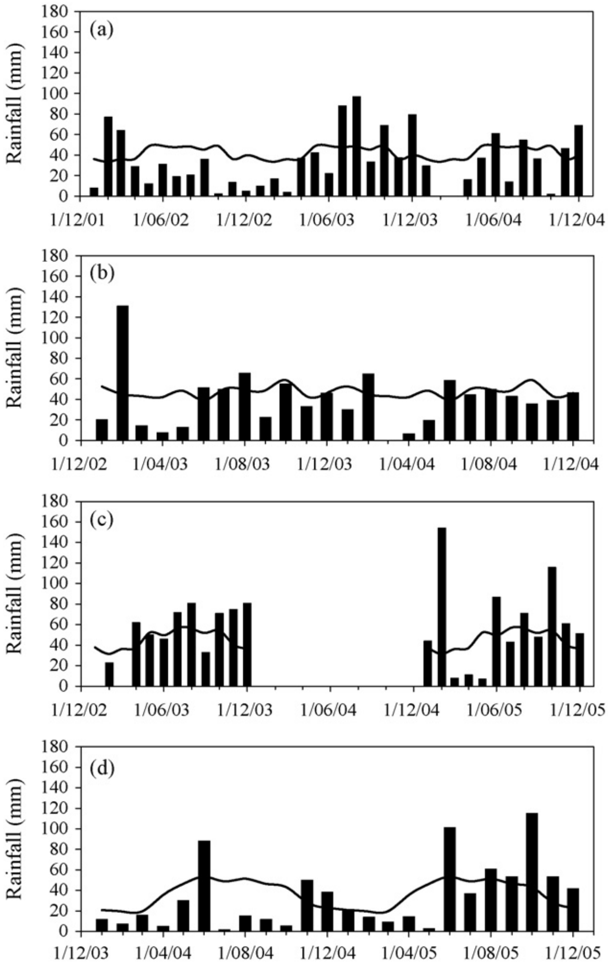

Fig. 1. Bars denote monthly rainfall (mm) for (a) Burraja from 2002 to 2004, (b) Grogan for 2003 and 2004, (c) North Boorhaman for 2003 and 2005 and (d) Roseworthy for 2004 and 2005. Lines denote long-term mean rainfall.

3.2. Cross-site comparison of site, year, treatment and top-dressed N effects

Differences ($P < 0.05$) between the fixed terms site, year, treatment and top-dressed N were found in all measurements of cereal and lucerne productivity, except treatment differences in relation to harvest index (Table 3). Numerous significant interactions between site, year, treatment and top-dressed N were found in most measures of cereal and lucerne productivity, but of most importance was the site by treatment and site by top-dressed N interactions ($P < 0.001$). These analyses show that cereal and lucerne responses to treatment and top-dressing N were site specific and therefore independent site by site analyses are more appropriate for assessing the importance of in-crop lucerne suppression and top-dressing N in cereals growing with lucerne.

3.3. Soil water content and available soil N at the sowing of cereal crops

No differences in soil water content were measured under the cereal monoculture and cereal/lucerne treatments at Burraja, Grogan, Roseworthy A and Roseworthy B (Table 4). However, at

Table 3
Chi-squares outputs from fitted linear mixed model analyses for cross-site comparisons of site, year, treatment and top-dressed N effects on cereal and lucerne biomass at cereal maturity, grain yield, harvest index (grain yield/biomass) and grain protein

Fixed term	Cereal productivity					Lucerne productivity	
	d.f.	Biomass	Grain yield	Harvest index	Grain protein	d.f.	Biomass
Site	2	<0.001	<0.001	<0.001	<0.001	1	<0.001
Year	2	<0.001	<0.001	<0.001	<0.001	2	<0.001
Treatment	2	<0.001	<0.001	0.398	0.005	2	<0.001
TD_N	1	<0.001	<0.001	0.001	<0.001	1	0.001
Site × year	1	<0.001	<0.001	<0.001	0.014	0	na
Site × treatment	2	0.311	<0.001	<0.001	<0.001	1	<0.001
Year × treatment	3	<0.001	0.988	0.001	<0.001	3	0.025
Site × TD_N	2	<0.001	<0.001	0.378	<0.001	1	0.053
Year × TD_N	2	<0.001	<0.001	0.472	<0.001	2	0.941
Treatment × TD_N	2	0.138	0.495	0.245	0.696	2	<0.001
Site × year × treatment	1	0.631	0.105	0.122	0.001	0	na
Site × year × TD_N	1	0.272	0.772	0.681	0.02	0	na
Site × treatment × TD_N	2	0.495	0.483	0.436	0.317	1	0.084
Year × treatment × TD_N	3	0.596	0.225	0.632	0.496	3	0.331
Site × year × treatment × TD_N	1	0.588	0.337	0.339	0.012	0	na

Cereal productivity data from all sites, lucerne productivity data from Burraja, North Boorhaman, Roseworthy A and Roseworthy B sites. na: Not assessable.

Burraja the soil profile under the lucerne monoculture was 19 and 22 mm drier ($P < 0.05$) than the cereal monoculture and cereal/lucerne treatments, respectively. At North Boorhaman there was a significant year by treatment interaction, as no differences existed under all treatments in 2003, by 2005 however, both the lucerne monoculture and cereal/lucerne treatments were 47 and 35 mm, respectively, drier ($P < 0.05$) than the cereal monoculture.

Independent analyses of available soil N at all sites showed no year by treatment interaction, except at Grogan as there were

Table 4
Soil water content (mm) to 1.6 m at the sowing of cereal crops at all sites and years

Treatment structure	Year	Treatment	Burraja	Grogan	North Boorhaman	Roseworthy A	Roseworthy B
Year × treatment	2002	Cereal monoculture	312				
		Cereal/lucerne	324				
		Lucerne monoculture	317				
	2003	Cereal monoculture	332	419	416		
		Cereal/lucerne	350		413		
		Cereal/supp lucerne		411			
		Lucerne monoculture	317		410		
	2004	Cereal monoculture	342	416			
		Cereal/lucerne	323				
		Cereal/supp lucerne		400			
		Lucerne monoculture	296				
	2005	Cereal monoculture			402		
		Cereal/lucerne			367		
		Lucerne monoculture			355		
Treatment		Cereal monoculture	329	417	409	369	319
		Cereal/lucerne	332		390	354	325
		Cereal/supp lucerne		405			
		Lucerne monoculture	310		382		
Year	2002		318				
	2003		333	415	413		
	2004		320	408			
	2005				375		
$\mathrm{LSD}_{0.05}$ year × treatment			n.s.	n.s.	22	na	na
$\mathrm{LSD}_{0.05}$ treatment			18	n.s.	16	n.s.	n.s.
$\mathrm{LSD}_{0.05}$ year			n.s.	n.s.	13	na	na

n.s.: Not significant; na: not assessable.

Table 5
Available soil N (kg/ha) to 1.2 m at Burraja, Grogan and North Boorhaman and 0.6 m at both Roseworthy sites, at the sowing of cereal crops

Treatment structure	Year	Treatment	Burraja	Grogan	North Boorhaman	Roseworthy A	Roseworthy B
Year × treatment	2002	Cereal monoculture	62				
		Cereal/lucerne	72				
		Lucerne monoculture	68				
	2003	Cereal monoculture	95	132			
		Cereal/lucerne	80	123			
		Lucerne monoculture	95				
	2004	Cereal monoculture	57	231		93	
		Cereal/lucerne	28	159		72	
		Lucerne monoculture	52				
	2005	Cereal monoculture				55	
		Cereal/lucerne				59	
		Lucerne monoculture					
Treatment		Cereal monoculture	71	181	32	74	55
		Cereal/lucerne	60	141	39	66	54
		Lucerne monoculture	72		34		
Year	2002		67				
	2003		90	127			
	2004		46	195		79	
	2005					57	
$LSD_{0.05}$ year × treatment			n.s.	32	na	n.s.	na
$LSD_{0.05}$ treatment			n.s.	22	n.s.	n.s.	n.s.
$LSD_{0.05}$ year			17	22	na	19	na

n.s.: Not significant; na: not assessable.

no differences between treatments in 2003, but in 2004 the cereal monoculture had accumulated an additional 72 kg N/ha (Table 5). The only other differences ($P < 0.05$) in available soil N was found between years at Burraja and Roseworthy A.

3.4. *Cereal performance in monoculture, in the presence of lucerne and in the presence of suppressed lucerne*

At Burraja there were significant ($P < 0.05$) year by treatment interactions in cereal biomass and harvest index (Table 6). The cereal monoculture produced 60 and 51% in 2002, and 23 and 30% in 2003, more cereal biomass than the cereal/suppressed lucerne and cereal/lucerne treatments, respectively, but no differences between treatments existed in 2004. While in 2002 the cereal monoculture achieved a superior ($P < 0.05$) harvest index compared with the cereal/suppressed lucerne and cereal/lucerne treatments, in 2003 the opposite resulted, where harvest index was lower ($P < 0.05$) in the cereal monoculture. In addition there were significant differences ($P < 0.05$) in productivity between years, within individual treatments, also contributing to these interactions. Cereal grain yield and grain protein at Burraja were unaffected by the presence of lucerne, only differences between years were observed. The only difference between the cereal/suppressed lucerne and cereal/lucerne treatments was a reduction ($P < 0.05$) in lucerne contamination and furthermore, contamination was also affected by seasonal conditions.

A significant ($P < 0.05$) year by treatment interaction was found at Grogan, where cereal biomass was 30% lower in the cereal/suppressed lucerne treatment compared with the cereal monoculture in 2003, but no differences were found in 2004 (Table 6). Unlike Burraja, over the 2 years at Grogan the cereal monoculture yielded 16% more ($P < 0.05$) grain than the cereal/suppressed lucerne treatment. Harvest index and grain protein were unaffected by the presence of lucerne.

Over the 2 years, cereal biomass and grain yields were 15 and 24%, respectively, greater ($P < 0.05$) in the cereal monoculture compared with the cereal/lucerne treatment at North Boorhaman (Table 6). Significant year by treatment interactions were found in harvest index and grain protein. Harvest index was superior ($P < 0.05$) in the cereal monoculture in 2005 but not in 2003, in comparison with the cereal/lucerne treatment, as well as differences ($P < 0.05$) between years within the cereal monoculture treatment contributing to this interaction. While grain protein was higher ($P < 0.05$) in the cereal monoculture in 2003, it was not in 2005 compared with the cereal/lucerne treatment, and furthermore differences ($P < 0.05$) between years within treatments again contributed to this interaction.

At Roseworthy A, cereal biomass was 24 and 29% lower ($P < 0.05$) in the cereal/suppressed lucerne and cereal/lucerne treatments, respectively, compared with the cereal monoculture over the 2 years (Table 6). A significant ($P < 0.05$) year by treatment interaction was found in grain yield where the cereal monoculture out yielded the cereal/suppressed lucerne and cereal/lucerne treatments by 16 and 26%, respectively, in 2005, but no differences were measured in 2004. In addition individual treatments experienced significant differences

Table 6
Cereal biomass at maturity, grain yield, harvest index (grain yield/biomass) and grain protein in monoculture, in the presence of lucerne, and in the presence of suppressed lucerne at all sites; and lucerne contamination (foreign) of cereals growing with lucerne at Burraja and both Roseworthy sites

Treatment structure	Year	Treatment	Biomass (t DM/ha)	Grain yield (t/ha)	Harvest index	Protein (%)	Foreign[a]
Burraja							
Year × treatment	2002	Cereal monoculture	2.84	0.70	0.25	15.2	
		Cereal/supp lucerne	1.12	0.24	0.22	15.2	
		Cereal/lucerne	1.37	0.28	0.20	15.2	
	2003	Cereal monoculture	16.20	5.23	0.32	10.6	
		Cereal/supp lucerne	12.50	5.47	0.44	8.9	
		Cereal/lucerne	11.42	5.17	0.46	9.0	
	2004	Cereal monoculture	7.24	2.39	0.33	12.0	
		Cereal/supp lucerne	7.20	2.27	0.32	12.0	
		Cereal/lucerne	6.39	2.07	0.33	12.3	
Treatment		Cereal monoculture	8.76	2.77	0.30	12.6	
		Cereal/supp lucerne	6.94	2.66	0.33	12.0	22[b]
		Cereal/lucerne	6.39	2.51	0.33	12.2	58[b]
Year	2002		1.78	0.40	0.22	15.2	81[b]
	2003		13.37	5.29	0.41	9.5	20[b]
	2004		6.94	2.24	0.33	12.1	18[b]
LSD$_{0.05}$ year × treatment			1.37	n.s.	0.03	n.s.	
LSD$_{0.05}$ treatment			0.79	n.s.	n.s.	n.s.	9
LSD$_{0.05}$ year			0.79	0.20	0.02	1.1	13
Grogan							
Year × treatment	2003	Cereal monoculture	9.07	2.38	0.26	15.5	
		Cereal/supp lucerne	6.34	1.67	0.27	14.4	
	2004	Cereal monoculture	9.57	3.10	0.33	14.7	
		Cereal/supp lucerne	9.62	2.93	0.30	18.2	
Treatment		Cereal monoculture	9.32	2.74	0.29	15.1	
		Cereal/supp lucerne	7.99	2.30	0.28	16.3	
Year	2003		7.72	2.02	0.26	14.9	
	2004		9.59	3.02	0.31	16.4	
LSD$_{0.05}$ year × treatment			1.62	n.s.	n.s.	n.s.	
LSD$_{0.05}$ treatment			0.94	0.28	n.s.	n.s.	
LSD$_{0.05}$ year			n.s.	0.81	0.03	n.s.	
North Boorhaman							
Year × treatment	2003	Cereal monoculture	13.21	3.81	0.29	12.4	
		Cereal/lucerne	10.26	2.87	0.29	10.8	
	2005	Cereal monoculture	10.80	4.22	0.40	9.4	
		Cereal/lucerne	9.92	3.22	0.33	9.5	
Treatment		Cereal monoculture	11.83	4.04	0.36	10.7	
		Cereal/lucerne	10.06	3.07	0.31	10.0	
Year	2003		11.73	3.34	0.29	11.6	
	2005		10.34	3.72	0.37	9.5	
LSD$_{0.05}$ year × treatment			n.s.	n.s.	0.05	0.7	
LSD$_{0.05}$ treatment			1.57	0.50	0.03	0.4	
LSD$_{0.05}$ year			n.s.	n.s.	0.03	0.5	
Roseworthy A							
Year × treatment	2004	Cereal monoculture	5.79	1.62	0.28		
		Cereal/supp lucerne	4.68	1.44	0.32		
		Cereal/lucerne	4.38	1.29	0.31		
	2005	Cereal monoculture	8.84	3.73	0.42		
		Cereal/supp lucerne	6.46	3.12	0.50		
		Cereal/lucerne	5.96	2.75	0.46		
Treatment		Cereal monoculture	7.31	2.67	0.35	11.58	
		Cereal/supp lucerne	5.57	2.28	0.41	11.15	0.09[c]
		Cereal/lucerne	5.17	2.02	0.39	11.23	0.44[c]

Table 6 (*Continued*)

Treatment structure	Year	Treatment	Biomass (t DM/ha)	Grain yield (t/ha)	Harvest index	Protein (%)	Foreign[a]
Year	2004		4.95	1.45	0.30		
	2005		7.08	3.20	0.46		
$LSD_{0.05}$ year × treatment			n.s.	0.34	n.s.	na	
$LSD_{0.05}$ treatment			1.54	0.24	n.s.	n.s.	0.19[c]
$LSD_{0.05}$ year			1.26	0.20	0.07	na	
Roseworthy B							
Treatment	2005	Cereal monoculture	7.81	4.06	0.53	11.8	
		Cereal/supp lucerne	5.11	3.07	0.60	11.2	0.09[c]
		Cereal/lucerne	6.23	3.11	0.50	10.7	0.54[c]
$LSD_{0.05}$ treatment			n.s.	0.49	n.s.	n.s.	0.16

Mean of two N rates at Burraja, Grogan and North Boorhaman. n.s.: Not significant. [a]Foreign indicates lucerne pod and flower contamination, it was determined at [b]Burraja in a hectolitre of grain sample and at [c]Roseworthy as a percentage of grain weight.

($P < 0.05$) in yearly productivity, which also contributed to this interaction. Unlike the other sites the cereal/suppressed lucerne treatment yielded 11% more ($P < 0.05$) grain than the cereal/lucerne treatment in 2005. However, like Burraja, the cereal/suppressed lucerne treatment recorded lower ($P < 0.05$) lucerne contamination than the cereal/lucerne treatment. Once again harvest index and grain protein were unaffected by the presence of lucerne.

Grain yield was reduced ($P < 0.05$) by 24 and 23% in the cereal/suppressed lucerne and cereal/lucerne treatments, respectively, compared with the cereal monoculture at Roseworthy B (Table 6). Conversely harvest index and grain protein were unaffected by the presence of lucerne. The cereal/suppressed lucerne measured lower ($P < 0.05$) lucerne contamination of the harvested cereal grain than the cereal/lucerne treatment.

3.5. Comparison of potential versus actual cereal grain yield in the presence and absence of lucerne

Potential cereal grain yield formulated by French and Schultz (1984) was plotted against actual grain yields measured in the cereal monoculture, cereal/suppressed lucerne treatment at Grogan and cereal/lucerne treatments at the remaining sites (Fig. 2). Cereal monoculture grain yields were close to potential (>85% of potential), except at Grogan in 2003, North Boorhaman where N was not applied in both years, and where N was applied in 2003, and at both Roseworthy sites in 2005. In comparison grain yields from cereals growing with lucerne were well below potential (<85% of potential) in all years and sites, except Burraja in 2003, Grogan in 2004 and Roseworthy A in 2004.

3.6. Lucerne performance in monoculture, in the presence of cereal and when suppressed in the presence of cereal

A significant year by treatment interaction ($P < 0.05$) was found at Burraja, where lucerne biomass collected at cereal maturity was reduced by 85 and 72% in 2003, and 90 and 81% in 2004, in the cereal/suppressed lucerne and cereal/lucerne treatments, respectively, compared with the lucerne monoculture (Table 7). However, no differences between treatments existed in 2002. A year by treatment interaction was also found at North Boorhaman, but this interaction was due to a significant decline ($P < 0.05$) in lucerne biomass production in the lucerne monoculture, but no loss of productivity in the cereal/lucerne treatment. At Burraja and both the Roseworthy sites, there were no differences in lucerne biomass production between the cereal/suppressed lucerne and the cereal/lucerne treatments.

3.7. Impact of top-dressed N on cereal productivity in monoculture, in the presence of lucerne and in the presence of suppressed lucerne

Independent site analyses at Burraja, Grogan and North Boorhaman showed no year by treatment by top-dressed N interaction (data not shown). There was also no significant treatment by top-dressed N interaction at Burraja, in all measures of cereal productivity (Table 8). However, there was a

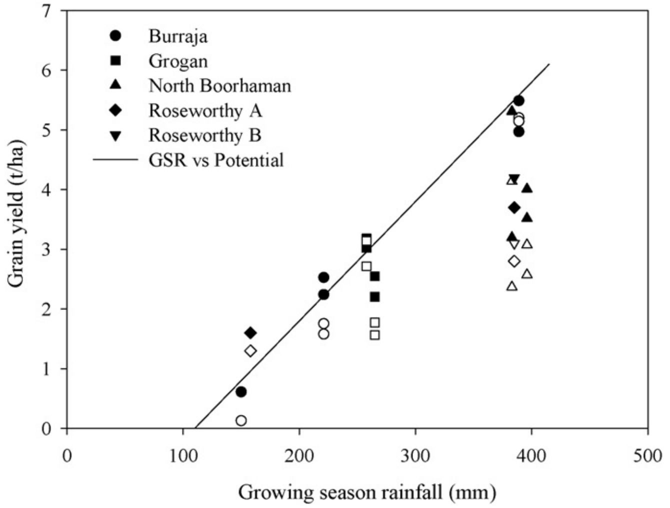

Fig. 2. Comparison of potential (formulated by French and Schultz, 1984, for wheat) vs. actual cereal grain yields both without lucerne (solid symbol) and with lucerne (open symbol). Data includes the two N rates from Burraja, Grogan and North Boorhaman. Cereal/lucerne treatments presented from Burraja, North Boorhaman and both Roseworthy sites and cereal/supp lucerne treatment at Grogan. Barley crops from Burraja and both Roseworthy sites in 2005, have also been included.

Table 7
Lucerne biomass production (t DM/ha) at cereal maturity in lucerne monoculture, in the presence of cereal and when suppressed in the presence of cereal

Treatment structure	Year	Treatment	Burraja	North Boorhaman	Roseworthy A	Roseworthy B
Year × treatment	2002	Cereal/supp lucerne	0.48			
		Cereal/lucerne	0.32			
		Lucerne monoculture	0.79			
	2003	Cereal/supp lucerne	0.55			
		Cereal/lucerne	1.05	1.99		
		Lucerne monoculture	3.72	8.91		
	2004	Cereal/supp lucerne	0.23		0.14	
		Cereal/lucerne	0.48		0.30	
		Lucerne monoculture	2.45			
	2005	Cereal/supp lucerne			0.70	0.31
		Cereal/lucerne		1.58	0.51	0.41
		Lucerne monoculture		6.68		
Treatment		Cereal/supp lucerne	0.42		0.42	0.31
		Cereal/lucerne	0.61	1.76	0.41	0.41
		Lucerne monoculture	2.32	7.63		
Year	2002		0.53			
	2003		1.77	5.45		
	2004		1.05		0.22	
	2005			4.13	0.60	
$LSD_{0.05}$ year × treatment			0.56	1.42	n.s.	na
$LSD_{0.05}$ treatment			0.32	8.99	n.s.	n.s.
$LSD_{0.05}$ year			0.32	9.71	0.24	na

Mean of two N rates at Burraja, Grogan and North Boorhaman. n.s.: Not significant; na, not assessable.

Table 8
Cereal biomass at maturity, grain yield, harvest index (grain yield/biomass) and grain protein in monoculture, in the presence of lucerne, and in the presence of suppressed lucerne in response to top-dressed N at Burraja, Grogan and North Boorhaman

Treatment structure	Year	Treatment	Cereal biomass (t DM/ha)		Grain yield (t/ha)		Harvest index		Protein (%)	
			N+	N0	N+	N0	N+	N0	N+	N0
Burraja										
Treatment × TD_N		Cereal monoculture	12.26	11.18	3.68	3.94	0.30	0.35	12.4	10.2
		Cereal/supp lucerne	10.76	8.95	3.99	3.75	0.35	0.41	12.0	8.9
		Cereal/lucerne	9.43	8.37	3.58	3.66	0.37	0.42	12.1	9.2
Year × TD_N	2003		14.46	12.29	5.32	5.27	0.38	0.44	10.0	9.0
	2004		7.18	6.71	2.18	2.30	0.31	0.35	14.3	9.9
TD_N			10.82	9.50	3.75	3.78	0.34	0.39	12.1	9.4
$LSD_{0.05}$ treatment × TD_N			n.s.		n.s.		n.s.		n.s.	
$LSD_{0.05}$ year × TD_N			1.12		n.s.		n.s.		0.7	
$LSD_{0.05}$ TD_N			0.78		n.s.		0.03		0.5	
Grogan										
Treatment × TD_N		Cereal monoculture	9.32	9.32	2.62	2.86	0.28	0.31	16.9	13.3
		Cereal/supp lucerne	8.13	7.85	2.14	2.46	0.26	0.31	18.0	14.5
Year × TD_N	2003		7.74	7.68	1.89	2.16	0.24	0.29	16.4	13.5
	2004		9.71	9.48	2.87	3.16	0.30	0.33	18.5	14.3
TD_N			8.73	8.58	2.38	2.66	0.27	0.31	17.5	13.9
$LSD_{0.05}$ treatment × TD_N			n.s.		n.s.		n.s.		n.s.	
$LSD_{0.05}$ year × TD_N			n.s.		n.s.		n.s.		n.s.	
$LSD_{0.05}$ TD_N			n.s.		0.25		0.03		0.8	
North Boorhaman										
Treatment × TD_N		Cereal monoculture	14.37	9.29	4.75	3.33	0.33	0.38	11.2	10.2
		Cereal/lucerne	11.77	8.35	3.68	2.46	0.31	0.31	10.3	9.7
Year × TD_N	2003		12.71	10.75	3.59	3.09	0.29	0.29	12.0	11.1
	2005		13.34	7.37	4.69	2.75	0.35	0.38	9.8	9.1

Table 8 (*Continued*)

Treatment structure	Year	Treatment	Cereal biomass (t DM/ha) N+	Cereal biomass (t DM/ha) N0	Grain yield (t/ha) N+	Grain yield (t/ha) N0	Harvest index N+	Harvest index N0	Protein (%) N+	Protein (%) N0
TD_N			13.07	8.82	4.22	2.90	0.32	0.34	10.8	10.0
LSD$_{0.05}$ treatment × TD_N			1.72		n.s.		n.s.		n.s.	
LSD$_{0.05}$ year × TD_N			1.26		0.40		n.s.		n.s.	
LSD$_{0.05}$ TD_N			0.80		0.25		n.s.		0.4	

n.s.: Not significant.

year by top-dressing N interaction where additional N resulted in a 15% increase ($P < 0.05$) of cereal biomass in 2003, but no response in 2004. Across all treatments and years, top-dressing N resulted in lower ($P < 0.05$) harvest index and greater ($P < 0.05$) grain protein.

Top-dressing N at Grogan had no effect on cereal biomass, and actually resulted in a 12 and 15% decline ($P < 0.05$) in grain yield and harvest index, respectively, across all treatments and years (Table 8). Conversely grain protein responded to additional N, with a 3.6 unit increase across all treatments and years.

At North Boorhaman additional N resulted in a treatment by top-dressed N interaction, where N top-dressed to the cereal monoculture resulted in a 35% increase ($P < 0.05$) in cereal biomass, compared with a 29% increase in the cereal/lucerne treatment (Table 8). Furthermore there was also a much greater ($P < 0.05$) response to top-dressing N in 2005 compared with 2003 across all treatments, expressed in both the cereal biomass and grain yield. Across all treatments and years, top-dressing N increased grain yield by 31% and grain protein by 0.8 units.

3.8. Impact of top-dressed N on lucerne productivity in monoculture, in the presence of cereal and when suppressed in the presence of cereal

Independent site analyses at Burraja and North Boorhaman, showed no year by treatment by top-dressed N interaction (data not shown), and at Burraja there was no effect from additional N on lucerne productivity (Table 9). However, at North Boorhaman a significant treatment by top-dressed N interaction was discovered, where the application of N to the lucerne monoculture resulted in a 28% increase ($P < 0.05$) in lucerne biomass across all years, but no such response existed in the cereal/lucerne treatment.

4. Discussion

4.1. Are cereal responses to the presence of lucerne and in-crop lucerne suppression consistent across experimental sites?

Across the five sites, generally companion cropping resulted in cereal grain yield reductions, within the ranges of 6–63% as previously reported by both Egan and Ransom (1996) and Humphries et al. (2004). Growing season rainfall had a strong influence on both the performances of cereals growing with and without lucerne.

However, growing season rainfall alone does not fully explain cereal responses in the presence of lucerne. Unlike the other sites, there was no grain yield reduction from companion cropping at Burraja, despite growing season rainfall ranging from decile 1 to 7, but the cereal biomass data showed the potential existed. The low harvest index in the cereal monoculture in 2003 demonstrates how excessive crop lodging prevented the difference in cereal biomass from being expressed in grain yield. Furthermore at Burraja in 2002 and 2004, cereal biomass and harvest index responded differently to the presence of lucerne, despite decile 1 and 2 growing season

Table 9
Lucerne biomass production (t DM/ha) at cereal maturity in lucerne monoculture, in the presence of cereal and when suppressed in the presence of cereal in response to top-dressed N at Burraja and North Boorhaman

Treatment structure	Year	Treatment	Burraja N+	Burraja N0	North Boorhaman N+	North Boorhaman N0
Treatment × TD_N		Cereal/supp lucerne	0.37	0.41		
		Cereal/lucerne	0.73	0.79	1.66	1.86
		Lucerne monoculture	3.43	2.74	8.90	6.37
Year × TD_N	2003		1.92	1.61	6.00	4.90
	2004		1.09	1.02		
	2005				4.74	3.52
TD_N			1.51	1.32	5.28	4.11
LSD$_{0.05}$ treatment × TD_N			n.s.		1.65	
LSD$_{0.05}$ year × TD_N			n.s.		n.s.	
LSD$_{0.05}$ TD_N			n.s.		0.75	

rainfall, respectively. On inspection of the lucerne biomass (Table 7), production was unaffected by the presence of cereals in 2002, but not in 2004, suggesting that variation in lucerne productivity and therefore its competitiveness with neighbouring cereals was also contributing to companion crop performance. We surmise that in 2002 decile 1 growing season rainfall in combination with greater lucerne competitiveness could have encouraged greater post-anthesis water stress in cereals growing with lucerne. The different lucerne biomass responses to the presence of cereal between years may have been due to an accelerated decline in plant density from companion cropping in comparison with plant density in the lucerne monoculture. Other researchers such as Egan and Ransom (1996) have shown that a decrease in lucerne plant density can result in greater cereal productivity. There is also evidence at Grogan that declining lucerne productivity, possibly due to reduced plant populations, contributed to improved companion crop biomass performance in 2004 compared with 2003, despite decile 3 rainfall in both years.

Another example of site-specific factors influencing the outcome of companion crop performance was at North Boorhaman in 2005, where a low harvest index in the companion crop treatment in comparison with the cereal monoculture, suggests post-anthesis water stress. Despite favourable late growing season rainfall (Fig. 1), the lower soil water content measured at sowing of the cereal crops under the cereal/lucerne treatment, appears to have contributed to this negative response.

Despite favourable growing season conditions at North Boorhaman in 2003, the potential grain yields in the cereal monoculture were low (Fig. 2), the wheat experienced some frost damage and a stripe rust (*P. striiformis*) outbreak, inhibiting cereals from achieving their water-limited grain yield potential. In the same year a similar outcome occurred at Grogan, where the combinations of frost damage, stripe rust and high available soil N levels (Table 5), led to cereals ''haying off'' (van Heraarden et al., 1998).

The biotic and abiotic stresses highlighted here for each site, have contributed to variation in cereal grain responses in relation to the presence of lucerne, the application of N and in-crop lucerne suppression (Table 3), and therefore assessing their importance to companion cropping systems across south-eastern Australia made more complex. One consolation is that the cross-site analyses shows cereal biomass responses to the presence of lucerne and in-crop lucerne suppression were unaffected by site ($P = 0.311$), suggesting that site variation was effecting translocation in cereals during grain formation.

4.2. Can in-crop lucerne suppression increase cereal productivity?

The main contribution of in-crop lucerne suppression was to improve grain quality, by reducing lucerne (pod and flowers) contamination of the harvested cereal grain. Depending on the rate of application, the herbicide clopyralid would either desiccate or stunt lucerne plants, temporarily halting growth, delaying maturity, and ensuring that lucerne pod formation did not coincide with cereal crop maturity. At all sites this practice was successful in reducing contamination. However, at Burraja in 2002 lucerne contamination was much higher, probably because at the time of application the dry conditions had induced symptoms of water stress in the lucerne plants, probably resulting in reduced herbicide efficacy. Therefore, the effectiveness of in-crop lucerne suppression appears to be influenced by rainfall stimulating lucerne growth and consequently clopyralid uptake (Davies et al., 2006). In our study in-crop lucerne suppression had little effect on increasing cereal productivity, because it did not reduce lucerne growth (Table 7), resulting in similar demands for resources as unsuppressed lucerne growing with cereals. Further research to evaluate the timing and duration of lucerne suppression on cereal grain yield may be warranted.

4.3. Can top-dressed N applications increase cereal productivity in the presence of lucerne?

In our experiments N was applied to test the hypothesis that N utilisation by lucerne was a constraint to cereal growth in the presence of lucerne. Hirth et al. (2001) measured significantly lower soil mineral N at the autumn break under lucerne pastures compared with annual pastures in four out of five seasons. Although the authors do not speculate why this result occurred, it was probably due to lucerne's largely continuous active growth immobilising available mineral N (Peoples and Baldock (2001). Angus et al. (2000) had also concluded that N availability was likely to be a limiting factor to crop growth in the presence of lucerne, particularly when there was adequate soil water supply.

In our experiments top-dressing N resulted in improved cereal grain yields only at North Boorhaman. Regardless of whether cereals were growing with or without lucerne, growing season rainfall and available soil N levels at sowing largely influenced whether top-dressed N led to improvements in cereal grain yield. Furthermore at North Boorhaman lucerne biomass responded to N application only in the lucerne monoculture (Table 9), indicating that the cereals were more effective at utilising applied N in the presence of lucerne. At North Boorhaman, the combination of favourable growing season rainfall in both 2003 and 2005 (decile 6 and 7, respectively) and low available soil N levels (<35 kg N/ha at sowing in 2005) were sufficient to allow N application to be expressed in the cereal biomass, grain yield and grain protein. In 2003, Burraja experienced a decile 7 growing season rainfall, and again top-dressing N increased cereal biomass and grain protein (Table 8), but unfortunately resulted in extensive crop lodging, and therefore the potential increase in grain yield was never realised as indicated by the lower harvest index. When unfavourable growing season rainfall occurred at Burraja in 2004 (deciles 2) there was no response to the application of N in both cereals growing with and without lucerne.

In our study, differences in available soil N between crops growing with and without lucerne was only found at Grogan, therefore supporting the findings of Angus et al. (2000) and Hirth et al. (2001). However, the combination of high available soil N (>127 kg N/ha at sowing in both years) and decile 3 growing season rainfall, led to a negative grain yield response to the application of N. The low harvest index and high grain protein measured in cereals receiving N indicates that cereals ''hayed off'' (van Heraarden et al., 1998).

In 2005 top-dressed N at North Boorhaman resulted in cereals yielding an extra 1.9 t/ha, a large response in comparison to 2003. The magnitude of this response may have been due in part to the extra 40 kg N/ha applied in 2005, and the exhausted available soil N levels after 3 consecutive years of cereal crops, severely limiting cereal production where N was not applied (Table 8 and Fig. 2).

4.4. Future research opportunities

The economic feasibility of companion cropping still remains in question given that the grain yield reductions from companion cropping were as high as 15% even when growing season rainfall was favourable (decile >6 at North Boorhaman). However, focusing solely on reduced grain yields ignores other factors that contribute to the economics of the total companion cropping system; for example, the economic value of grazing lucerne-crop stubbles over the summer. At this stage the authors are unaware of any comprehensive economic analyses that examines companion cropping at a whole farm level. Such analyses would need to put a value on the quantity and nutritional quality of the summer feed supply, which may vary considerably depending on the summer rainfall, as well as the savings in reduced frequency of lucerne removal and re-establishment costs. Until such an analysis is undertaken it is premature to conclude whether and or where the practice has commercial merit.

Other agronomic options that could be studied include choice of companion forage species, lucerne density, spatial arrangement of lucerne and crop, and tactical use of suppression and nitrogen fertiliser in response to seasonal grain yield potential. Choice of companion forage species, could include selection of winter dormant (possibly spring dormant?) lucerne varieties, or other perennials that are less competitive during the cereal growing season, but still possess deep roots and high water use over summer to satisfy hydrological requirements.

Research into plant density could explore the relationships between lucerne density, crop yield reductions and profile soil water, to determine if it is possible to utilise low lucerne density stands to minimise grain yield reductions but maintain dry sub soils to combat dryland salinity. In addition spatial arrangement of lucerne in relation to the companion crop through recent technological developments in no-till seeders and GPS creates the possibility for innovative combinations of perennial forages and annual crops. Possibilities include lucerne—crop alleys at a range of scales with potential benefits for both crop and forage production.

With regards to tactical (in-season) use of suppression and N fertiliser, our research has demonstrated the strong influence that growing season rainfall (grain yield potential) has on the response of grain yield to agronomic treatments. The possibility exists through technical developments such as seasonal forecasts and in-crop simulation modelling to intervene with agronomic treatments only when there is a high likelihood of a positive grain yield response.

All of these suggestions need to be assessed in association with the first recommendation above that a whole farm profit approach, accounting for both grain yield reductions and forage yield benefits, is required.

5. Conclusion

N application to cereals growing with lucerne can increase cereal grain yields, but only when accompanied by favourable growing season rainfall and low available soil N levels. In-crop lucerne suppression generally does not enhance cereal grain yields in the presence of lucerne. However, when applied with adequate surface soil moisture to allow for clopyralid uptake by lucerne, suppression can significantly reduce lucerne contamination of the harvested cereal grain. While agronomic intervention can improve cereal performance in the presence of lucerne under some conditions, the practice of grain production from companion cropping remains a high-risk option.

Acknowledgements

We thank Robert Belford for intellectual input and Lawrence Burk for technical support. In addition the Co-operative Research Centre for Plant Based Management of Dryland Salinity and the Grains Research and Development Corporation, The Department of Primary Industries Victoria, Commonwealth Scientific and Industrial Research Organisation and the University of Adelaide for funding this research.

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