Zentrum für Entwicklungsforschung

Resource utilization and sustainability of conservation-based rice-wheat cropping systems in Central Asia

Inaugural-Dissertation
zur
Erlangung des Grades
Doktor der Agrarwissenschaften
(Dr. agr.)

der Hohen Landwirtschaftlichen Fakultät
der
Rheinischen Friedrich-Wilhelms-Universität
zu Bonn

vorgelegt am im Mai 2011

von

KRISHNA PRASAD DEVKOTA

aus

GORKHA,NEPAL

1. Referent: Prof. Dr. P.L.G. Vlek

2. Referent: Prof. Dr. Frank A. Ewert

Tag der Promotion: 12.07. 2011

Erscheinungsjahr: 2011

Diese Dissertation ist auf dem Hochschulschriftenserver der ULB Bonn
http://hss.ulb.uni-bonn.de/diss_online elektronisch publiziert

ABSTRACT

Excessive and inefficient water use, intensive soil tillage and decreasing soil fertility have caused land degradation and desertification, which are threatening the sustainability of rice-wheat systems in the irrigated lowlands of Central Asia. Water-saving and conservation agriculture (CA) practices such as alternate wet and dry irrigation (WAD), direct seeding on raised beds, zero tillage flat lands, and residue retention can help counterbalancing these threats. A randomized complete block design experiment with four replications was conducted from 2008-2010 in rice-wheat rotation systems in Khorezm region, Uzbekistan. Objectives were to (1) investigate the growth and yield formation of rice, (2) examine mineral-nitrogen (N) dynamics in a rice-wheat system, and (3) evaluate the sustainability of a rice-wheat system under water-saving irrigation and CA practices. Next, the rice growth model ORYZA2000 was parameterized and evaluated to assess the impact of increased temperature on phenology and grain yield of rice at various emergence dates under IPCC (2007) projected A1F1 and B1 climate change scenarios. The rice variety used was a puddle rice variety subjected to dryland conditions.

The field experiment centered on six WAD rice treatments involving dry-direct seeded rice (DSR) under raised bed planting (BP) and zero tillage (ZT) planting on flat land combined with three levels of residue retention, i.e., residue harvested (RH), 50% residue retention (R50), and 100% residue retention (R100). These were compared with wet-DSR grown under conventional tillage (CT) with continuous flood irrigation (CT-FI) and with intermittent irrigation (CT-II). The WAD and CT-II treatments were irrigated only when the soil water potential in the top 20 cm soil reached around -20 kPa. CT-FI was irrigated as practiced by the farmers in the region. Wheat was surface seeded into the standing rice field in all treatments. To assess the impact of climate change with ORYZA2000, field experiments with six seeding dates and three varieties were conducted in 2008-2009.

WAD irrigation led to a 68-73% water-saving potential but reduced rice yield by 30-56%; however, the yield of surface seeded wheat was higher by more than 1.5 t ha^{-1} than the irrigated wheat yield in Khorezm in both years. With WAD, this yield penalty was caused by water stress, higher amount of standing residue retention, and N stress, which reduced biomass accumulation and root growth, delayed phenological development, reduced number of spikelets, and led to a high percentage of unfilled grains. WAD plus residue retention (R50 and R100) in rice led to N losses. Combined over two seasons of rice and one season of wheat, the N loss was highest (>350 kg ha^{-1}) with R100 and lowest with CT-FI (261 kg ha^{-1}) and could have been caused by leaching and denitrification. No mineral N was lost in any of the wheat treatments.

Rice-wheat system productivity, gross margin, and benefit to cost (B:C) ratio were highest in CT-FI followed by RH, and lowest with R100 in BP and ZT. The discharge of irrigation water through seepage and percolation from the rice fields amounted to about 90% with CT. Yields can be increased with water-saving under CA practices with proper residue management, optimization of irrigation, N drilling (nitrogen placement 5-10 cm deep into the soil), strip-till transplanting (seed/seedling placement in a shallow-tilled strip), and the use of suitable aerobic rice varieties. With the present anaerobic varieties used under aerobic conditions, yield penalties are

discouraging despite the high savings in water use. As long as farmers do not pay for irrigation water, the incentives may be insufficient to provoke any change.

The parameterized ORYZA2000 simulated phenology and grain yield of rice with a high accuracy (RMSE<15%). An increased temperature caused a decline in yields by 20% (6% $°C^{-1}$ or 393 kg ha^{-1} $°C^{-1}$) in 2079 compared to 2000. Under current conditions, the best seeding dates are ~July 5 for short-, ~June 15 for medium-, and ~ June 5 for long-duration rice varieties (varieties maturing in <100, 100-110 and >110 days, respectively). Seeding dates were not changed under the B1 climate change scenario but could be delayed by 10 days under the A1F1 scenario. Development of heat-tolerant, medium- and long-duration rice varieties is crucial under climate change scenarios.

KURZFASSUNG

Ressourcenutzung und Nachhaltigkeit von bodenschonenden Reis-Weizen-Anbausystemen in Zentralasien

Exzessive und ineffiziente Wassernutzung, intensive Bodenbearbeitung sowie abnehmende Bodenfruchtbarkeit haben zu Landdegradation und Wüstenbildung geführt. Dies bedroht die Nachhaltigkeit der Reis-Weizensysteme der bewässerten Tieflandregionen in Zentralasien. Wassersparende Bewässerung und konservierende Bodenbearbeitung (CA) mit, zum Beispiel, alternierender Bewässerung (WAD), direkter Aussaat auf erhöhtem Pflanzbett (BP), pflugfreier Anbau (ZT), und Belassen der Ernterückstände auf dem Feld können den obengenannten negativen Auswirkungen entgegenwirken. Eine Versuch unter *randomized complete block design* mit vier Wiederholungen wurde 2008-2010 in Reis-Weizen-Rotationssystemen in der Region Khorezm, Usbekistan, durchgeführt. Das Ziel war, folgendes zu bestimmen: (1) Wachstum und Ertragsbildung von Reis, (2) mineralische Stickstoff-(N)-Dynamik in einem Reis-Weizensystem, und (3) Nachhaltigkeit eines Reis-Weizensystems bei wassersparender Bewässerung und CA. Als nächstes wurde das Reiswachstumsmodell ORYZA2000 parameterisiert und evaluatiert, um die Auswirkungen gestiegener Temperaturen auf Reisphänologie und -ertrag bei verschiedenen Keimungsterminen unter den A1F1 und B1 Klimawandelszenarien (IPCC 2007) zu ermitteln. Der eingesetzte Reis war eine Nassreissorte, die unter trockenen Bedingungen verwendet wurde.

Der Feldversuch umfasste sechs WAD Reisbehandlungen mit Trocken-Direktaussaat (DSR) mit Bettbepflanzung (BP) und Anbau ohne Bodenbearbeitung (ZT) kombiniert mit drei unterschiedlichen Behandlungen mit Ernterückständen, d.h., vollständig geerntete Rückstände (RH), Belassen von 50% der Rückstände (R50), und Belassen von 100% der Rückstände (R100). Die Ergebnisse wurden mit denen von Nass-DSR mit konventioneller Bodenbearbeitung (CT), mit Dauerbewässerung (CT-FI) sowie mit intermittierender Bewässerung (CT-II) verglichen. Die WAD- und CT-II-Behandlungen wurden nur bewässert wenn das Bodenwasserpotenzial in den oberen 20 cm des Bodens ca. -20 kPa erreichte. CT-FI wurde so bewässert, wie es bei den Bauern in der Region üblich ist. Der Weizen wurde in allen Behandlungen oberflächlich zwischen den Reispflanzen ausgesät. Um die Auswirkungen des Klimawandels mit ORYZA2000 zu ermitteln, wurden Feldversuche mit sechs Aussaatterminen in 2008 und 2009 durchgeführt.

Die WAD Bewässerung führte zu einem 68-73%igen Wassersparpotenzial, jedoch war der Reisertrag bis zu 30-56% geringer. Der Ertrag des oberflächlich ausgesäten Weizens war jedoch 1.5 t ha^{-1} höher als der Ertrag des bewässerten Weizens in der Khorezm-Region in beiden Jahren. Gründe für den geringeren Reisertrag bei WAD waren Wasserstress, höhere Mengen von Ernterückständen sowie N-Stress. Diese Faktoren führten zu einer Abnahme von Biomassenbildung und Wurzelwachstum, Verzögerung der phänologischen Entwicklung, einer geringeren Anzahl von Ährchen und einem hohen Prozentsatz leerer Körner. WAD zusammen mit Ernterückständen (R50 und R100) führte bei Reis zu N-Verlusten. Kombiniert über zwei Anbauperioden von Reis und eine von Weizen war der N-Verlust am höchsten mit R100 (>350 kg ha^{-1})

und am niedrigsten mit CT-FI (261 kg ha^{-1}). Gründe könnten Auswaschung oder Denitrifikation gewesen sein. In keinem der Versuche mit Weizen wurden Verluste von mineralischem N beobachtet.

Im Reis-Weizensystem waren Produktivität, Bruttoergebnis und Aufwand-Nutzen-Quotient am höchsten in CT-FI, gefolgt von RH, und am niedrigsten in den R100-Behandlungen in BP und ZT. Der Verlust von Bewässerungswasser in den Reisfeldern durch Versickerung und Perkolation betrug ca. 90% bei CT. Bei CA können höhere Erträge bei wassersparenden Maßnahmen mit entsprechender Nutzung der Ernterückstände, Optimierung der Bewässerung, Applikation von N in 5-10 cm Bodentiefe, Streifenlockerung und Pflanzung der Reissetzlinge, und Nutzung geeigneter aerober Reissorten erzielt werden. Wenn anaerobe Reissorten unter aeroben Bedingungen eingesetzt werden, sind die geringeren Erträge entmutigend trotz der hohen Wassereinsparungen. Solange die Bauern nicht für das Wasser bezahlen, ist es unwahrscheinlich, dass sie wassersparende Maßnahmen einsetzen werden.

Das parameterisierte ORYZA2000 simulierte Reisphänologie und -körnerertrag mit hoher Genauigkeit (RMSE<15%). Eine höhere Temperatur führte zu Ertragseinbußen von 20% (6% °C^{-1} bzw. 393 kg ha^{-1} °C^{-1}) in 2079 im Vergleich zu 2000. Unter den bestehenden Bedingungen sind die besten Saattermine um den 5. Juli für die Kurz-, um den 15. Juni für Mittel-, und um den 5. Juni für Langzeit–Reissorten (welche, respektive, in >100, 100-110, und >110 Tagen reifen). Aussaattermine könnten unter dem B1-Szenario unverändert bleiben, während sie unter dem A1F1-Szenario 10 Tage später sein könnten. Die Entwicklung von hitzetoleranten, Mittel- und Langzeit-Reissorten ist entscheidend bei den vorhergesagten Szenarien des Klimawandels.

АННОТАЦИЯ

ИСПОЛЬЗОВАНИЕ РЕСУРСОВ И УСТОЙЧИВОСТЬ СЕВООБОРОТА «РИС-ПШЕНИЦА» ПРИ ПРИМЕНЕНИИ ПОЧВОЗАЩИТНЫХ И РЕСУРСОСБЕРЕГАЮЩИХ ТЕХНОЛОГИЙ В ЦЕНТРАЛЬНОЙ АЗИИ

Чрезмерное и неэффективное потребление водных ресурсов, интенсивная обработка земли и снижение плодородия почвы привели к деградации земель и опустыниванию, что является угрозой для устойчивой системы выращивания культур рис-пшеница на орошаемых землях Центральной Азии. Однако, почвозащитные и ресурсосберегающие технологии (ПРТ), такие как, чередование поливов по сухой и влажной почве (СВП), прямой сев на постоянные гребни, нулевая обработка почвы и сохранение растительных остатков на поле могут быть использованы в противовес этим проблемам.

Для изучения указанных вопросов нами в 2008-2010 гг. в условиях Хорезмской области Узбекистана были проведены полевые изыскания в системе севооборота «рис-пшеница». Опыт представлял собой полный рендомизированный блок с четырьмя повторениями. Целью эксперимента являлось: (1) изучение роста и формирования урожая риса, (2) изучение динамики почвенного минерального азота (N) в севообороте «рис-пшеница», (3) оценка устойчивости системы выращивания культур «рис-пшеница» при применении водосберегающих, почвозащитных и ресурсосберегающих технологий. Дополнительно была проведена калибровка и верификация модели ORYZA2000 для оценки влияния повышенной температуры на биометрические показатели и урожай зерна риса в зависимости от сроков сева культуры по сценариям A1F1 и B1, разработанных Межгосударственной комиссией по изменению климата (IPCC 2007). В опыте использовался сорт риса пригодный для выращивания на орошаемых почвах в условиях постоянно затопляемых чеков.

Опыт включал в себя 6 вариантов СВП с севом риса на постоянные гребни (СПГ) и нулевой обработкой земли (СНО) при трех уровнях сохранения растительных остатков, т.е. удаление растительных остатков с поверхности поля (Р0), сохранение 50% растительных остатков (Р50) и сохранение 100% растительных остатков на поле (Р100). Эти варианты были сопоставлены с традиционным севом риса в воду в условиях постоянно затопляемых чеков (СВ-ПЗЧ) и промежуточным поливом (СВ-ПП). Поливы на вариантах СВП и СВ-ПП производился исключительно в то время, когда водный потенциал 0-20 см слоя почвы достигал около -20 кПа. Поливы на варианте СВ-ПЗЧ проводились обычным способом (практика фермеров). Пшеница на всех вариантах эксперимента высеивалась разбросным способом в растущий рис до уборки его урожая. Дополнительно, в 2008-2009 гг. проводился полевой опыт с шестью сроками сева трёх сортов культуры для оценки с помощью модели ORYZA2000 влияния изменения климата на урожайность риса.

При использовании СВП водосбережение составило 68-73%, но урожай зерна риса при этом снизился на 30-56%. Однако в этом случае урожай зерна пшеницы был выше на 1,5 т/га в сравнении с обычной технологией полива в

обоих годах исследований. Причиной снижения урожайности на вариантах СВП послужил недостаток поливной воды, чрезмерное количество растительных остатков и недостаток азотных удобрений. Все это привело к снижению накопления биомассы, недостаточному развитию корневой системы и запоздалому развитию растений, сокращению количества колосьев и высокому проценту пустых зерён. Применение СВП и сохранение растительных остатков (Р50 и Р100) на рисовом поле привело к потерям азота. При возделывании риса в течении двух сезонов выращивания риса и одного сезона пшеницы наибольшие потери N (>350 кг/га) наблюдались на варианте с сохранением растительных остатков Р100, а наименьшие потери N (261 кг/га) на варианте СВ-ПЗЧ, что могло быть вследствие выщелачивания и денитрификации. Потери минерального N на пшеничном поле не наблюдались.

Продуктивность севооборота «рис-пшеница», валовой доход и коэффициент прибыли и затрат были наибольшими на варианте СВ-ПЗЧ с удалением растительных остатков с поля, а самые низкие показатели достигнуты на вариантах СПГ и СНО с сохранением растительных остатков Р100. На вариантах СВ потери оросительной воды на инфильтрацию и просачивание на рисовом поле составили около 90%. Результаты исследований показали, что урожай риса может быть увеличен путём применения водосберегающих технологий и сохранения соответствующего количества растительных остатков на поле, оптимизацией поливов, рядкового внесения N-удобрений в почву на глубину 5-10 см, пересадкой саженцев или севом семян в обработанную узкой полосой почву и использования соответствующих сортов аэробного риса. Урожайность существующих анаэробных сортов риса в аэробных условиях довольно низка, несмотря на высокий уровень водосбережений. В настоящее время трудно пробудить у фермеров желание к изменениям, поскольку они не производят плату за поливную воду.

Откалиброванная модель ORYZA2000 симулировала биометрические показатели и урожай зерна риса с высокой точностью (RMSE<15%). Сценарий показал, что повышение температуры воздуха приводит к падению урожайности на 20% (6% $°C^{-1}$ или 393 кг/га $°C^{-1}$) в 2079 году в сравнении с 2000 годом. В настоящих условиях, наиболее оптимальной датой сева раннеспелых сортов риса является ~5 июля, среднеспелых сортов - ~15 июня и позднеспелых сортов - ~5 июня (соответственно для сортов риса с вегетационным периодом <100, 100-110 и >110 дней). Эти даты сева не меняются при приложении сценария изменения климата B1, а в случае сценария A1F1 эти сроки сева могут быть позднее на 10 дней. Выведение жароустойчивых средне- и позднеспелых сортов риса является очень важным фактором при сценариях изменения климата.

TABLE OF CONTENTS

1 GENERAL INTRODUCTION

1.1 Problem setting

In Central Asian countries, agriculture is a major component of the culture, diet, employment and economy. Data of the CIA Factbook (2010) show that in these countries, agriculture accounts for 6-24.6% of the GDP (24.6% in Kyrgyzstan, 21.2% in Uzbekistan, 19.2% in Tajikistan, 10.2% in Turkmenistan, and 6% in Kazakhstan) and 32-50% of the employment force (49.8% in Tajikistan, 48.2% in Turkmenistan, 48% in Kyrgyzstan, 44% in Uzbekistan and 31.5% in Kazakhstan). The population growth rate in Central Asia is high, especially in Tajikistan (1.85%), Kyrgyzstan (1.41%), Turkmenistan (1.14%) and Uzbekistan (0.94%). In the region, a population growth from 61 million in 2008 to 80 million in 2050 is expected. Hence considerable efforts are needed to increase crop production and meet the anticipated increase in food demand (UNFPA 2009).

Due to the arid climatic conditions in the region, where potential evapotranspiration always exceeds precipitation, agricultural production fully relies on irrigation. About 90% of the total annual water take-off in the region is used in the agricultural sector, of which 83% is used for irrigation (Myagkov 2006; Abdullaev et al. 2006) and 17% for leaching salt (Abdolniyozov 2000). Furthermore, because water is often provided by state distribution agencies free of charge or at low cost (ZEF 2001), irrigation water application is very high, and amounts to 4200-7000 m^3 t^{-1} for rice (Aldaya et al. 2010; Bobojonov 2008) and 1400-4000 m^3 t^{-1} for wheat (Aldaya et al. 2010). Furthermore, 5000-10000 m^3 ha^{-1} y^{-1} are required for leaching salt (Abdolniyozov 2000; Ochs and Smedema 1996). Water application for rice is 6-7 times higher than for cotton in Khorezm region of Uzbekistan (Veldwisch 2008).

Khorezm is one of the main rice growing regions in Central Asia. The demand for irrigation water in Khorezm region is increasing because of (1) excessive and inefficient water use and poor and insufficiently maintained irrigation and drainage network systems (Ibrakhimov 2005; Conrad 2007), which have also lead to severe land and water degradation, (2) irrigation through highly wasteful surface irrigation (Bucknall et al. 2003), and (3) the introduction of private farming has led to an increase in the irrigation-water demand through the spread of rice production (Veldwisch 2008).

Only 50-70% of the water from the Amu Darya River (Bekturova et al. 2007) and 38% from the Syr Darya River (EC 1995) reaches the crops due to losses in the inter-farm and intra-farm irrigation canals. Thus, the rapidly expanding irrigated crop production in Central Asia (2.0 to 7.9 million ha between 1925 and 2005) is using practically the entire available flow of the two main rivers, i.e., the Amu Darya and the Syr Darya (UNEP 2005). All these factors are directly or indirectly contributing to increased secondary soil salinization and soil degradation (Cai et al. 2003; Kitamura et al. 2006), and are leading to desertification of the irrigated agricultural lands in the Central Asia region (Figure 1.1). Next to the severe irrigation-water scarcity, these factors have led to the drying of the Aral Sea and to desertification of its adjacent areas, which is known worldwide as the 'Aral Sea syndrome' (UNESCO 2000).

Crop production under conventional agriculture practices in the irrigated drylands is influenced by the tillage, residue, nutrient, and water management practices. Decades of intensive soil tillage, constant removal of crop residues, extensive use of chemical inputs and over-irrigation have contributed to declining soil fertility (Riskieva 1989; Sommer et al. 2008a), which have led to increasing secondary soil salinization and cropland degradation (Figure 1.1). Nitrogen (N) is considered the most limiting nutrient in the Khorezmian soil (Ibragimov 2007). The total organic N content usually comprises around 90-95% of the soil total N content in the plowing layer of agriculture soils, and is closely associated with the soil organic matter (Vlek et al. 1981). Overall, the inherent fertility of all Khorezmian soil types is low.

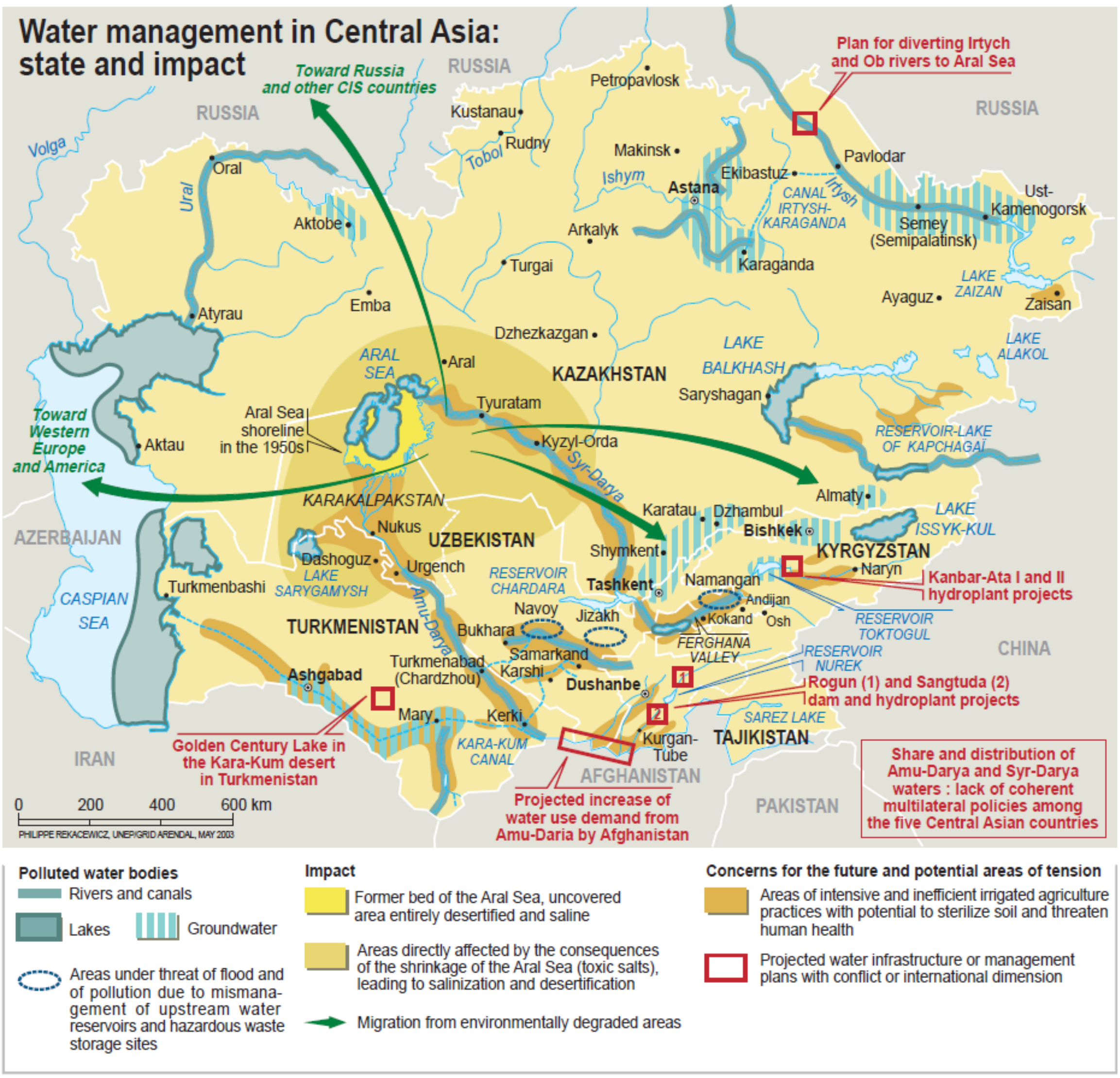


Figure 1.1 Water management in Central Asia: state and impact. (Source: P. Rekacewicz UNEP/GRID-Arendal; http://maps.grida.no/)

Due to crop residue removal and excessive soil tillage, the soils are in particular highly susceptible to wind erosion in spring, which in turn reduces the organic matter content in the soil. Furthermore, an excessive use of irrigation water raises the groundwater table, and this has increased secondary soil salinization contributing further to soil degradation (Figure 1.1). During the vegetation period, about 67% of the fields in Uzbekistan have groundwater levels above the threshold values that induce secondary salinization (Ibrakhimov et al. 2007).

Previous findings confirm that nitrogen (N) use efficiency in the conventional production systems in Uzbekistan, such as in the Khorezm region is low (Kienzler 2010). High temperatures and intensive irrigation and soil tillage under conventional practices enhance the mineralization of soil N (Vlek and Uzo Mokwunye et al. 1989), which leads to N losses through denitrification (Scheer et al. 2008a) and leaching (Kienzler 2010). The high N losses are not only a source of environmental pollution, but also increase production costs. All these factors threaten the sustainability of crop production in Uzbekistan. Hence, the development of new integrated resource management strategies is urgently needed for sustainable crop production in the region (O'Hara 2000; Toderich et al. 2008; Martius et al. 2009).

1.2 Potential and challenges of rice and wheat cultivation in Central Asia

Wheat and rice are the first and second major food crops in Central Asia, and are produced on 17 and 0.18 million ha, respectively (FAOSTAT 2010). More than 70% of the rice is produced in rice-wheat systems in the irrigated lowlands of the Amu Darya and Syr Darya river basins (Aral Sea Basin; Figure 1.2). In the region rice is an important part of the national diet particularly in Uzbekistan, Kazakhstan and Tajikistan, where it forms the basis for the national dish *pilov* (Uzbek *palov*; Karakalpak *palua*; Kazak *palau*; Kirghiz *paloo*, Tajik *palov*) (Nesbitt et al. 2010), and the per capita (per person per year) consumption in this region is about 20 to 25 kg (Ismali 2006).

In Uzbekistan, rice is a highly remunerative crop, which fetches a price several times higher than that of wheat and 2-3 times higher than the world market price (Djanibekov 2008). But due to the increasing water scarcity in the region, the government's policy is to reduce the area of crops that need extensive irrigation. To the knowledge, no research has been conducted on water-saving technologies for rice cultivation under the arid conditions in this region. Current rice cultivation methods, i.e., wet-direct seeding or transplanting, are very high water demanding. Farmers flood the rice fields permanently to sustain a 15-20 cm standing water collar throughout the growing season, which leads to the use of more than 40,000 m^3 ha^{-1} irrgation water in wet-direct seeded rice (DSR) and 30,000 m^3 ha^{-1} in transplanted rice (Aldaya et al. 2010; Bobojonov 2008; FAO 1997).

Rice area and production have been declining annually by 2.47% and 3.71%, respectively (calculations based on data from FAOSTAT 2010). In 2009, on average, 46% of the total rice area in Central Asia is in Kazakhstan, followed by 26% in Turkmenistan, 19% in Uzbekistan, 5% in Tajikistan and 3% in Kyrgyzstan (Figure 1.2).

The rice area in the region has been decreasing since independence. Currently, these countries meet their rice need mainly from imports, and 54,480 t milled rice was imported in 2008. Droughts, decreasing irrigation water availability, salinity, and the cold temperatures are the major problems for rice cultivation in the region (Ismali 2006).

Figure 1.2 Rice growing areas in Central Asia, 2009. Unit: proportion of grid cell area. (Source: Monfreda et al. 2008).

Wheat is the main staple food in all Central Asian countries. It plays a pivotal role in reaching food security in the region as it accounts for more than 80% of area that is under cereal cultivation (FAOSTAT 2010). About 83% of the total wheat area of Central Asia is in Kazakhstan, followed by 8% in Uzbekistan, 5% in Turkmenistan, 2% in Tajikistan and 2% in Kyrgyzstan (Figure 1.3). In the region, wheat occupies approximately 17 million ha, and production amounts to 28 million tons. The average productivity (grain yield per unit area) of wheat in the region is about 1.62 t ha^{-1}, which is lower compared to wheat yields in neighboring West Asia (2.51 t ha^{-1}) and Eastern Europe (2.70 t ha^{-1}), Asia (2.95 t ha^{-1}) and the world average (3.02 t ha^{-1}). The lower productivity in the region is largely due to the fact that 80% of the wheat is cultivated under rainfed conditions in Kazakhstan. In the past ten years, area, production and productivity of wheat have shown annual growth rates of 3.42%, 7.87% and 3.3%, respectively. A remarkable improvement in productivity has been achieved under irrigated wheat management, in particular on 1.4 million ha in Uzbekistan, where a productivity of 4.74 t ha^{-1} was achieved in 2009. However, these gains in wheat productivity, and thus food security, are seriously threatened by production constraints such as availability of irrigation water, terminal drought, heat, and soil salinity. There is a need to increase water productivity (amount of grain production per unit of water application, kg grain m^{-3} water) of wheat under irrigated management.

Figure 1.3 Wheat growing areas in Central Asia. Unit: proportion of grid cell area. (Source: Monfreda et al. 2008).

1.3 Potential water-saving irrigation technologies in rice production

The decline in water availability in irrigated rice systems demands increasing water productivity, for instance through the use of water-saving technologies. Instead of keeping the field continuously flooded with 15-20 cm standing water, the floodwater depth can be decreased and the soil can still be kept around saturation (SSC; saturated soil culture). Alternate wet and dry (AWD) irrigation can also be used to save irrigation water (Figure 1.4; Tuong et al. 2005). Similarly, under severe water-scarce conditions, aerobic rice varieties can be used where irrigation water can be applied as in upland crops.

As the irrigated lowlands of Central Asia suffer from severe secondary soil salinization, the frequent intermittent wet and dry (WAD) method of irrigation may be a suitable alternative (Figure 1.4). With such procedures, the field is flash-flooded using 4-5 cm irrigation water as described by Lu et al. (2002), which can save a significant amount of irrigation water while maintaining yields equivalent to those using conventional methods. Furthermore, as puddling and intensive tillage is avoided and rice is direct-seeded under non-puddled, unsaturated soil conditions and intermittent irrigation is applied, this method can contribute to overcoming the disadvantages of the conventional methods such as soil degradation, water logging and secondary salinization.

At field scale, explored water-saving innovations include continuous soil saturation (Borrell et al. 1997), alternate wetting and drying or intermittent irrigation (Bouman and Tuong 2001; Dong et al. 2004; Li 2001; Tabbal et al. 2002), rice cultivation on raised beds (Ockerby and Fukai 2001), aerobic rice system (Bouman et al. 2005; Yang et al. 2005), non-flooded mulch cultivation (Liu et al. 2003), and dry-direct seeding in zero tillage flat and permanent raised beds (Sayre and Hobbs 2004; Gupta et al. 2003; Singh et al. 2002). The water-saving technologies described in a wealth of literature show a range of water-saving methods and their effect on yields. For instance, an overview of 31 experiments conducted mostly in tropical and subtropical regions of southeast Asia showed that a 30-50% water saving and 10-40% yield reduction in rice grown under various water-saving irrigation practices (Bouman and Tuong 2001). This variation can be ascribed to differences in weather, soil type, cultivar, and management practices.

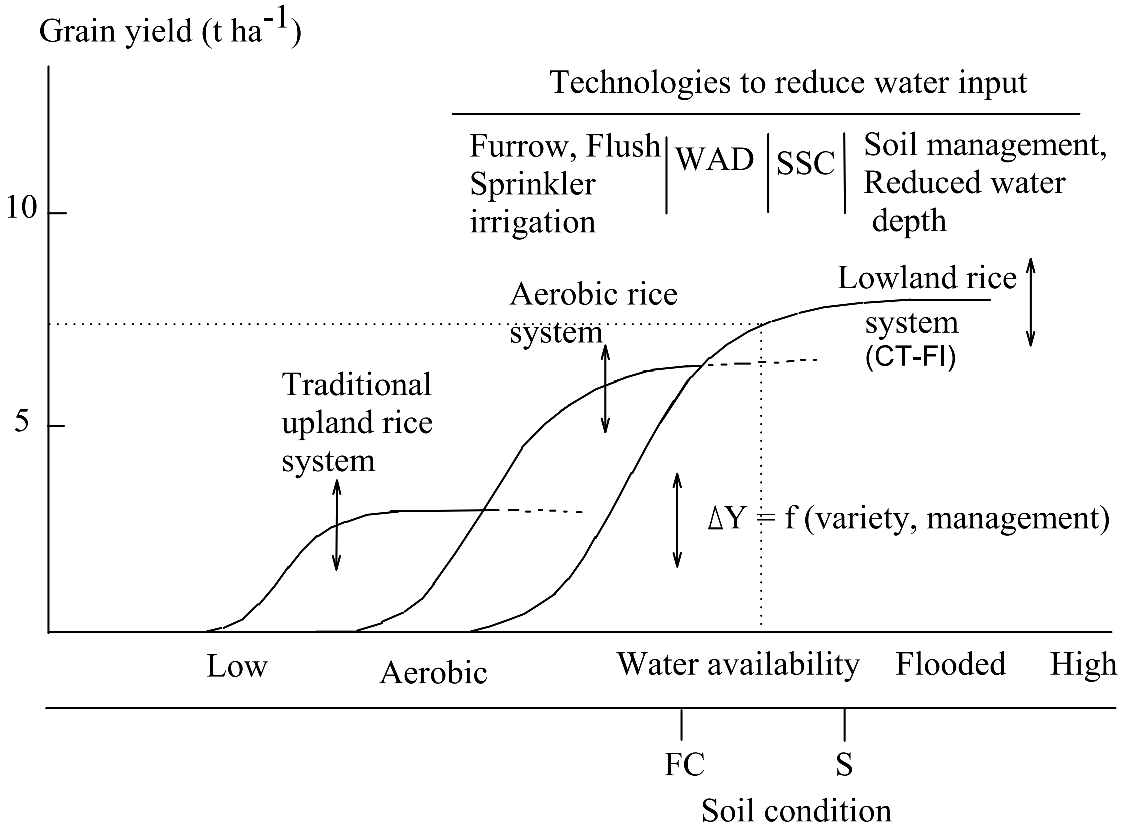


Figure 1.4 Yield response to water availability and soil moisture conditions with different irrigation methods. SSC=saturated soil culture, WAD=frequent intermittent wet and dry irrigation, CT-FI=conventional tillage flood irrigation, FC=field capacity, S=saturation point, ΔY=change in yield. Dotted lines indicate soil moisture conditions and attainable yield under WAD water-saving irrigation. Modified after Tuong et al. (2005).

1.4 Potential for conservation agriculture practices in rice-wheat system

Conservation agriculture (CA) practices that involve reduced tillage, optimum residue retention and proper crop rotation (Sayre and Hobbs 2004) had been adopted by farmers on more than 100 million ha worldwide (as of 2008) especially for the cultivation of upland crops (Derpsch and Friedrich 2009). Among the CA practices, conservation tillage, i.e., dry-direct seeded rice on raised beds and flat, is becoming increasingly popular in rice cultures in southern USA, (Griggs et al. 2007) and has potential to cover a large area in the Indo-Gangetic Plains after fine-tuning in cultivars and cultural practices (Saharawat et al. 2010). Conservation tillage practices avoid the deleterious effects of puddling on soil structure and fertility, improve water- and nutrient-use efficiency and reduce production cost (Timsina and Conner 2001). Under conventional methods of rice production, repeated and continuous puddling destroys the soil physical structure and creates hardpans at shallow soil depths (Saharawat et al. 2010), and delays planting, which in turn adversely affects the performance of the succeeding wheat (Hobbs and Moris 1996). Puddling and transplanting under conventional systems are highly labor, water, time, and energy intensive.

‘Conservation agriculture aims to conserve, improve and make more efficient use of natural resources through integrated management of available soil, water and biological resources combined with external inputs. It contributes to environmental conservation as well as to enhanced and sustained agricultural production. It can also be referred to as resource efficient or resource effective agriculture’-(FAO as cited by Hobbs et al. 2008).

Conservation agriculture practices can have advantages over conventional practices in irrigated drylands as they increase water storage, reduce water loss and wind erosion, improve crop yield and water productivity, and reduce energy and labor use (Wang 2006). Further, CA practices increase soil organic matter (Rasmussen 1999), increase carbon sequestration (Uri et al. 1999), and produce yields equivalent to or higher than those under conventional agriculture (Karunatilake et al. 2000; Guerif et al. 2001). Mulching with crop residue in CA increases soil infiltration rate (Huang et al. 2001; Deng et al. 2003; Qiao et al. 2006) and decreases soil evaporation loss of water and soil salinity (Bezborodov et al. 2010; Pang et al. 2009; Egamberdiev 2007). With non-flooded rice (water-saving irrigation), CA practices such as mulching and conservation tillage as practiced in upland crops (such as in wheat) can also be used for rice cultivation (Hobbs and Gupta 2003). Use of raised beds for rice is one of the recently proposed innovations to deal with water scarcity in rice-wheat systems, inspired by the success in such systems in Mexico (Sayre and Hobbs 2004). Bed planting increases water productivity, reduces production cost (Sayre and Hobbs 2004), reduces labor requirement and improves weed management practices (Connor et al. 2003; Hobbs and Gupta 2003). Furthermore, as the beds remain permanently untilled, it saves associated costs, allows timely planting of wheat, and provides opportunities for crop diversification (Sayre and Hobbs 2004).

Research in the Jizzak and Pakhtakor regions of Uzbekistan has shown that raised-bed planting of wheat and rice improves both the yield and the water productivity

(Christmann et al. 2009). Planting wheat under irrigated conditions on permanent raised beds in 13 case studies around the world achieved on average 8% higher yields with 25-35% water saving (Sayre and Hobbs 2004). In irrigated wheat fields in the Khorezm region of Uzbekistan, although no change in yields was observed, operational cost savings made the permanent bed system superior to all other systems (including zero-tillage) (Tursunov 2009).

Nitrogen is the most limiting nutrient for crop production in rice-based cropping systems (Thuy et al. 2008). Nitrogen dynamics in flood-irrigated rice have been extensively studied (De Datta and Buresh 1989; Buresh and De Datta 1991; George et al. 1992; Kundu and Ladha 1995). Mineral N dynamics in dry-direct seeded rice under frequent intermittent wet and dry irrigation may differ from those in continuous flood irrigation. In continuous flood-irrigated rice, as the soil is mostly under anaerobic conditions, ammonium nitrogen (NH_4-N) is available (Vlek and Byrnes 1986), while under aerobic conditions N is available in the form of nitrate nitrogen (NO_3-N) (George et al. 1992). Increased accumulation of NO_3-N in the soil profile increases the potential for N leaching to shallow water tables (Keeney and Follett 1991). Further, the frequent aerobic-anaerobic phases promotes N losses by denitrification (Vlek and Byrnes 1986). Thus, availability of soil mineral N (NO_3- and NH_4-N) in the soil and the rate of uptake by rice and wheat crops may differ with irrigation method. The addition to this, the retained crop residues can further affect the transformation and distribution of fertilizer N into different soil-N fractions (Chou et al. 1982), and higher N losses have been reported with residue retention or incorporation through denitrification (Aulakh et al. 1984) or immobilization (Quemada and Cabrera 1995).

1.5 Impact of climate change on rice production in Central Asia using crop model ORYZA2000

The IPCC (2007) has predicted that surface air temperatures will increase by 3–4 °C in the Central Asian countries by the end of 21st century. It further predicted that under increased temperatures, crop yields are likely to decrease up to 30% in the Central Asian region even when the direct positive physiological effects of increased CO_2 are accounted for. The predicted negative impact of climatic change on crop yields could even be higher in rice, because during the rice-growing season in Central Asia, the current maximum day temperatures are either close to, or higher than the critical threshold of 33-35 °C (Nakagawa et al. 2002; Yoshida 1981).

Adjustment of the sowing date of rice plays vital role in improving its growth and increasing the yield under both current and climate change conditions. In the region, the sowing time of the rice crop is important: (i) to ensure that vegetative growth occurs during a period of satisfactory temperatures and high levels of solar radiation, (ii) to ensure to escape from high and low temperature stress during flowering and grain filling period which causes panicle sterility in rice. Further, both early and delayed sowing may result in poor emergence and reduced number of spikelets and ultimately yield is affected (Hayat et al. 2003).

Under climate change conditions, modification in sowing dates could have a very positive impact on national and regional rice production. Under arid climate conditions, adjustment in seeding dates could be the future adaptation strategies to escape from the severe spikelet sterility that is caused by high and low temperatures. Furthermore, through the selection of varieties with higher tolerance of spikelet sterility, yield levels can be improved under both current and climate change scenarios (Matthew et al. 1997).

The model ORYZA2000 was especially developed to simulate rice growth and development (Bouman et al. 2001), and researchers have applied the ORYZA series to explore the impact of climate change on rice over a range of environments in several rice-growing countries of Asia; the model has been evaluated more than any other rice growth model (Matthew et al. 1995; Shen et al. 2011; Krishnan et al. 2007). ORYZA2000 is equally capable to simulate phenology, leaf area, grain yield and biomass production with CERES-Rice, SIMRIW, and other rice growth models (Timsina and Humphreys 2006; Mall and Aggrawal 2002; Kropff et al. 1994), and has better capability to simulate spikelet sterility due to high and low temperatures than other models.

1.6 Research objectives

Considering the existing irrigation and tillage practices and cost of production for rice and wheat, the two major staples essential for food security, the overall goal of this research was to identify a resource conservation technology for rice and wheat production involving an optimum use of water, tillage and production resources. The specific objectives were:

1. To investigate the growth, yield formation, and water use of rice grown under water-saving irrigation and CA practices in the Khorezm region of Uzbekistan and identify the possible causes of crop yield reduction under alternative soil and water management conditions;
2. To examine mineral N dynamics in a rice-wheat system seeded under water-saving intermittent wet and dry irrigation and CA practices in irrigated arid drylands;
3. To evaluate the effects of water-saving irrigation combined with CA practices on system productivity, water application, water balance, salinity dynamics, and net return of a rice-wheat system in Central Asia;
4. To evaluate the rice growth model ORYZA2000 and to assess the impact of increased temperature on phenology and grain yield of rice at various emergence dates under climate change scenarios.

1.7 Outline of the thesis

The thesis consists of seven chapters with a general introduction (Chapter 1), description of the study region (Chapter 2), four research papers (Chapters 3-6), general discussion, conclusions and outlook (Chapter 7).

Following the general introduction, the geographical and demographical setting of Central Asia (Aral Sea Basin) are described in Chapter 2 to facilitate understanding of the empirical findings presented in the subsequent chapters; details are given on climate, soil and land use at the study site in Khorezm. In Chapter 3, rice growth and development, yield and yield components, water application and water productivity, plant N uptake and soil mineral N content under water-saving irrigation and CA practices are described. In Chapter 4, the potential N loss from continuous aerobic-anaerobic cycles in a rice-wheat cropping system is analyzed based on soil mineral N dynamics, i.e., nitrate (NO_3-) and ammonium (NH_4-N) dynamics, groundwater NO_3, and water-filled pore space. Chapter 5 deals with rice-wheat cropping system productivity, system water application and balance, salt dynamics and an economic analysis of irrigation and tillage methods and residue levels. In Chapter 6, the parameterization and evaluation of the rice growth model ORYZA2000, and the simulation of rice phenology, grain yield and spikelet sterility due to high and low temperatures under IPCC (2000) A1F1 and B1 scenarios in 2050-2079 for three rice varieties on six emergence dates in Central Asia are presented. Chapter 7 comprises general discussion, conclusions and outlook in relation to the potential of water-saving and conservation agriculture practices in Central Asia. The main findings of this study and recommendations for further research are also presented in this chapter.

2 STUDY REGION

2.1 Geographical and demographical setting

This study was conducted during 2008-2010 in the Khorezm region of Uzbekistan within the framework of the German-Uzbek ZEF/UNESCO Khorezm project. The Khorezm region is located in northwest Uzbekistan at 60.05°- 61.39°N latitude and 41.13°-42.02°E longitude and with an elevation ranging from 90-138 m above sea level. The region covers an area of about 6200 km^2 and is bordered by the Amu Darya River to the northeast, the Karakum desert to the south, the Kyzylkum desert to the east, the Republic of Turkmenistan to the southwest, and the Autonomous Republic of Karakalpakstan to the north (Figure 2.1). The region is divided into 10 administrative districts, i.e., Bogot, Gurlen, Khazarasp, Khiva, Khonka, Kushkupir, Pitnjak, Shavot, Urgench, Yangibozor, and Yangiaryk. In 2007, the region had a population of 1.51 million, and about 80% of this population live in rural areas (Bekchanov et al. 2010), with incomes largely depending on irrigated agriculture.

The Khorezm region is one of the most intensively cultivated areas in Uzbekistan, and has 270,000 - 300,000 ha under irrigated agriculture (Conrad 2007). All irrigation water in the region comes from the Amu Darya River. In view of its downstream location on the Amu Darya, Khorezm is especially vulnerable to water shortage and droughts. The probability of receiving an adequate supply of irrigation water has decreased due to an increased water demand and the extension of the irrigated area (Müller 2006). Furthermore, the extensive and inefficient irrigation in Khorezm has drastically increased secondary soil salinization and degradation of the irrigated land, which is threatening the sustainability of the ecological and socio-economic situation in the region.

The field experiments were conducted at the research site of the ZEF/UNESCO project in Urgench district (60°40’12’’N and 41°32’44’’E) of Khorezm region (Figure 2.1).

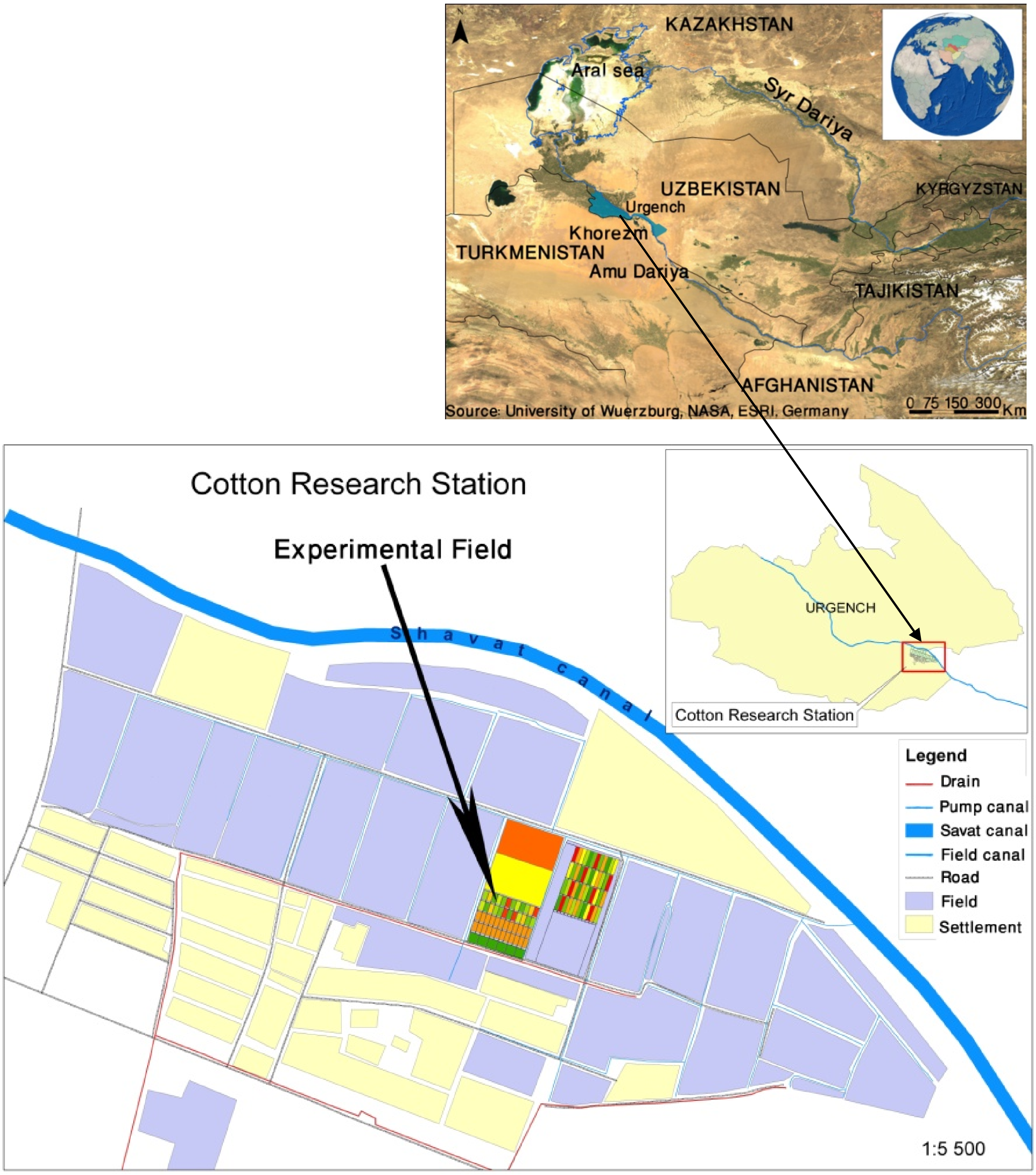


Figure 2.1 Khorezm region in the northwest of Uzbekistan and location of the study area.

2.2 Climate

The climate of the Khorezm region is according to Köppen-Geiger Climate Classification System, a typical continental, arid climate with long, hot and dry summers and short, very cold dry winters (Kottek et al. 2006). Potential evapotranspiration (1200 mm y^{-1}) always greatly exceeds precipitation. Higher precipitation generally occurs in April and November (Forkutsa 2006). The meteorological station in Urgench reported a mean annual temperature of 13.4 °C with a minimum in January/February (-7 °C) and a maximum in June/July (40 °C) for the last 37 years. Mean annual rainfall in the same period amounted to 94.6 mm (Figure 2.2). Precipitation usually occurs in the winter-spring period and, in the long-term average does not exceed 100 mm annually (Figure 2.3). About 73 % of the annual precipitation occurs in the winter-spring period, 19 % in autumn and 8 % in summer (Forkutsa 2006). According to Kiseliova and Lifshits (1971a), neither summer nor winter precipitation plays any role in the water balance of the region. The average yearly frost-free period is 205 days (Khamzina 2006) and the actual sunshine hours range from 2700 to 3000 per year (Meteo-infospace 2004).

The climatic conditions favor the cultivation of winter wheat, which can survive the low winter temperatures (Fowler et al. 1999). Rice cultivation under such continental climatic conditions, however, is possible only with assured irrigation. But, a declining availability of irrigation water in the region, where the average probability of obtaining irrigation water both in sufficient amounts and at the right time has declined by 16% in the past two decades (Müller 2006). This necessitates the development of a crop production technology that can increase water use efficiency. The introduction of water-saving irrigation, conservation tillage and mulching techniques may thus help to improve water productivity, conserve soil nutrients and preserve/re-introduce soil life, and prevent further soil loss through wind erosion.

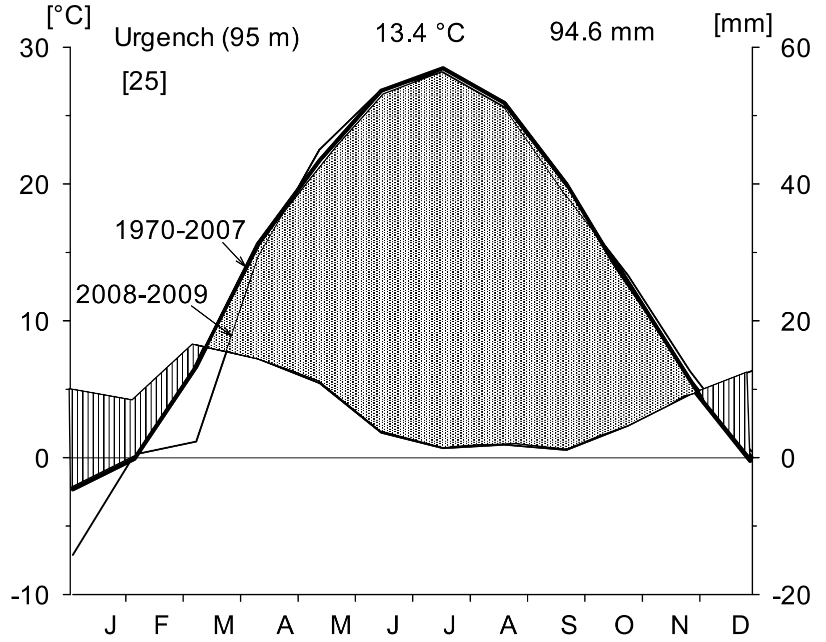


Figure 2.2 Mean monthly air temperature and monthly precipitation for Urgench, Khorezm, Uzbikistan, according to Walter and Leith (1967). Data from ZEF/UNESCO, GIS Laboratory, Urgench, Uzbekistan.

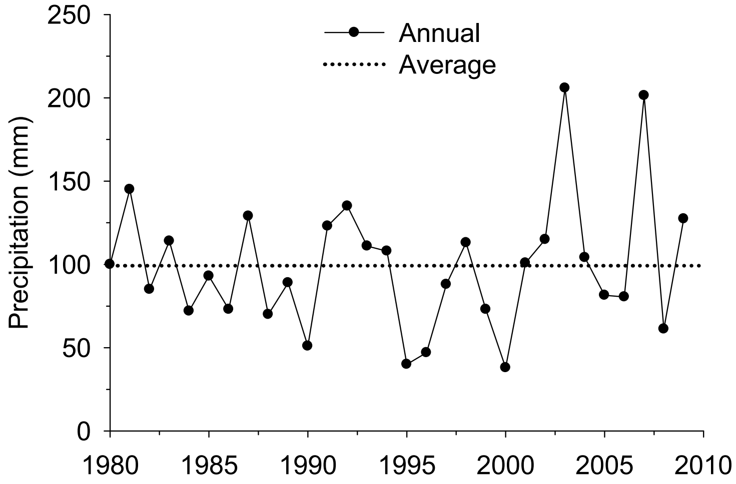


Figure 2.3 Long term precipitation measurements 1980-2009 (Modified after Forkutsa, 2006). Horizontal dotted line indicates the average annual rainfall.

2.3 Soil

According to the FAO classification, Khorezmian soils can be classified into three major types (FAO 2003): (i) calcaric gleysoils, i.e., meadow soils in the irrigated areas characterized by a shallow groundwater table often with elevated groundwater salinity and secondary salinization in the upper soil, (ii) calcaric fluvisoils, i.e., meadow soils commonly found mainly in the Amu Darya River in the eastern part of Khorezm, and (iii) yermic regosols, soils that are formed from alluvial rock debris deposits outside the irrigated areas and also from the dunes of the Karakum desert mainly in the south of Khorezm (Figure 2.4). However, the FAO classification is rather broad and does not include the detailed characteristics of the Russian/Uzbek classification. According to the latter classification, the major soil type of the region is an irrigated alluvial meadow, which covers 60% of the area. The other common soils in Khorezm are boggy-meadow (covering 16%), takyr-meadow (15%), boggy (5%), grey-brown and takyr (2%) (Rasulov 1989 as cited by Kienzler 2009). The soil textures are light, medium and heavy loams (Rizayev 2004 as cited by Scheer 2008).

The inherent fertility of all Khorezmian soil types is rather low, thus cultivation of agricultural crops requires the input of fertilizers.

The organic matter content in the Khorezmian soils ranges from 0.33 to 0.6 %. In the experimental field the soil organic matter (SOM) content was rather low with 0.4-0.5% in top 30 cm soil depth (Table 2.1). The low SOM contents in the study region is due to high temperatures and intensive irrigation and soil tillage practices, which enhance fast decomposition in the plow layer (Vlek et al. 1981). Hence with annual crop residue retention as is advocated under CA, the SOM could be increased at least for a short period.

Nitrogen is considered as the most limiting nutrient in the Khorezmian soil (Ibragimov 2007). The total organic N content usually comprises around 90-95% of the soil total N content in the plowing layer of agriculture soils, and is closely associated with the soil organic matter (Vlek et al. 1981). For Khorezm, organic N content in the soils has been reported to vary from 0.012-0.073% in 0-30 cm depth (Kienzler 2010). In the experimental field the total N content was 0.04 to 0.05% in top 30 cm soil depth (Table 2.1). Hence, the inherent fertility of all Khorezmian soil types is rather low, thus the cultivation of agricultural crops requires the input of fertilizers.

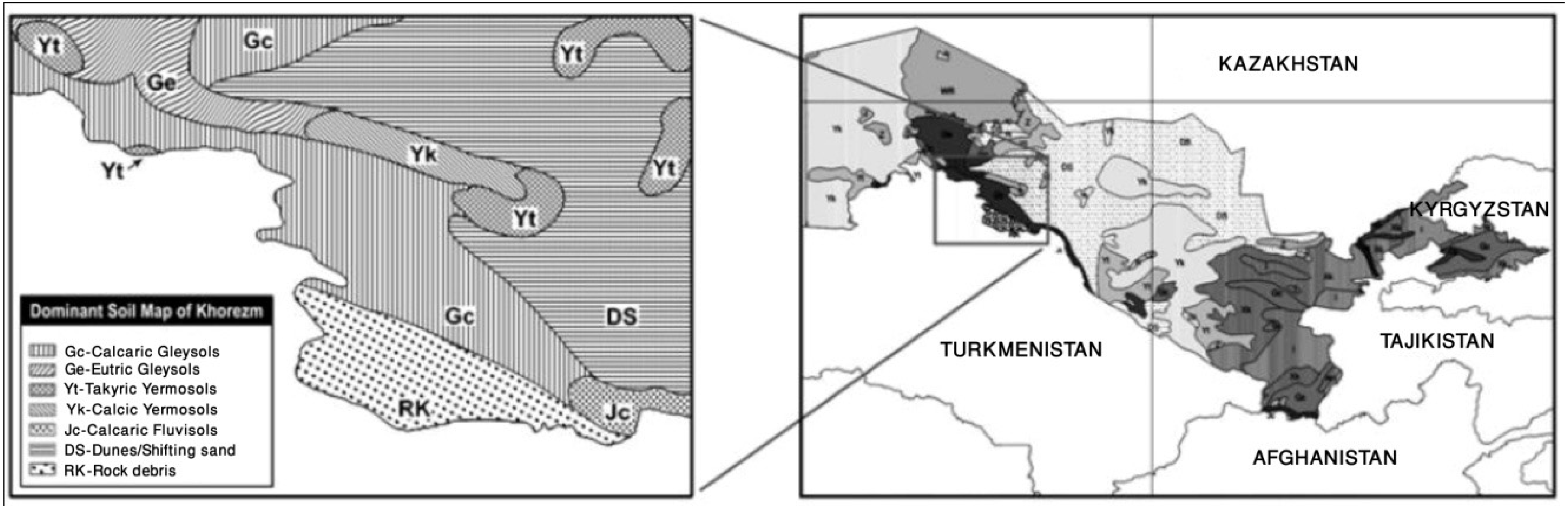


Figure 2.4 Predominant soils of Khorezm (FAO 2003)

The total soil P (0.10-0.21 %) and K (1.0-2.2 %) are relatively high in the 0-30 cm layer, the concentration of the plant-available form of P (P_2O_5) are generally moderate (15-93 mg P_2O_5 kg^{-1}) in the Khorezmian soils (Djumaniyazov 2006; Kienzler 2010). The exchangeable form of K (K_2O) in the soil reportedly ranged from low (84 mg K kg^{-1}) to high amounts (470 mg K kg^{-1}), greatly depending on preceding crops and fertilizer management (Djumaniyazov 2004; Kienzler 2010). In the experimental field the available phosphorus (22-28 mg kg^{-1}) and exchangeable potash (89-99 mg kg^{-1}) were in the moderate range (Table 2.1). Therefore these two nutrients did not receive priority in this study.

Table 2.1 Initial soil properties of the experimental site in 2008.

Depth	Bulk density	Soil pH	NH_4-N	NO_3-N	Total N	Soil organic carbon	Available phosphorus	Exchange-able potassium
cm	g cm^{-3}		—— mg kg^{-1} ——		——	% ——	———	mg kg^{-1} ———
0-10	1.35	5.57	5.4	5.3	0.05	0.36	27.9	98.5
10-20	1.41	5.56	6.5	4.4	0.05	0.30	25.9	95.0
20-30	1.42	5.57	6.3	5.2	0.04	0.26	21.9	89.3
30-60	1.52	5.69	6.3	4.0	0.03	0.23	19.2	81.4
60-90	1.57	5.78	5.2	3.9	0.03	0.19	17.6	76.8

Note: Soil organic matter = 1.56 x Soil organic carbon

Inefficient and excessive use of irrigation water on the agricultural lands in the region over several decades has led to highly saline soils (Ibragimov 2007). The fluctuation of the groundwater table in the region is mostly driven by irrigation and leaching activities (Ibrakhimov et al. 2004). During the growing period, i.e., March to October, the groundwater table rises up to 1.2-1.4 m and drops to about 1.8 m. The average salinity of the groundwater ranges between 1.68 g l^{-1} in October and 1.81 g l^{-1} in April (Ibrakhimov 2004). The higher groundwater levels enhance soil salinization by annually adding 3.5-14 t ha^{-1} of salts depending on the salinity level of the groundwater (Ibrakhimov et al. 2007). According to official government data (1999-2001), the entire irrigated area in the Khorezm region suffers from secondary soil salinization, and about 81% of the area has water-logging problems (Abdullaev 2003). Thus, prior to crop planting, i.e., in early spring, huge amounts of irrigation water are applied to leach the salts from fields. Although perhaps effective, the leaching with the huge amounts of water raises the groundwater tables further and hence increase the risk of increasing secondary salinization (Akramkhanov et al. 2010). In the absence of an efficient drainage system, which is common in most areas, the risk of re-salinization in the root zone increases (Forkusa 2006). Under saline and high groundwater table conditions, agriculture practices such as CA, which save on irrigation water and minimize soil salinity can help to sustain the agriculture systems.

2.4 Land use

Agriculture has been practiced in Khorezm region for thousands of years, mainly with millet, wheat, barley, water melons, and gourds (Forkutsa 2006). After the development of large irrigation and drainage systems from the mid 20th century onwards, agriculture began to bloom with the diversion of massive amounts of water from the river valleys to the surrounding areas mainly for cotton production. From that period onwards, the quality of the river water has deteriorated due to the discharge from the collector-drainage system to the river (Vinogradov and Langford 2001; Forkutsa 2006).

During the Soviet era, cotton became the priority crop, and about 70% of the irrigated land was used for cotton in 1970, but this declined to 56% in 1990 (before independence). The area has further declined since dependence due to the introduction of wheat as a second priority crop (Wehrheim and Martius 2008). Currently, about 265,000 ha of land are used for irrigated agricultural production in Khorezm (Bekchanov 2010). Cotton, wheat, rice, and fodder maize are the dominant crops in the region (Wehrheim and Martius 2008), where cotton uses 42% of the irrigated area followed by winter wheat (20%), rice (7%), while fodder (10%), fruits and vegetables (10%) and garden crops occupy the remaining irrigated area in 2007 (Figure 2.5). Thus, for introducing sustainable agricultural practices, which are advocated through CA, most gains can be made when addressing with priority the cotton and wheat based rotations.

In Uzbekistan, agricultural production is mainly state controlled. Three main farm types have been formed in different steps after independence from the Soviet Union (Scheer 2008): (1) shirkats - the agriculture cooperatives were formed as a transitory successor of former *kolhozes* and s*ovkhozes*, (2) *dehqon* farms - household farms, i.e., subsistence-oriented household plots that represent an important contribution to household food security, and (3) *fermer* enterprises - a new type of farm that has emerged during the past five years established on the basis of long-term leases with a commercial orientation (Wehrheim and Martius 2008).

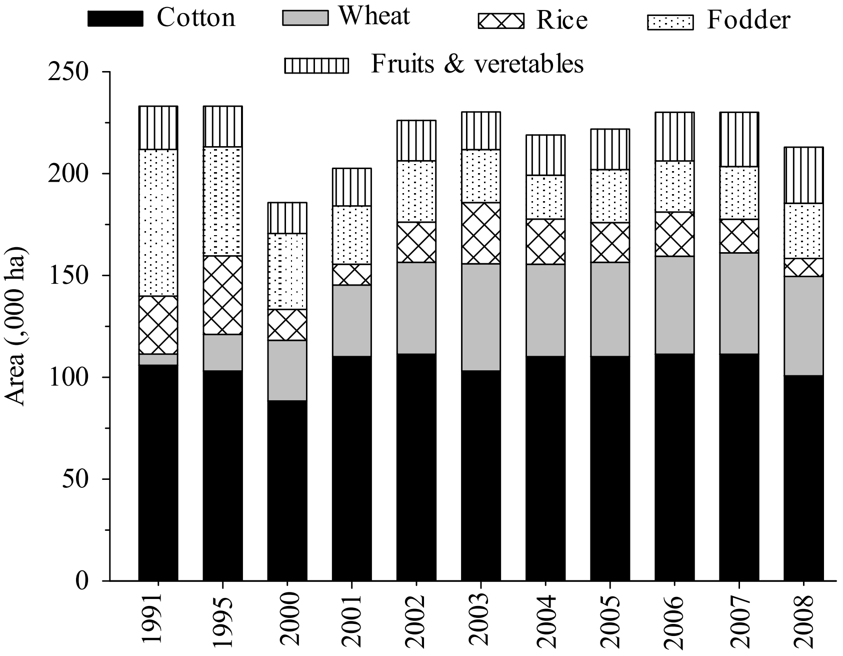


Figure 2.5 Area under different crops in Khorezm region (1991-2008) according to the regional department of statistics. (OblStat 2010)

2.5 Irrigation network

The extensive network of irrigation channels and the complementary drainage collectors in Khorezm were mainly built during the Soviet era from 1950 to 1970 (Katz 1976). Water is diverted from the Amu Darya River and supplied to the agricultural fields through a complex, hierarchical irrigation network consisting of main, inter-farm and on-farm canals. The total length of the network is 16,233 km and every year between 3.5 km^3–5 km^3 of water from the Amu Darya is supplied to the region and used mainly for agricultural purposes (SIC-ICWC 2006), whereas in individual years withdrawals of 5.38 km^3 irrigation water in the vegetation period 2005 were recorded (Conrad 2006).

Central Asia is the region with water scarcity problems due to an arid climate and poor water management (Micklin 1991). To solve the water scarcity in the region, crop irrigation management has to be improved, including the management of salinity in the region (Horst et al. 2004). Khorezm region of Uzbekistan is the representative of various regions of irrigated lowlands of Central Asia that has affected from a conventional agriculture practices, i.e., intensive soil tillage and flood irrigation. The combination of conservation tillage (permanent beds) and residue retention have been shown as alternative options for sustainable crop production systems under rainfed as well as irrigated systems (Limon-Ortega et al. 2000; Sayre and Hobbs 2004; Govaerts et al. 2005; Wang et al. 2006), which however has not been well studied in the salt affected irrigated drylands of Central Asia.

3 GROWTH AND YIELD OF RICE (*ORYZA SATIVA* L.) UNDER WATER-SAVING AND CONSERVATION AGRICULTURE PRACTICES IN IRRIGATED DRYLANDS OF CENTRAL ASIA

3.1 Introduction

Rice is the major source of food for more than 50% of the world's population (Maclean et al. 2002). More than 75% of the total rice worldwide is produced in flood-irrigated production systems. This ranks paddy rice production on top of the list of the largest consumers of water, using 30% of the total freshwater used in the world (Barker et al. 1999). Since only 15-30% of the water is consumed by the crop for transpiration and growth, flood-irrigated cultivation practices lead to very high water losses through various pathways: 10-30% through deep percolation, 30-50% through evaporation, and 10-25% through surface runoff (Falkenmark and Rockstorm 2004). Given the increasing competition by urban and industrial water users, and the predicted adverse impacts of climate change on water availability, the present practice of rice production under flood-irrigated conditions has to cope with future water scarcity. Tuong and Bouman (2003) reported that by 2025, about 15 out of 75 million ha of Asia's flood-irrigated rice area alone will experience water shortage.

Rice is the third major food crop in terms of area and production in Central Asia. In Uzbekistan, it is the second major food crop in terms of area (55,000 ha) and third in terms of production (194,700 t). Rice productivity averages 3.15 t ha^{-1} in Uzbekistan and 3.60 t ha^{-1} in Central Asia (FAOSTAT 2009). The administrative district Khorezm is the major rice-growing region in Uzbekistan. With an area of 11,293 ha and productivity of 4.3 t ha^{-1}, of the total rice in Uzbekistan, 32% is produced in this region (OblStat 2010). In the region, rice is mostly grown in rice-wheat rotation, and the rice-growing area is mostly located in the irrigated lowlands of Amu Darya and Syr Darya river basins (Christmann et al. 2009).

Water management is the single most important issue constraining and threatening production, productivity and sustainability of crop production systems in Central Asia (Gupta et al. 2009). Growing transplanted rice under arid climatic conditions requires more than 30,000 m^3 ha^{-1} irrigation water (UNESCO 2000; FAO 1997). Wet-direct seeding of rice after harrowing (2-3 times), chiseling (1-2 times), and leveling is the most widespread rice-cultivation method in the Khorezm region. Following seeding and germination, farmers keep a collar of 15-20 cm standing water throughout the rice-growing period. The total amount of water application for wet-direct seeded rice is even higher than for transplanted rice. Despite rice being the third major cereal and one of the most remunerative crops in Central Asian countries, its area is decreasing due to the diminishing supply and mismanagement of irrigation water (Christmann et al. 2009).

The decline in water availability for flood-irrigated rice production has triggered research on increasing water productivity and water use efficiency. At field scale, the explored water-saving innovations include continuous soil saturation (Borrell et al. 1997), alternate wetting and drying (Dong et al. 2004; Li 2001; Tabbal et al. 2002), rice cultivation on raised beds (Ockerby and Fukai 2001; Singh et al. 2003), aerobic rice systems (Bouman et al. 2005; Yang et al. 2005), non-flooded mulch cultivation (Liu et al. 2003; Lin et al. 2003b) and dry-direct seeding in zero tillage flat land and permanent beds (Sayre and Hobbs 2004; Gupta et al. 2003; Singh et al. 2002).

Raised bed planting (BP) or flat zero tillage planting (ZT) combined with residue retention improves soil health, reduces production cost, and increases production of maize and wheat under rainfed conditions (Govaerts et al. 2007). Furthermore, these management practices have the potential to reduce evaporation losses from the soil surface and to improve crop production in saline environments (Hobbs and Gupta 2003). Direct-seeded rice (DSR) on raised beds and flat areas avoids the deleterious effects of puddling on soil structure and fertility, improves water- and nutrient-use efficiency, and reduces production cost (Timsina and Conner 2001).

Permanent raised bed practices have been studied in rice-based cropping systems in Australia (Collinson et al. 1995; Borrell et al. 1997; Ockerby and Fukai 2001) and in rice-wheat systems in the Indo-Gangetic plains (Sharma et al. 2002; Sayre and Hobbs 2004; Bhushan et al. 2007). While growing rice under BP with frequent intermittent wet and dry (WAD) irrigation has the potential to save water, grain yield may be reduced. Borrell et al. (1997) reported 34% water saving but 16-34% rice yield losses under BP. Similarly, Sharma et al. (2002) reported 49-55% water savings but 52% yield reduction under BP, and 49-43% water savings and 36-46% yield reduction under ZT seeding compared to transplanted rice in semi-arid region of India.

Furthermore, 13-23% water savings but 14-25% yield reductions under BP were observed in India (Bhushan et al. 2007). Paddy-produced rice yields can be reduced by as much as 10-40% when the soil water potential in the root zone is allowed to reach -100 to -300 mbar (Bouman and Tuong 2001).

With WAD irrigation, conservation agriculture (CA) practices, such as mulching and zero- or minimum-tillage as practiced for other crops, can also be to the advantage of rice farmers (Hobbs and Gupta 2003). Growing rice under WAD conditions on raised beds or zero-tillage flats in rice-wheat cropping systems in humid tropical regions showed promising results, but this practice still needs further development (Humpherys et al. 2005). Alternate wet and dry irrigation can maintain or even increase grain yield (Tuong et al. 2005; Won et al. 2005; Yang et al. 2007), and the practice was therefore adopted by farmers in countries of East Asia such as Bangladesh, India, and Vietnam (Tuong et al. 2005; Bouman et al. 2007). On the other hand, alternate wet and dry often reduces, rather than increases, rice grain yield when compared with continuously submerged conditions (Mishra et al. 1990; Tabbal et al. 2002; Belder et al. 2004). Further, the use of an appropriate aerobic rice variety is crucial for better rice yields under dry-direct seeded aerobic conditions (Singh et al. 2008). It thus remains a major challenge to reduce water input without compromising yield and to optimize the use of scarce water in rice production. The objectives of this study therefore were to (i) investigate the growth, yield formation, and water use of rice grown under water-saving irrigation and CA practices in the Khorezm region of Uzbekistan, and (ii) to identify the possible causes of crop yield reduction under alternative soil and water management conditions.

3.2 Materials and methods

3.2.1 Site description

The field experiments were conducted in the 2008 and 2009 rice-growing seasons at the Cotton Research Institute in the Khorezm region (41°32'12" N, 60°40'44" E) located in north-western Uzbekistan on the left bank of the Amu Darya River within the transition zone of the Karakum and Kyzalkum deserts. The climate of the area is arid, with a long-term average annual rainfall of approximately 100 mm (Figure 2.2), but neither summer nor winter precipitation plays a significant role in the water balance of the region (see section 2.2).

The soil at the experimental site at the Cotton Research Institute, Urgench, is an irrigated alluvial meadow soil (Russian Classification) or arenosol, gleyic, calcaric, sodic (FAO, Classification), sandy loam to loamy sand in texture with high soil salinity (EC 2-16 dS m^{-1}), shallow groundwater table (0.5 to 2 m), and poor in soil organic matter (0.40-0.80%). As these soils have developed in the former valleys and floodplains of the Amu Darya River (Tursunov and Abdullaev 1987), hydraulic conductivity is fairly high (Table 3.1). At field capacity, the top 10 cm soil has a volumetric soil moisture content of 30%, which corresponds to the soil metric potential of -10 kPa.

Table 3.1 Soil physical and hydraulic properties at different depths at the experimental site in the Khorezm region of Uzbekistan.

Soil depth (cm)	Texture (%)			Bulk density (g cm^{-3})	Volumetric water content (%)			Hydraulic conductivity (m d^{-1})
	Sand	Silt	Clay		Saturation	Field capacity	Permanent wilting point	
0-10	23	58	19	1.35	48	30	12	0.30
10-20	33	49	18	1.41	47	28	12	0.28
20-30	26	62	12	1.42	45	28	10	0.58
30-50	29	63	8	1.52	43	27	9	0.82
50-80	49	43	8	1.57	41	23	9	0.86

3.2.2 Treatments and experimental design

To quantify the effect of WAD irrigation and CA practices, the findings of seven treatments in 2008, and eight in 2009 combining three tillage methods, three levels of crop residue retention, and two irrigation methods were compared (Table 3.2). Tillage methods involved (i) conventional tillage for field preparation and wet-DSR, i.e., direct broadcasting of 24-hour water-soaked pre-germinated rice seed into the standing water, (ii) raised bed planting, i.e. dry-DSR on permanent raised beds by tractor-drawn bed planter, and (iii) flat zero tillage planting, i.e. dry-DSR on untilled flat plots at 20-cm row spacing using the same bed planter (Figure 3.1). Bed configuration was similar to that reported by Sayre and Moreno Ramos (1997) and Sayre and Hobbs (2004).

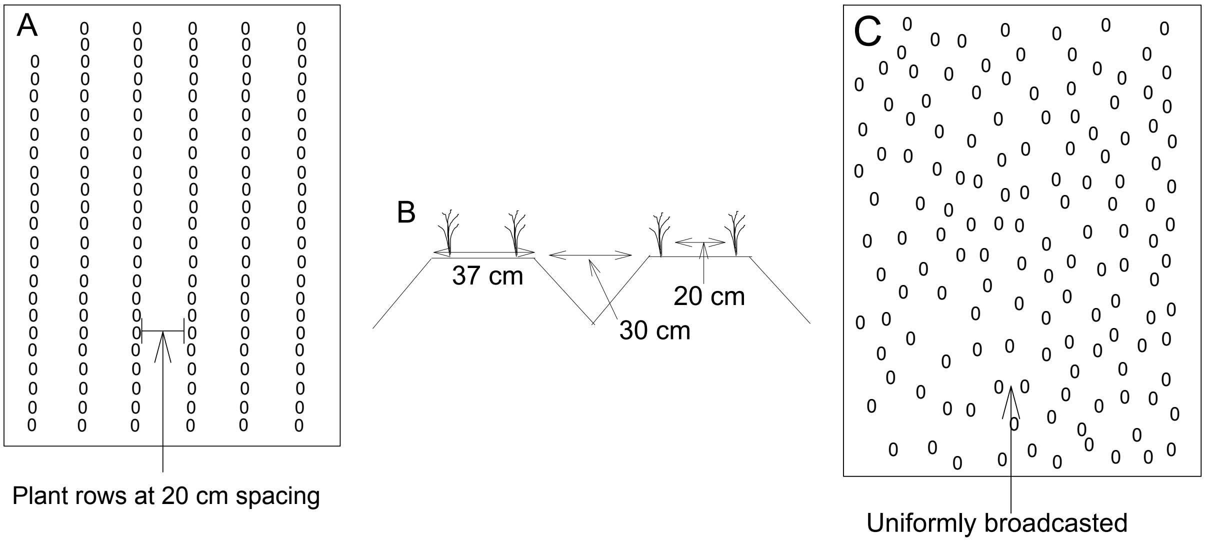


Figure 3.1 Schematic representation of rice seeding in zero tillage flat fields (A), raised-bed (B), and conventional tillage methods (C).

The three levels of residue retention included (i) residue harvested (RH) – crop harvested from the base leaving 3-5 cm stubble as in the usual farmers' practice, (ii) 50% residue retention (R50) – all straw harvested retaining 15-20 cm straw stubble, and (iii) 100% residue retention (R100) – all straw harvested retaining 35-40 cm straw stubble. At the onset of the experiment in 2008, there were no crop residues from the previous crop, therefore chopped wheat residues at 1.5 t ha^{-1} in the R50 and 3.0 t ha^{-1} in the R100 treatments were equally spread over the soil surface. In 2009, standing residue from rice 2008 and wheat 2009 were retained; the cumulative residue amount was 8.5 t ha^{-1} in the R50 (1.5 t ha^{-1} initial plus 2.9 t ha^{-1} from rice plus 4.1 t ha^{-1} from winter wheat) and 14.3 t ha^{-1} in the R100 treatment (3.0 t ha^{-1} initial, 4.6 t ha^{-1} from rice, 6.7 t ha^{-1} from winter wheat; Table 4.2).

Table 3.2 Treatments evaluated in 2008 and 2009 rice field experiments in the Khorezm region of Uzbekistan.

Treatment	Description
BP-RH	Bed planting, residue harvested, WAD irrigation
BP-R50	Bed planting, 50% residue retention, WAD irrigation
BP-R100	Bed planting, 100% residue retention, WAD irrigation
ZT-RH	Zero tillage, residue harvested, WAD irrigation
ZT-R50	Zero tillage, 50% residue retention, WAD irrigation
ZT-R100	Zero tillage, 100% residue retention, WAD irrigation
CT-FI	Conventional method of tillage and field preparation, residue harvested, conventional flood irrigation
CT-II	Conventional method of field preparation, residue harvested, intermittent irrigation

Six WAD rice treatments, i.e., BP and ZT with three levels of residue retention, were irrigated almost daily during the first 15 days after sowing (DAS). After 15 days, WAD rice was flood irrigated when the volumetric soil moisture content at 20 cm soil depth dropped 5-10% below the field capacity, i.e., a soil metric potential of around -20 kPa (Figure 3.2), i.e., the field was re-irrigated at 1-5 day intervals. Thus, the WAD irrigation used here differs from the alternate wet and dry practice used previously (Dong et al. 2004; Li 2001, Tabbal et al. 2002; Bouman et al. 2001; Zhang et al. 2008). In these previous studies, fields had been submerged for several days or throughout a certain crop growth stage and dried to a certain soil moisture level, and then the irrigation cycle was repeated. For the irrigation of the CT-FI rice, the farmers' practice of continuous flood irrigation to maintain a 5-15 cm standing water level until one week before crop harvest was adopted. To quantify the effect of irrigation and tillage methods, a treatment with conventional tillage and frequent intermittent WAD irrigation (here for the sake of easiness to differentiate irrigation in this treatment has been said only the intermittent irrigation; CT-II) was included in 2009.

In addition to the above treatments, in 2009 two other treatments, i.e., zero-tillage-continuous flood irrigation up to panicle initiation and intermittent irrigation thereafter (ZT-FI-II) and zero-tillage-continuous flood irrigation (ZT-FI), were also evaluated.

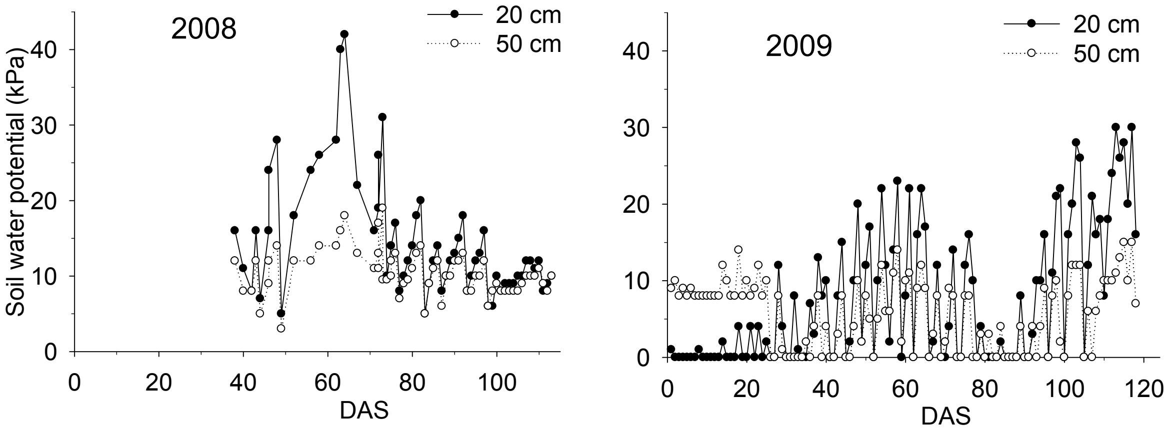


Figure 3.2 Soil metric potential at 20 and 50 cm soil depths in 2008 and 2009; average standard error over the growing season was 7% of the mean in 2008 and 6% of the mean in 2009; DAS=days after sowing

The experiment was conducted as a randomized complete block design (RCBD) with 4 replications (Figure 3.3). The field was laser levelled before experimentation. Each plot was sized 480 m^2 (41 m x 11.7 m) in the WAD treatments and 2000 m^2 in the CT-FI. WAD treatments were laid out at 70 m distance from the flood-irrigated treatment to reduce the possible site effects of the raised groundwater table due to CT-FI.

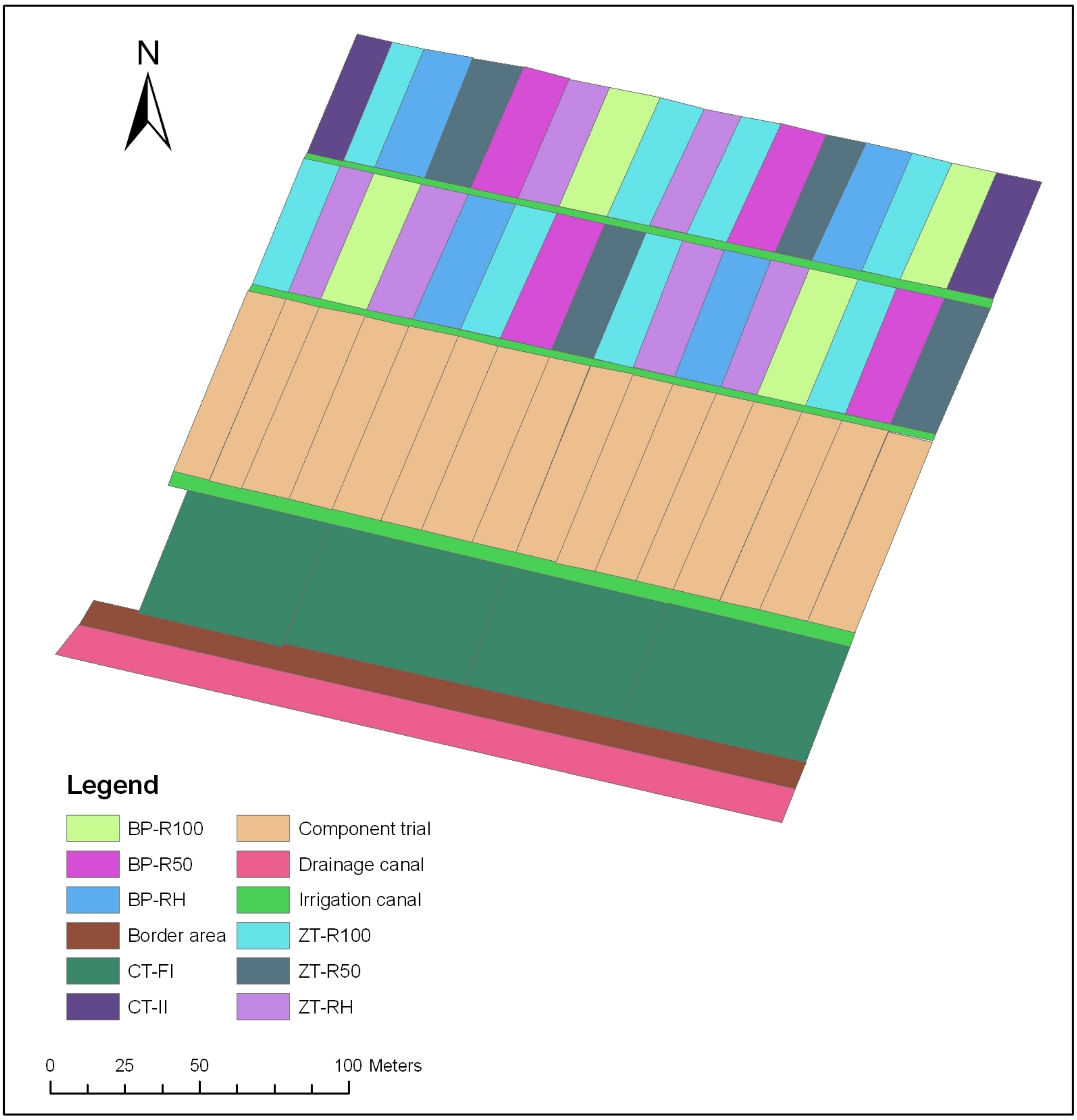


Figure 3.3 Layout plan of the rice-wheat cropping system experimental field 2008-2010, Khorezm, Uzbekistan.

3.2.3 Cultivation practices

The local rice variety Nukus-2 (short duration, i.e. 90-100 days, high yielding, and input responsive) was seeded on 18 June 2008 and on 21 June 2009 using a seed rate of 140 kg ha^{-1} in the WAD treatments. At the same time and rate, seed soaked in water was seeded in CT-FI. Fertilizer was applied as 257 kg N ha^{-1} in 2008 and 250 kg N ha^{-1} in 2009, and 120 kg P_2O_5 and 80 kg K_2O ha^{-1} in both years (Table 3.3). The selection of the rice variety, seed rate and fertilizer rate was based on the common farmers' practice according to the information of the local National Rice Research Institute. Nukus-2 is considered a variety suitable for wet-DSR in CT-FI systems in the Khorezm region.

Table 3.3 Time and dose (kg ha^{-1}) of fertilizer application in rice grown under different cultivation methods in 2008 and 2009.

Nutrient	Dose (kg ha^{-1})			Fertilizer type	Application method and time^{a}
	BP	ZT	Conventional		
2008					
Nitrogen	29	29	31	Ammonium phosphate	Incorporation at field preparation
Phosphorus	120	120	120	Ammonium phosphate	Incorporation at field preparation
Potash	80	80	80	Muriate of potash	Incorporation at field preparation
Nitrogen	80	80	-	Urea	Drilled at planting
Nitrogen	20	20	20	Urea	Topdressed at 16 DAS
Nitrogen	43	43	123	Urea	Topdressed at 34 DAS
Nitrogen	43	43	43	Urea	Topdressed at 53 DAS
Nitrogen	43	43	43	Urea	Topdressed at 64 DAS
2009					
Nitrogen	30	30	30	Urea	Topdressed at 17 DAS
Nitrogen	79	79	79	Urea and ammonium phosphate	Topdressed at 30 DAS
Phosphorus	120	120	120	Ammonium phosphate	Topdressed at 30 DAS
Postash	80	80	80	Muriate of potash	Topdressed at 30 DAS
Nitrogen	100	100	100	Urea	Topdressed at 45 DAS
Nitrogen	41	41	41	Urea	Topdressed at 59 DAS

^{a} DAS=days after sowing, BP=bed planting, ZT=zero tillage planting in flat plots.

In 2008, following the establishment of ZT and BP plots (Figure 3.1); two pre-sowing irrigations were applied to allow weeds to germinate. Next, all weeds were treated with Glyphosate at the rate of 2 ml l^{-1} water 2-3 days before rice seeding. Gulliver (Azimsulfuron 50 WG) at 25 g ha^{-1} in the WAD treatments and at 5 g ha^{-1} in 2008 and 10 g ha^{-1} in 2009 in CT-FI was applied 28 DAS in both years to control post-emergence weeds. In addition, weeds were manually removed 4 and 7 weeks after emergence in WAD and through one minor hand weeding at 4 weeks after emergence in CT-FI.

3.2.4 Measurements

Daily weather data (rainfall, air temperature, solar radiation, relative humidity, and wind speed) were continuously recorded at 30-minute intervals by a solar-energy-driven data logger (Mikromec-multisens 5.0, Technetics, Freiburg, Germany) installed within the boundary of the experimental field. These parameters were averaged to obtain daily values. Soil metric potential was measured in two replications for scheduling irrigation by installing standard tensiometers (Eijkelkamp, EcoTech GmBh) at 20 and 50 cm soil depths.

Rice phenological development and morphological differences caused by the implementation of treatments were recorded through visual observations using the Standard Evaluation System (SES) for Rice (IRRI 2002). Plants for the determination of biomass production and leaf area index (LAI) were collected from a 0.25 m^2 area in each experimental plot at 15-day intervals. The leaf area was measured each time from 25 g fresh leaf sub-samples using a LICOR-3100 area meter. The sub-sample and the remaining leaf samples were dried separately and, based on dry weight and the respective leaf area of the sub-sample, the LAI was calculated as leaf area per unit land area. Roots, stem, leaves, senesenced leaves and panicles were separated and oven dried separately for 72 hours at 65 °C till constant weight and weighed for biomass estimation with a digital balance. The plots were irrigated one day before plant sampling to facilitate uprooting by pulling. Generally, roots from 0.25 m^2 up to 15-20 cm soil depths were uprooted. The roots were washed using a fine polythene mesh, oven dried to constant weight, and root biomass production was measured. Layer-wise root biomass production (0-10, 10-20, 20-30, 30-60 cm soil depths) was estimated from the root samples taken from within and between the crop rows from at the flowering stage in 2009.

Rice grain yield was determined by harvesting plants from three randomly selected 2.25 m^2 areas, i.e. 6.75 m^2 per plot, and expressed on an oven-dried basis. The number of plants germinated was determined by counting the plants in a 0.5 m^2 area in each plot at first plant sampling. Fertile and sterile panicles m^{-2} were determined by counting all plants harvested in the 6.75 m^2 area. The presence of at least a one filled spikelet in a panicle was defined as an effective panicle; panicles with completely unfilled spikelets and plants without panicles were classified as sterile. Spikelets per panicle were determined by counting the number of filled spikelets in 20 randomly selected panicles. Spikelets m^{-2} were then calculated by multiplying the number of effective panicles m^{-2} with the number of filled spikelets per panicle. Filled and unfilled spikelets were separated by thumb feeling. The percentage of unfilled spikelets (100 x unfilled spikelet number/total spikelet number) and 1000-seed weight were determined by oven drying the counted filled spikelets from 20 panicles. The harvest index (HI) was calculated as the ratio of oven-dry grain yield to the total aboveground biomass. Aboveground plant parts collected for biomass and LAI estimation were ground separately and analyzed for tissue-N concentration according to the Kjeldahl method (Bremner and Mulvaney 1982), and the aboveground plant N uptake was estimated by multiplying tissue-N concentration by biomass.

Irrigation water input in the WAD and CT-FI rice treatments was measured by three separate Standard Trapezoidal Cipolletti weirs (0.5 m crest width) with automated data loggers (Divers) for level measurement (DL/N-70). Divers, which measured the water level at 1-minute intervals, were installed 40 cm ahead of the Cipolletti crest. The height of water above the crest width at a particular time was measured 2-3 times manually during irrigation. Following calibration, the amount of water discharged (m^3 s^{-1}) from the respective weirs was calculated based on the equation provided by Kraatz and Mahajan (1975).

Soil for determining mineral N content was sampled at the main rice growth stages from three different points in each plot at 0-10, 10-20, 20-30, 30-50 and 50-80 cm soil depths. Plant and soil samples were analyzed for N at the Soil Science Institute, Tashkent, using the standard procedures applied at this institute (Kuziev 1977). Plant N was analyzed by the Kjeldahl method (Bremner and Mulvaney 1982). Soil NO_3-N content (mg kg^{-1}) was determined according to the Granvald-Ljashu method, while the NH_4-N content (mg kg^{-1}) was determined by colorimetric analysis using the Nessler reagent (Protasov 1977). Total mineral N content in top 80 cm soil layers was determined by adding NO_3- and NH_4-N content of different soil layers. Soil temperatures at 10 and 30 cm soil depths in the RH and R100 plots were measured daily at 6:00 pm using the temperature sensor connected with the pF-meter (EcoTech GmbH) during the rice-growing season 2009**.**

3.2.5 Statistical analysis

Dependent variables were subjected to analysis of variance using PROC GLM (SAS Institute 2002-2008) for RCBD. Repeated measure analysis was performed to account for the measurements over time on biomass production, LAI, root growth, leaf N concentration and N uptake. Given the significant year x treatment interaction effect, ($p<0.05$), data were analyzed and presented year-wise. As the interaction between BP and ZT with three levels of residue retention was insignificant for all variables, data on tillage and residue were pooled during subsequent analyses. To quantify the main effect of tillage methods, residue levels, and irrigation methods, orthogonal single degree of freedom contrasts were used. Contrasts were analysed to quantify (i) CT-FI vs. RH and thus the effect of irrigation at the same level of residue management irrespective of tillage, (ii) BP vs. ZT and thus the effect of BP and ZT planting, (iii) RH vs. R50, R50 vs. R100, and RH vs. R100 and thus the effect of different levels of residue retention, and (iv) RH vs. CT-II and thus the effect of tillage at the same level of residue retention and irrigation method. Differences between individual treatments were analyzed using Fisher's Protected Least Significant Difference (LSD). Treatments differences were considered statistically significant at $p<0.05$. Pearson’s correlation coefficients were calculated from two-year averaged means of treatments to identify the relations between various yields and yield components, water use, residue levels, and N uptake.

3.3 Results

3.3.1 Weather

The minimum and maximum temperature, and rainfall during the rice-growing periods are presented in Figure 2.2. In 2009, total rainfall amounted to 70 mm, most of which occurred during the rice-flowering period, while it was only 5 mm in 2008. Until August 10 (panicle initiation stage), the average daily minimum temperature was 21.0 and 20.5 °C, wheras after August 10 to harvest it declined sharply to 13.7 °C in 2008 and 12.0 °C in 2009.

3.3.2 Crop phenology

Rice grown under CT-FI required significantly fewer days to emergence, panicle initiation, flowering, and physiological maturity compared to the WAD treatments. In the RH treatments, panicle initiation was delayed by 3-4 days, flowering by 1-5 days, and physiological maturity by 3-6 days compared to CT-FI (Table 3.4).

Phenological development was further delayed ($p<0.001$) in plots with high residue retention. Seedling emergence was delayed by 1-2 days, panicle initiation by 2-5 days, flowering by 3-9 days, and physiological maturity by 3-8 days in R100 compared to RH (Table 3.4). In 2009, under CT-II flowering and physiological maturity took more days ($p<0.001$) than under the RH and CT-FI treatments. No significant difference was observed in phenological development between the RH treatments under BP and ZT, while in the residue-retained treatments of BP flowering was faster by 2-4 days (Table 3.4). The treatments ZT-R100 followed by ZT-R50 showed the slowest development rates.

Table 3.4 Main phenological stages of rice in days after sowing under different irrigation and tillage methods and residue levels in 2008 and 2009.

Treatment^{a}	Emergence		Panicle initiation		Flowering		Physiological maturity	
	2008	2009	2008	2009	2008	2009	2008	2009
BP-RH	6a	5c	44c	46c	73b	74d	105c	113d
BP-R50	7a	6b	46b	48b	77a	77c	109b	115cd
BP-R100	7a	7a	50a	51a	78a	77c	112a	117c
ZT-RH	6a	5c	44c	46c	73b	74d	105c	113cd
ZT-R50	6a	6b	46b	49b	77a	80b	109b	122a
ZT-R100	7a	7a	50a	51a	78a	84a	112a	123ab
CT-FI	4b	4e	38d	42d	66c	72d	100d	105e
CT-II		4d		45c		77b		118b
Gross mean	6	6	45	47	75	77	107	116
P value	^{c}	^{d}	^{d}	^{d}	^{d}	^{d}	^{d}	^{d}
LSD (0.05)	1.5	0.4	1.5	1.0	1.5	1.5	1.6	1.9
CV (%)	16.3	4.5	2.5	1.7	1.5	1.4	1.1	1.2

^{a} BP-RH=bed planting residue harvested, BP-R50=bed planting 50% residue retention, BP-R100=bed planting 100% residue retention, ZT-RH=zero tillage residue harvested, ZT-R50=zero tillage 50% residue retention, ZT-R100=zero tillage 100% residue retention, CT-FI=conventional tillage continuous flood irrigation, CT-II=conventional tillage intermittent irrigation. ns=nonsignificant ($P>0.05$), ^{b} $P<0.05$, ^{c} $P<0.01$ and ^{d} $P<0.001$.

3.3.3 Biomass production

At physiological maturity, rice in 2008 produced a 15% higher ($p<0.001$) total aboveground biomass than in 2009 (10.9 vs. 9.5 t ha^{-1}). The highest ($p<0.01$) biomass production was observed under CT-FI in both years, followed by RH treatments in 2008 and CT-II in 2009 (Figure 3.4). No significant interactions were observed between BP and ZT with all three levels of residue retention at all sampling dates in both years. In 2008, differences in rice biomass production between residue and tillage treatments were insignificant. Similar to 2008, tillage did not have a significant effect on biomass production in 2009, whereas residue retention showed substantial impact, with rice grown with RH outperforming the other two residue treatments. The lowest total above-ground biomass among all treatments in both years was observed in R100.

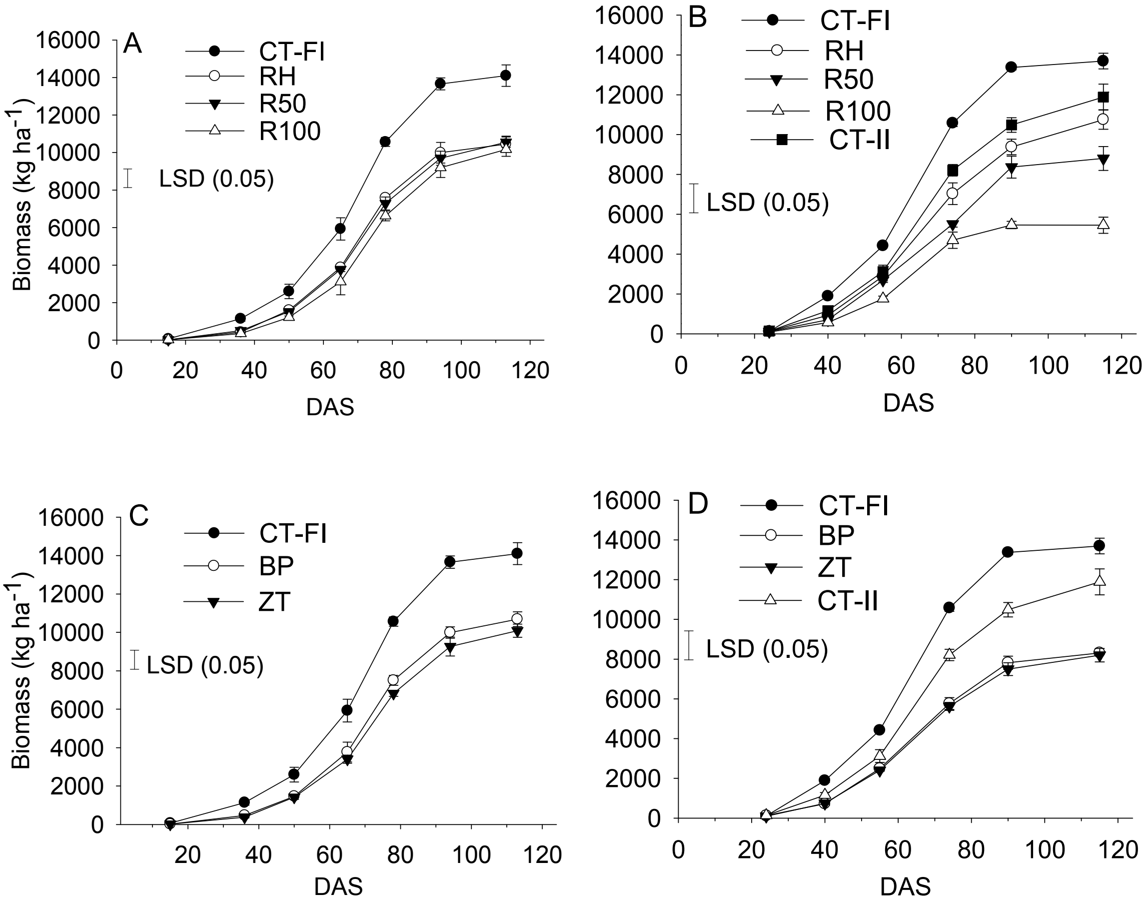


Figure 3.4 Total aboveground biomass accumulation (kg ha^{-1}) of rice under different irrigation methods and residue levels during growing seasons in 2008 (A) and 2009 (B), and under different tillage methods in 2008 (C) and 2009 (D); DAS=days after sowing; LSD (0.05) is difference between treatments over time at P=0.05; vertical bars indicate standard errors; CT-FI=conventional tillage with continuous flood irrigation, RH=residue harvested, R50=50% residue retention, R100=100% residue retention, BP=bed planting, ZT=zero tillage planting, and CT-II=conventional tillage intermittent irrigation

.

3.3.4 Leaf area

Similar to biomass production, the temporal LAI trend was higher ($p<0.001$) in CT-FI followed by CT-II and RH at all growth stages in both years (Figure 3.5). The maximum LAI of 6.5 in 2008 and 5.6 in 2009 was observed at or shortly after flowering (about 80 DAS) in CT-FI.

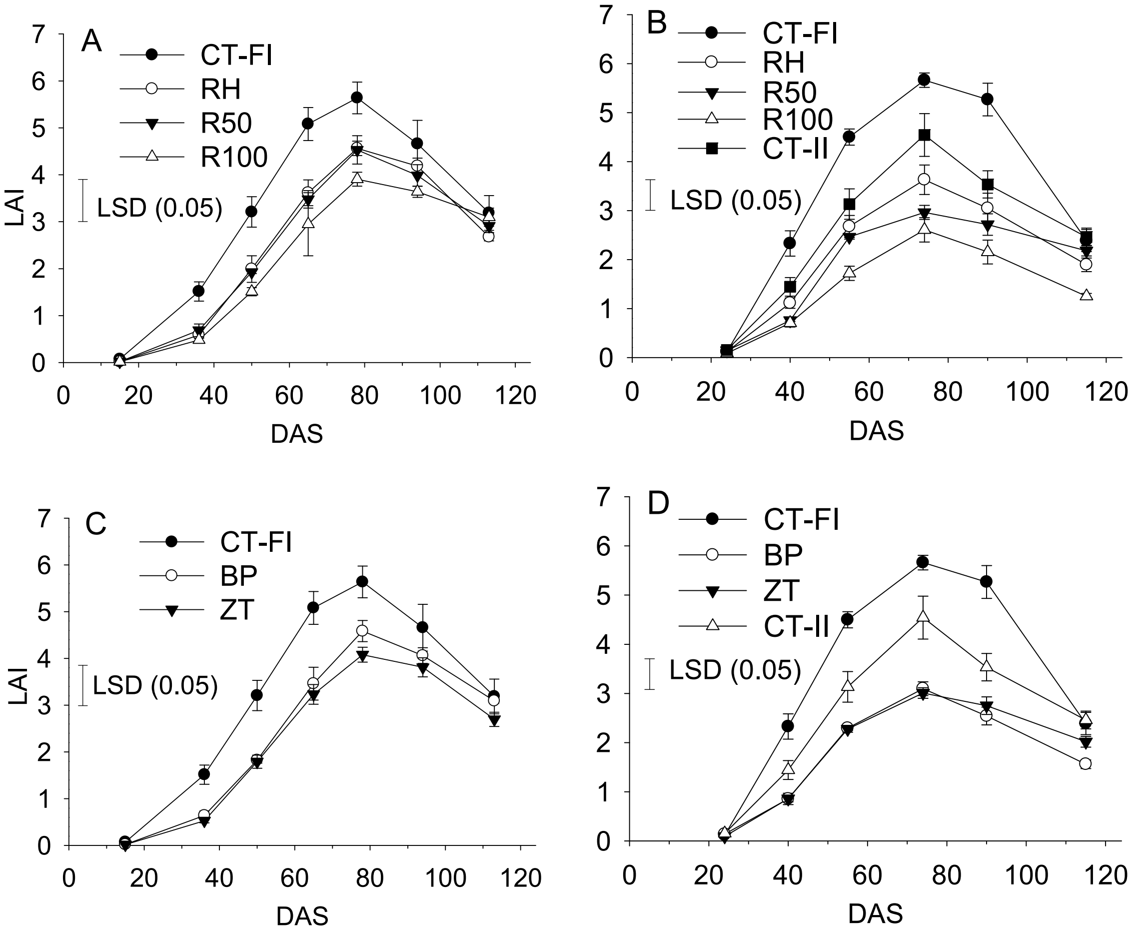


Figure 3.5 Leaf area index (LAI) development of rice as affected by irrigation methods and residue levels in 2008 (A) and 2009 (B), and tillage methods in 2008 (C) and 2009 (D); DAS=days after sowing; LSD (0.05) is difference between treatments over time at P=0.05; vertical bars indicate standard errors (for legend see Figure 3.4).

3.3.5 Root growth

The temporal trend of root biomass accumulation in all treatments was similar to that of aboveground biomass production in both years. Root dry matter accumulation under CT-FI was significanlty higher than under WAD at all growth stages in both years

(Figure 3.6). Root bimass production was not different between BP and ZT in both years, while it decreased ($p<0.05$) under higher amounts of residue in 2009. At flowering stage in 2009 in the WAD treatments, 84% of the total root dry biomass was concentrated in the surface soil layer (0-15 cm) followed by 7, 5, and 4% in 15-30, 30-45 and 45-60 cm soil depths, respectively.

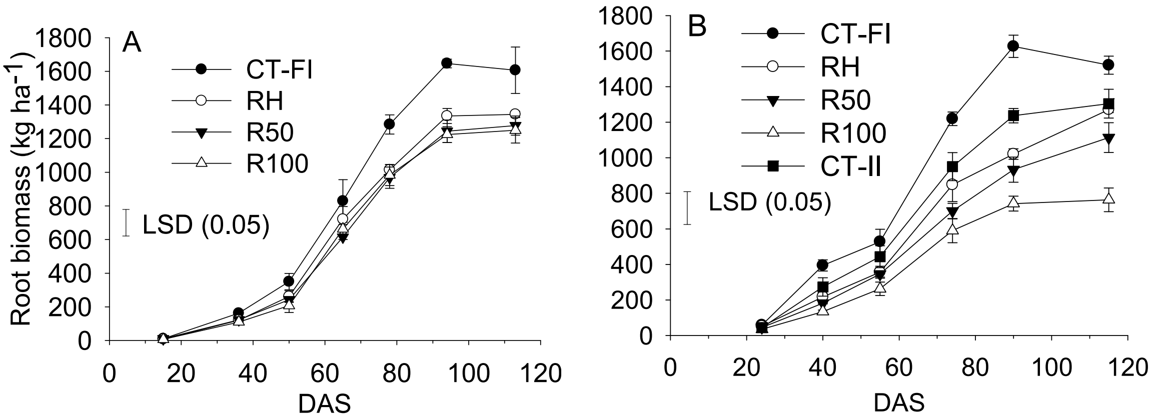


Figure 3.6 Root biomass accumulation (kg ha^{-1}) as affected by irrigation method and residue level during growing seasons 2008 (A) and 2009 (B); DAS=days after sowing; LSD (0.05) is difference between treatments over time at P=0.05; vertical bars indicate standard errors (for legend see Figure 3.4).

3.3.6 Grain yield

The averaged grain yield of rice was 33% lower ($p<0.001$) in 2009 than in 2008 (3293 vs. 4916 kg ha^{-1}). The yield reduction in 2009 in all WAD rice treatments was significant, while it was non-significant in CT-FI (Figure 3.7). The WAD rice treatments yielded less ($p<0.001$) than the CT-FI treatment, and showed an average yield reduction of 30% (4630 vs. 6633 kg ha^{-1}) in 2008 and 56% (2729 vs. 6197 kg ha^{-1}) in 2009 (Table 3.5). No significant interactions were observed between BP and ZT with the three levels of residue retention. Irrespective of residue level, rice yield was not different ($p>0.21$) between BP and ZT in both years. Although non-significant, BP had a 6% higher yield than ZT.

Insignificant differences in yield were observed between residue level in 2008, while differences were significant in 2009. Yields with RH were 28% and 40% lower than those with CT-FI in 2008 and 2009, respectively. Yield reduction in the WAD treatments increased with increasing amounts of standing residue. Irrespective of tillage, R50 showed a 2% lower yield in 2008 and 21% in 2009 than RH. Similarly, R100 showed a 10% lower yield in 2008 and 59% in 2009 than R50. CT-II had a 39% lower yield than CT-FI, while no yield difference (p=0.85) was observed between RH and CT-II in 2009.

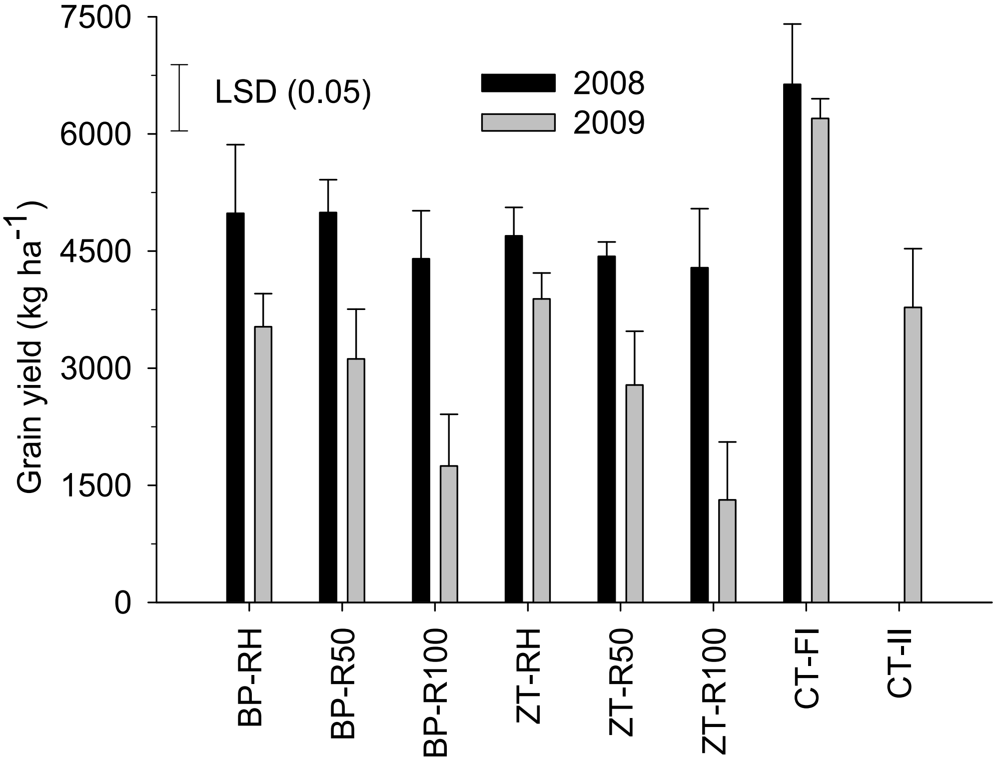


Figure 3.7 Grain yield of rice (kg ha^{-1}) under different irrigation and tillage methods and residue levels in 2008 and 2009; LSD (0.05) is difference between treatments and year at P=0.05; vertical bars indicate standard errors (for legend see Table 3.4).

There was no significant difference in grain yield between ZT-II and CT-II and also between ZT-FI and CT-FI (Figure 3.8). However, grain yield under flood irrigation (ZT-FI and CT-FI) was significantly higher than under WAD (ZT-II and CT-II).

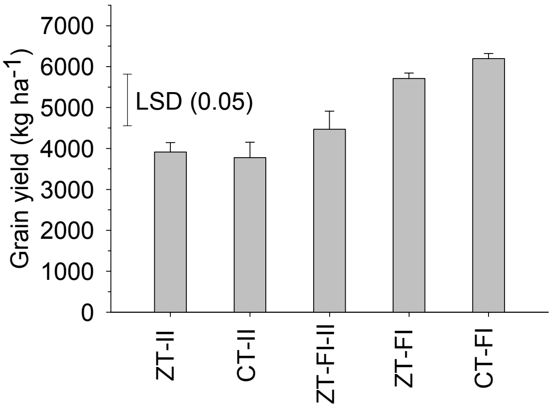


Figure 3.8 Grain yield (kg ha^{-1}) of rice as affected by different irrigation and tillage methods in 2009; ZT-II=zero tillage intermittent irrigation, CT-II=conventional tillage intermittent irrigation, ZT-FI-II=zero tillage continuous flood irrigation up to panicle initiation and intermittent irrigation thereafter, ZT-FI=zero tillage continuous flood irrigation and CT-FI=conventional tillage continuous flood irrigation. LSD (0.05) is difference between treatments at P=0.05; vertical bars indicate standard error of mean.

3.3.7 Yield components

All major rice yield components were consistently lower ($p<0.05$) in the WAD treatments compared to CT-FI in both years (Table 3.5). Interactions between BP and ZT with three levels of residue retention were not significant for all yield components. Irrespective of tillage and residue level, WAD irrigated rice had a lower number of spikelets m^{-2} (26% in 2008 and 50% in 2009), spikelets per panicle (26% in 2008 and 47% in 2009), HI (5% in 2008 and 31% in 2009), and 1000-seed weight (5% in both years) compared to the CT-FI. Rice in WAD treatments had a higher number of sterile panicles and percentage of unfilled spikelets.

The number of plants at emergence was higher ($p<0.001$) in the CT-FI than in the WAD treatments, and was not significantly different among WAD rice treatments in both years (Table 3.5). At harvest, however, the total number of plants were not significantly different among both irrigation treatments in both years. Numbers of effective panicles were not significantly different among all treatments in 2008, while they were significantly lower in the BP-R100 and ZT-R100 treatments in 2009. In 2009, panicle sterility was affected by both wet and dry irrigation and residue retention. It was highest (102 ± 7 m^{-2}) in the R100 treatments followed by R50 and RH.

The irrigation regime affected ($p<0.001$) the number of spikelets per panicle (Table 3.5). These were lower in RH than in CT-FI by 20% in 2008 and 39% in 2009. The number of spikelets was also affected by the presence of higher amounts of standing residue, with the lowest values observed in the R100 treatment followed by R50 and RH. Similarly, sink size, represented by the number of spikelets m^{-2}, showed a strong response to water regime in both years. It was lower ($p<0.01$) in the RH treatment by 22% in both years compared to CT-FI. The number of spikelets m^{-2} was further affected by residue retention.

Another major yield-limiting factor in WAD rice was the percent unfilled spikelets (Table 3.5). In 2008, this was only affected by the higher amount of residue retention; the value was higher in R100 than in RH. In 2009, it was affected both by irrigation and residue retention, with the values in RH and R100 being higher than those in CT-FI and R100, respectively.

The 1000-seed weight was higher in the CT-FI compared to the WAD treatments (Table 3.5). Unlike other yield components, it was not consistently affected by residue retention or tillage practice. The HI ranged from 42-47% in 2008 and 23-45% in 2009 (Table 3.5). It was not different ($p=0.12$) among treatments in 2008 but was affected ($p=0.001$) by irrigation in 2009. It was also affected by residue retention and was higher in RH than in R100 in 2009. All yield-determining components were consistently lower under ZT-R100 followed by BP-R100, ZT-R50, BP-R50 and RH treatments in both years.

Irrespective of residue level, averaged yield components in BP and ZT were not significantly different, but PB had more spikelets m^{-2}, higher HI and higher 1000-seed weight by 6, 5, and 3%, respectively (Table 3.5). Yield components in CT-II rice in 2009 were lower than under CT-FI rice but the differences were not significant.

Table 3.5 Yield and yield components of rice as affected by irrigation and tillage method and residue level in 2008 and 2009.

Treatment	Grain yield (kg ha^{-1})		Effective panicles (m^{-2})		Sterile panicles (m^{-2})	Spikelets (panicle^{-1})		Spikelets (m^{-2})		Unfilled spikelets (%)		1000-Seed Wt. (g)		HI (%)	
	2008	2009	2008	2009	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
BP-RH	4981b	3529bc	363	369a	36cd	70.2b	51.1bc	25558b	18809bc	14c	39b	22.06bc	21.11a	46.2	33.2b
BP-R50	4992b	3117bc	406	359a	51cd	59.1c	47.3cd	23950b	16933cd	18bc	45ab	22.78ab	21.97a	44.5	34.7b
BP-R100	4399b	1746d	397	230b	87b	57.0c	43.3cd	22608b	10041e	22ab	51a	21.88c	21.26a	43.0	31.2b
ZT-RH	4693b	3886b	419	365a	58c	56.1c	56.9b	23491b	20814b	14c	37b	22.09abc	21.46a	46.0	34.0b
ZT-R50	4430b	2782c	402	341a	103ab	54.9c	42.1de	22044b	14415d	26a	44ab	21.58c	21.48a	44.5	32.7b
ZT-R100	4286b	1313d	406	219b	117a	54.9c	39.3e	22316b	8403e	29a	42ab	20.54d	19.59b	42.2	22.7c
CT-FI	6633a	6197a	399	336a	11e	78.9a	88.6a	31474a	29693a	14c	14c	22.85a	22.13a	46.7	45.5a
CT-II	-	3777b	-	352a	34de	-	53.5bc	-	18896bc	-	43ab	-	21.68a	-	32.0b
Gross mean	4916	3293	399	323	63	61.6	52.6	24492	17426	20	39	21.97	21.34	44.8	33.3
P value	^{c}	^{c}	ns	^{c}	^{c}	^{c}	^{c}	^{c}	^{c}	^{b}	^{c}	^{c}	^{c}	ns	^{c}
LSD (0.05)	908	862	42.3	48.6	23.4	7.6	7.4	3950	3006	7.52	9.8	0.77	1.11	3.57	6.08
Contrasts¶							P>F								
RH vs. CT-FI	^{c}	^{c}	ns	ns	^{a}	^{c}	^{c}	^{c}	^{c}	ns	^{c}	^{a}	ns	ns	^{c}
PB vs. ZT	Ns	ns	ns	ns	^{b}	^{b}	ns	Ns	ns	^{a}	ns	^{c}	^{a}	ns	^{a}
RH vs. R50	Ns	^{b}	ns	ns	^{b}	^{a}	^{b}	Ns	^{c}	^{b}	^{a}	ns	ns	ns	ns
R50 vs. R100	Ns	^{c}	ns	^{c}	^{a}	ns	ns	Ns	^{c}	ns	ns	^{c}	^{c}	ns	^{c}
RH vs. R100	Ns	0.00	ns	^{c}	^{c}	^{b}	^{c}	Ns	^{c}	^{b}	^{a}	^{a}	^{a}	^{c}	^{c}
RH vs. CT-II	-	ns	-	ns	ns	-	ns	-	ns	-	ns	-	ns	-	ns
CV (%)	12.6	18.0	7.12	10.34	25.3	7.56	9.6	12.57	11.92	26.0	17.0	2.39	3.56	5.4	12.4

Contrast is shown as difference in mean values of the treatments. For treatment description see Table 3.4 and Figure 3.4. ns=nonsignificant (P>0.05),^{a} P<0.05, ^{b} P<0.01 and ^{c} P<0.001.

3.3.8 Water application and productivity

The amount of irrigation water applied differed among tillage methods in both years. The total amount of water applied to rice in the CT-FI treatment (paddy cultivation) was 66,909 and 59,058 m^3 ha^{-1} in 2008 and 2009, respectively (Table 3.6). In contrast, water quantities applied to WAD treatments were 27% (19,007 m^3 ha^{-1}) and 33% (19,280 m^3 ha^{-1}) of the total amount applied in CT-FI in 2008 and 2009, respectively. This indicates a water saving potential of 68-73% for the wet and dry irrigation. The amount of water applied in ZT was higher than in BP by 19% in both years, indicating that BP has a higher water saving potential than ZT.

Irrigation, tillage, and residue levels affected ($p<0.01$) rice water productivity in both years (Table 3.6). Water productivity was higher in WAD rice than in CT-FI except for ZT-R100 in 2009. In both years, irrespective of residue level, BP had 26% higher ($p\leq0.01$) water productivity than ZT. The RH treatments had higher water productivity than the residue retained treatments. In both years, ZT-R100 had the lowest water productivity among the WAD treatments, and this was even lower than under CT-FI in 2009. Water productivity in the CT-II treatment was the same as in the RH treatments of WAD rice.

Table 3.6 Irrigation water application (m^3) and water productivity ($g\ m^{-3}$) of rice grown under different irrigation and tillage methods and residue levels in 2008 and 2009.

Treatment[a]	Irrigation water applied (m^3)		Water productivity ($g\ m^{-3}$)	
	2008	2009	2008	2009
BP-RH	17,362	17,680	309a	224a
BP-R50	17,362	17,680	311a	198a
BP-R100	17,362	17,680	274ab	110cd
ZT-RH	20,651	20,880	247bc	210a
ZT-R50	20,651	20,880	231bc	147bc
ZT-R100	20,651	20,880	224c	70d
CT-FI	66,909	59,058	108d	117cd
CT-II	-	21,705	-	194ab
Gross mean	-	-	243	159
P value	-	-	[b]	[b]
LSD (0.05)	-	-	45.6	48.7
CV (%)	-	-	12.6	21.1

[a] For treatment descriptions see Table 3.4. [b] $P<0.001$.

3.3.9 Soil mineral nitrogen

The initial soil mineral N was higher in 2008 than in 2009 in all treatments. The total soil mineral N content in 0-80 cm soil depth was higher in the CT-FI than in the WAD treatments during the main rice growth stages in both years. It was higher under CT-FI than under RH by 12 and 42% at panicle initiation and by 8 and 24% at flowering stage in 2008 and 2009, respectively (Figure 3.9). In both years, however, soil mineral N was not significantly different among different residue levels after the panicle initiation stage.

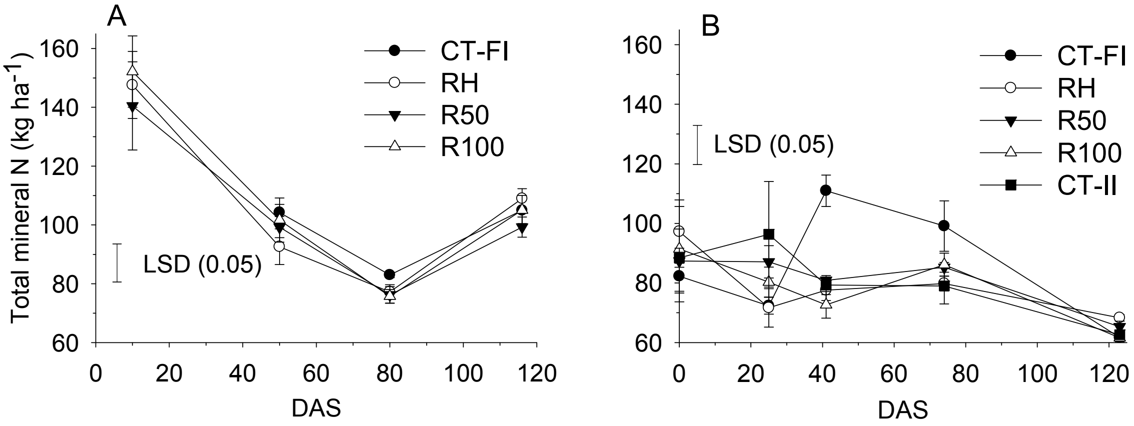


Figure 3.9 Total mineral N (kg ha^{-1}) in 0-80 cm soil depth under different residue levels in 2008 (A) and 2009 (B); DAS=days after sowing; LSD (0.05) is difference between treatments over time at P=0.05; vertical bars indicate standard errors (for legend see Figure 3.4).

3.3.10 Plant N concentration and N uptake

In all treatments, the average vegetative plant and leaf N concentration decreased over time and the treatment effect disappeared at around 50-60 DAS in both years. In 2008, the N concentration of the aboveground vegetative organs was highest in ZT-R100 and lowest in CT-FI at all crop growth stages (Figures 3.10A). In 2009, the WAD treatments showed higher plant N concentration compared to CT-FI before the panicle initiation stage, while after that, this gradually decreased and was higher in CT-FI (Figures 3.10B). Plant N concentration was not significantly different between BP and ZT with all levels of residue retention in both years. A similar trend as that for aboveground vegetative plant N concentration was observed for leaf N concentration in both years (Figures 3.10C and 3.10D).

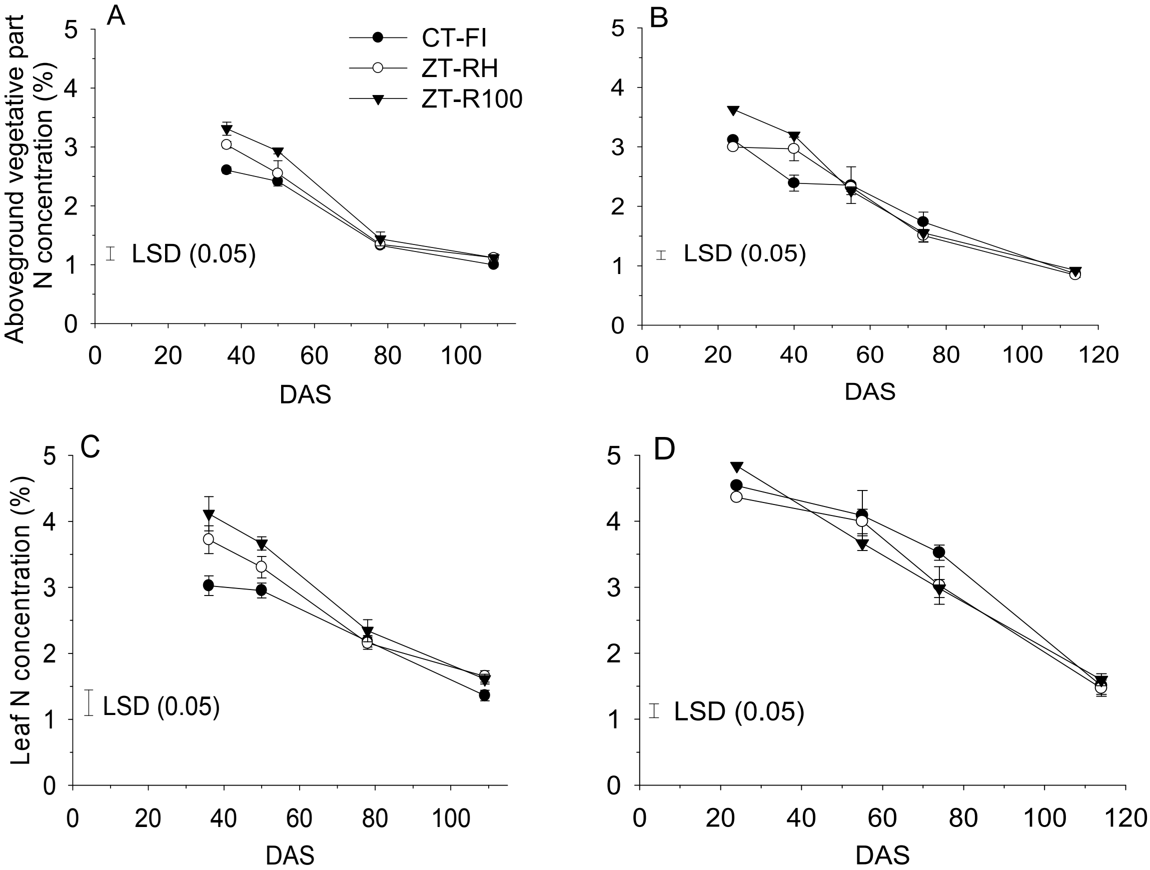


Figure 3.10 Aboveground vegetative plant N concentration (%) and leaf N concentration (%) in rice during the growing seasons 2008 (A, C) and 2009 (B, D), respectively, as affected by residue retention level and irrigation method; DAS=days after sowing; LSD (0.05) is difference between treatments over time at P=0.05 (for legend see Table 3.4).

The rice grain N concentration was higher in 2009 than in 2008. Compared to CT-FI, values were higher ($p<0.05$) in the WAD treatments in both years (Figure 3.11).

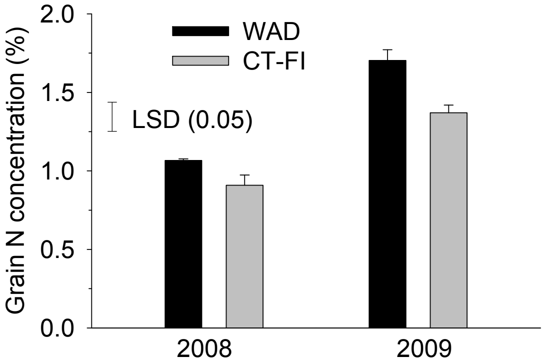


Figure 3.11 Rice grain N concentration (%) at harvest as affected by irrigation method; WAD=intermittent wet and dry irrigation, CT-FI=conventional tillage flood irrigation; LSD is difference between treatments and year at P=0.05.

The total N accumulation in aboveground rice biomass at physiological maturity ranged from 104-145 kg ha^{-1} in 2008 and 52-139 kg ha^{-1} in 2009 (Figure 3.12). At most of the sampling dates N accumulation was consistently higher ($p<0.05$) in the CT-FI than in the WAD treatments. Irrespective of tillage, RH treatments had consistently higher N uptake followed by R50 and R100 in both years; it was significantly higher in 2009. Irrespective of residue level, N uptake was not significantly different between BP and ZT in both years, and between CT-II and RH treatments in 2009.

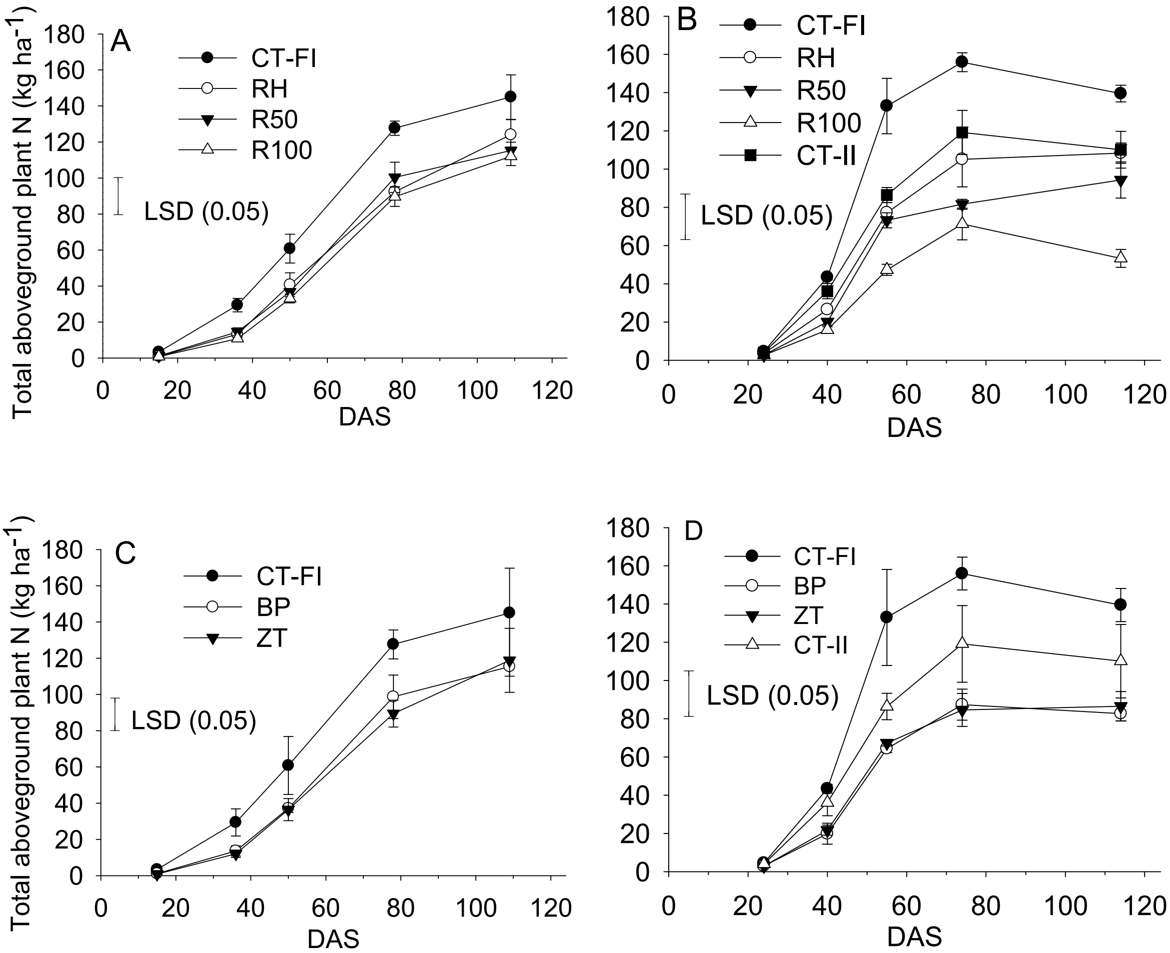


Figure 3.12 Aboveground total plant N accumulation (kg ha^{-1}) in rice under different irrigation methods and residue retention levels in 2008 (A) and 2009 (B) and under different tillage methods in 2008 (C) and 2009 (D); DAS=days after sowing; LSD (0.05) is difference between treatments over time at P=0.05 (for legend see Figure 3.4).

3.3.11 Soil tempreature

The soil temperatures measured at 10 and 30 cm depths were negatively affected by the quantity of residues retained in the plots (Figure 3.13). Temperatures in the RH treatments were higher by 1.0 °C d^{-1} at 10 cm and 1.5 °C d^{-1} at 30 cm soil depths. Differences in soil temperature between these treatments were more pronounced after the panicle initiation stage (40-45 DAS).

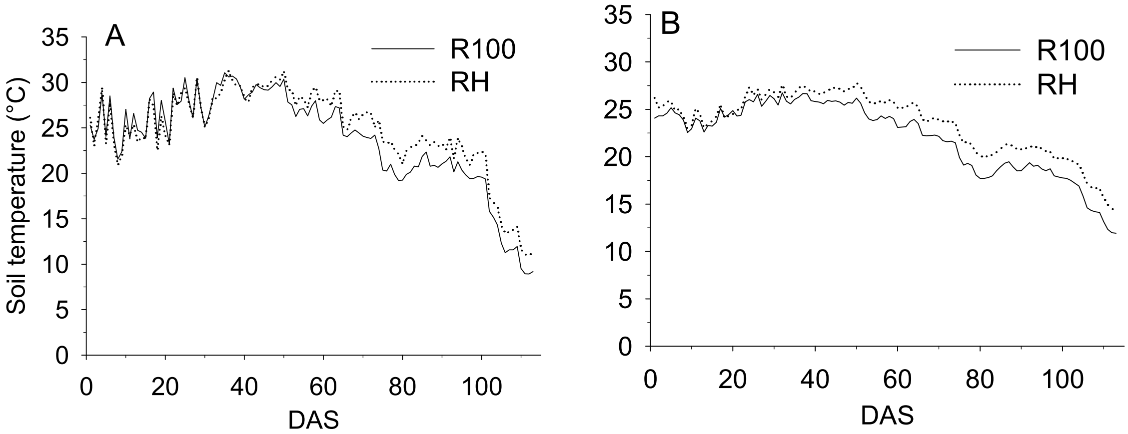


Figure 3.13 Daily soil temperature (°C) dynamics over the season as measured at 6:00 pm at 10 cm (A) and 30 cm (B) depths in residue harvested (RH) and 100% residue retained (R100) treatments in 2009; DAS=days after sowing; averaged standard error at 10 cm depth is 3.6% of the mean in R100 and 3.1% in RH, and at 30 cm is 5.1% in R100 and 4.5% in RH.

3.3.12 Correlation coefficients between different variables

There were strong positive correlations between grain yield and yield components. Correlations between grain yield and aboveground biomass production are (r=0.92**), spikelet m^{-2} (r=0.99**), grains per panicle (r=0.96**), 1000-seed weight (r=0.73*), and unfilled spikelets percentage (r=-0.85**) (Table 3.7). Similarly, there is a strong correlation between grain yield and yield components with water applied and N uptake, but a strong negative correlation with the amount of residue retention.

Table 3.7 Pearsons' correlation coefficients (r) between rice grain yield (yield) (kg ha^{-1}), total aboveground biomass (AGB) (kg ha^{-1}), panicles m^{-2} (PPm^{-2}), filled grains per panicle (FGPP), spikelets m^{-2} (SPm^{-2}), unfilled spikelets percentage (USP), 1000-seed weight (TSW) (g), HI (%), water applied (WA) (m^{3} ha^{-1}), N uptake (kg ha^{-1}) and amount of residue retained (RR) (kg ha^{-1}) in rice 2008-2009.

	Yield	AGB	PPm^{-2}	FGPP	SPm^{-2}	USP	TSW	HI	WA	N uptake
Yield	-	-	-	-	-	-	-	-	-	-
AGB	0.92^{b}	-	-	-	-	-	-	-	-	-
PPm^{-2}	0.56ns	0.59ns	-	-	-	-	-	-	-	-
FGPP	0.96^{b}	0.85^{a}	0.34ns	-	-	-	-	-	-	-
SPm^{-2}	0.99^{b}	0.89^{b}	0.57ns	0.97^{b}	-	-	-	-	-	-
USP	-0.85^{a}	-0.60ns	-0.47ns	-0.86^{a}	-0.89^{b}	-	-	-	-	-
TSW	0.73^{a}	0.69^{a}	0.66^{a}	0.60ns	0.70^{a}	-0.51ns	-	-	-	-
HI	0.82^{a}	0.55ns	0.56ns	0.78^{a}	0.84^{a}	-0.92^{b}	0.71^{a}	-	-	-
WA	0.86^{a}	0.73^{a}	0.14ns	0.91^{b}	0.84^{a}	-0.73^{a}	0.43ns	0.65^{a}	-	-
N uptake	0.93^{b}	0.93^{b}	0.72^{a}	0.84^{b}	0.93^{b}	-0.76^{a}	0.61ns	0.68^{a}	0.71^{a}	-
RR	-0.71^{a}	-0.87^{b}	-0.73^{a}	-0.60ns	-0.71^{a}	0.45ns	-0.56ns	-0.40ns	-0.36ns	-0.87^{b}

Data were pooled over treatments and 2008 and 2009; n=8, ns=nonsignificant ($P>0.05$), $^{a}P<0.05$, $^{b}P<0.01$ and $^{c}P<0.001$.

3.4 Discussion

Rice production in arid drylands suffers presently from an application of large amounts of irrigation water to maintain flooded conditions. Previous studies, especially those conducted under warm tropical conditions have shown possibilities for reducing water application rates for rice cultivation through the use of water-saving irrigation combined with conservation agriculture practices, although these also experiencing concurrently yield reductions (Bouman and Tuong 2001; Jat et al. 2009; Bhushan et al. 2007). The causes of such yield reductions had been numerous, and turned out to be depending on climatic conditions or location (Kreye et al. 2009; Singh et al. 2011; Gathala et al. 2006; Belder et al. 2004; Kato et al. 2009). Before the introduction of such water-saving and CA practices in the rice-growing regions of Central Asia, it was therefore compulsory to identify the potential of these practices and possible magnitudes of yield reduction in rice. The results of this study indicate that when using suitable anaerobic rice varieties such as Nukus-2, a change in the rice cultivation method from flood-irrigated (CT-FI treatment) to wet and dry (WAD) irrigation combined with CA practices saved 68-73% irrigation water but reduced crop yields by 30-56% as previously observed in other regions. The discrepancies in rice yield reduction and water saving between this study and previous studies are likely to be caused by the differences in soil hydrological properties, the duration and method of irrigation, and crop and soil management practices.

The relatively high yield gap between conventional flood-irrigated and water-saving irrigation of rice compared to that in similar experiments conducted in tropical regions could also be due to the difference in climatic conditions. The higher yield gap between flooded and non-flooded rice in semi-arid regions of India (Singh et al. 2011; Jat et al. 2009; Saharawat et al. 2010), and no yield difference in tropical regions of Japan and China (Zhang et al. 2008; Tuong et al. 2005; Won et al. 2005; Yang et al. 2007) further support this. In this study, WAD irrigation (Figure 3.2) caused crop-water stress, which in turn may have caused a reduction in soil-mineral N (Figure 3.9). Furthermore, the retention of high amounts of standing residues decreased soil temperatures (Figure 3.13) and light interception through shading. These water and residue effects delayed phenological development (Table 3.4), reduced biomass production (Figure 3.4), leaf area index (LAI; Figure 3.5), root growth (Figure 3.6), and N uptake (Figure 3.12), which all contributed to reduced grain yield (Figure 3.7) caused by reduction of major yield components (Table 3.5).

The lower rice yield in the CT-FI treatment in 2009 compared to 2008 may be explained by differences in the micro-climatic conditions during the rice-growing period. The minimum critical temperature for grain filling of rice is reportedly 12-18 °C (Yoshida 1981). In this study, the minimum temperature during the grain-filling period (after 70 DAS) did not exceed 11.8 °C in 2008 and 10.3 °C in 2009.

3.4.1 Effect of irrigation method

Under alternate wet and dry conditions (submergence-non-submergence), anaerobic rice varieties cannot cope with the experienced water-stress effects when the soil water potential during the dry (non-submergence) phase reaches 0 to -30 kPa (Belder et al. 2004; Bouman and Tuong 2001; Lu et al. 2000; O’Toole and Baldia 1982; Wopereis et al. 1996). The seasonal average soil water potential of -12 kPa (-5 to -42 kPa) in 20 cm and -3 to -26 kPa in 50 cm soil depths in the WAD irrigated plots (Figure 3.2) confirms that rice was under water-stress conditions in these treatments.

Consequently, the lower aboveground biomass (Figure 3.4) and LAI (Figure 3.5) with WAD irrigation compared to CT-FI at all growth stages indicates reduced leaf surface area expansion at soil water potentials higher than field capacity (-10 kPa). Similar findings of reduced LAI when the soil water potential was allowed to drop to -10 to -30 kPa in alternate wet and dry irrigation was observed by Belder et al. (2004), Lu et al. (2001), Bouman and Tuong (2001) and Yoshida (1981). Leaf area expansion reduces in most cultivars as soon as the soil dries below saturation (Lilley and Fukai 1994; Wopereis et al. 1996). Photosynthesis was not measured in this study, but the above-mentioned reduction in leaf area (by reduced leaf expansion, rolling, and senescence) results in reduced light interception, which in turn reduces total crop photosynthesis, and a reduction in total biomass production is to be expected.

The clearly delayed phenological development in the WAD treatment (Table 3.4) was observed in other studies (Wopereis et al. 1996; Bouman and Tuong 2001; Boonjung and Fukai 1996; Puckridge and O'Toole 1981; Yoshida 1981) and was attributed to the frequently imposed water stressed periods of the non-flooded conditions. As the WAD treatments were intermittently irrigated from 15 DAS onwards, it is highly likely that the rice variety used was, despite its reputation in the study region of being able to cope with water stress, not able to tolerate water stress during critical growth stages, since the effect of water stress on yield is most severe when drought occurs during panicle development (Boonjung and Fukai 1996).

Rice is very susceptible to water stress in the period around flowering, since reduced water availability causes spikelet sterility (Lu et al. 2001; Wopereis et al. 1996; Cruz et al. 1986; Ekanayake et al. 1989). This was confirmed in this study by the strong positive correlation between grain yield and the number of spikelets m^{-2} (Table 3.7), which indicates that the yield difference between the CT-FI and WAD treatments was correlated with a reduction in sink size (spikelets m^{-2}). The low number of spikelets m^{-2} and high number of sterile panicles m^{-2} in combination with a high percentage of unfilled spikelets indicates that the number of spikelets m^{-2} in the WAD treatments was affected more by factors other than emergence and crop establishment. These did not differ, but factors that interfered later in the growing season such as water stress during panicle initiation and development did differ.

The effect of water stress during this crucial growth period could have been caused by three factors: (i) alternate drying and wetting cycle prolonged the tillering phase in WAD irrigated rice, which in turn caused a production of a higher number of sterile panicles, (ii) since rice under the CA practices was drilled in 2 cm depth at 20-30 cm row spacing using a relatively high seed rate (140 kg ha^{-1}), this could have increased competition among the plants for nutrients and water within the row, while the larger inter-row space was under-utilized. Also increased weed infestation in these open spaces could have further contributed to a reduction in grain yield although this was not measured, (iii) the low harvest index in WAD irrigated rice in 2009 indicates a lower partitioning of carbohydrates and nitrogen from the vegetative organs to the grain.

Although at present it cannot be ascertained which of these three or whether a combination of these phenomena contributed (most) to the reduction in spikelets m^{-2} and hence yield in the WAD treatments, it is without doubt that this reduction per se caused the yield reductions as postulated previously. For example, Kato et al. (2009) reported a reduction in the number of spikelets m^{-2} of 36% under non-flooded conditions in Japan, whilst a reduction of 13-37% was observed in dry- and 8-32% in wet-season rice in the Philippines (Peng et al. 2006), and of 38% in the USA (Obermuller and Millelsen 1973). Hence, the findings in this study together with those of other researchers (Kato et al. 2009; Peng et al. 2006; Obermuller and Millelsen 1973) confirm the positive correlation between filled grains per panicle with water use, and hence the water-stress-induced spikelet sterility in the WAD treatments.

A high percentage of filled grains is key to higher yields and harvest indices of rice under non-flooded (aerobic) conditions (Bouman et al. 2006). An increased number of unfilled spikelets under water stress at heading and flowering stages was also observed by Cruz et al. (1986), Wopereis et al. (1996), Li (1999) and Zhang et al. (1994). This is also confirmed by the positive correlation between harvest index with water use (Table 3.7), which indicates that water stress reduced dry matter partitioning to the grains in the WAD treatments. A reduced harvest index under water-saving technologies compared to paddy rice practices was also monitored by Ockerby and Fukai (2001).

Aside from the underlying traits, the WAD treatment reduced rice root growth substantially (Figure 3.6). Since all WAD treatments were irrigated in 1-5-day intervals, the rice plants thus experienced a frequent cycle of aerobic and anaerobic conditions (Forkutsa 2011, forthcoming), which may have affected not only panicle initiation and development but also root growth. Roots in the WAD treatments expanded horizontally rather than vertically, and most of the roots were in the upper soil layers, which is in line with previous findings by Fagi and Kartaatmadja (2002) and Giessen (1942) who postulated that under rapid dry-wet transitions, root growth becomes slow and reduced. It was generally indicated in previous studies that during the dry phase (oxidized conditions), a dry (aerobic) root system is formed, while when fields are flooded (reduced soil conditions), all dry roots gradually die and a wet-root (anaerobic) system is formed (Fagi and Kartaatmadja 2002). This would indicate that in the WAD irrigation treatments, instead of a rapid gain in root biomass, a continuous cycle of root formation and degeneration had taken place. A reduced root growth is also indicated by the observed stagnant crop growth (especially in 2009) in these treatments, which agrees with observations by Heenan and Thompson (1984), Banba and Ohkubo (1981) and Kukal et al. (2008) under intermittent irrigation and non-flooded conditions.

The lower N uptake (Figure 3.12) of rice in the WAD treatments was mainly due to slower growth rate and lower biomass accumulation than under CT-FI. The lower plant and leaf N concentration under CT-FI during the vegetative growth stages in both years can be attributed to the N dilution effect as a result of faster growth rate and higher amount of biomass accumulation. In contrast, higher N concentration under WAD conditions, especially in the ZT-R100 treatment, could have been due to the slower biomass production (Figure 3.4) and phenological development of rice (Table 3.4) compared to CT-FI. The comparatively lower leaf N concentration in WAD rice than in CT-FI in 2009 at flowering (Figure 3.10) corresponds with the lower mineral N content in the soil profile around the same period (Figure 3.9), indicating that rice in the WAD treatments was under N stress. This could be possible, as a higher amount of mineral N could have been lost from the WAD irrigation plots (Chapter 4). Due to frequent wet and dry periods, the soil redox potential changes rapidly, which could have accelerated the rapid N losses (Vlek and Craswell 1981). As N was always broadcasted in these experiments, except for one drill application during seeding in 2008 (Table 3.3), a significant N loss especially in the WAD treatments can be assumed. The drilling of 80 kg N ha^{-1} at seeding could also be the reason for the higher initial amount of mineral N in the soil profile in the WAD treatments in 2008 than in 2009, which could have led to the faster initial growth and development and higher rice yield.

The significant negative correlation between grain protein and physiological N use efficiency (-0.73*), grain yield (-0.67ns), remobilized N (-0.93**) and water use (-0.65ns) indicates that grain protein was affected by irrigation methods. A similar higher grain protein in rice grown under deficit irrigation conditions (Figure 3.11) was also reported by Pirmoradian et al. (2004) in Iran.

3.4.2 Effect of tillage and residue retention

The non-significant differences in growth (Figure 3.4), phenology (Table 3.4), N uptake (Figure 3.12), grain yield (Figure 3.7), and yield components (Table 3.5) of rice between the RH treatments under BP and ZT and CT-II (Figure 3.7) indicate that there is no significant effect of tillage on rice production. Further, no significant yield difference between ZT-II and CT-II and between ZT-FI and CT-FI (Figure 3.8) indicates that soil tillage had no effect on grain yield.

The decreased grain yield under the residue-retained treatments could have been caused by multiple factors, such as delayed seedling emergence (Table 3.4), slower growth and development rates (Figure 3.4 and 3.5), and lower N uptake (Figure 3.12). This in turn could have reduced the number of spikelets m^{-2}, increased the percentage of unfilled spikelets, and reduced the harvest index (Table 3.5). In any case, an increased level of crop residue retention caused differences in light interception, soil and canopy temperatures, and perhaps N loss via immobilization and/or denitrification or leaching. As the phenological development was delayed in the treatments with higher amounts of retained residue, the grain-filling and maturity periods (after September 10) coincided with a period of low temperatures of less than 13 °C; the critical threshold for grain filling is reportedly between 12 °C and 18 °C (Yoshida 1981; Borrell et al. 1997). Furthermore, low temperatures also induce spikelet sterility even if there is sufficient growth in other plant components (Matthews et al. 1995).

Consistently low soil temperatures under zero tillage conditions with residue retention as previously observed (Bazaya et al. 2009) and as experienced in the R100 treatments (Figure 3.13) might have limited the biological activity of the rice root system and inhibited the roots' capacity to absorb nutrients (Liu et al. 2003). Higher temperatures in the topsoil promote metabolic processes (Lavahun et al. 1996), which increase nutrient absorption and uptake (Bazaya et al. 2009). Besides lowering the soil temperature, the high amounts of standing residue retained under R100 had an observable shading effect on the rice up to the booting stage. This reduced light interception and could thus have reduced growth and delayed phenological development. In 2009, the high cumulative amounts of 11.3 t ha^{-1} standing residue in the R100 and 7.0 t ha^{-1} in the R50 treatments therefore very likely significantly reduced soil temperatures and light interception. A previous study by Singh et al. (2008) indicates that mulching of as low as 6 t ha^{-1} already caused a significant reduction in the yield of direct-seeded rice on permanent beds in three out of the four study years. Hence, although residue retention is seen as one of the pillars of CA, site-specific recommendations need to be developed regarding the amounts to be retained and their management. Obvious is that insufficient amounts of retained residue will not bring about effects such as increased soil-organic carbon and total nitrogen (Chivenge et al. 2007) and weed control (Teosdale et al. 1991), whilst too much residue may cause yield reductions in rice as observed in this study.

3.4.3 Water productivity and water-saving potential

Despite yield reductions, an almost two times higher water productivity and three times lower water application in the residue harvested (RH) treatments with WAD irrigation than in the CT-FI treatments in both years (Table 3.6) suggests that under diminishing water supply conditions, dry-direct seeded rice on raised beds or zero tillage flat land can be an alternative option for the arid regions of Central Asia, especially when using suitable rice varieties. Furthermore, the higher water productivity in BP than under ZT conditions (Table 3.6) suggests that water application in rice can be reduced without yield reduction (Figure 3.7). However, as higher amounts of standing residues led to a negative impact on rice growth, development, yield and yield components and thus on water productivity, alternative residue management options need to be developed.

Studies in various parts of the world show that 25-35% of irrigation water can be saved under permanent raised beds (Sayre and Hobbs 2004). The lower amount of irrigation water application in BP could be due to the steady flow of water in the furrows and to furrow compaction through the tractor wheels resulting in less percolation and increased lateral movement of water. Higher water productivity under alternate wet and dry irrigation than under conventional flood irrigation has also been reported by Belder et al. (2005b) and Bouman and Tuong (2001). Similar findings on higher water productivity of direct seeded rice in BP and ZT than with conventional methods have been reported by Jat et al. (2009), Bhushan et al. (2007) and Saharawat et al. (2010) in rice-wheat systems of southeast Asia.

There is a further potential to increase water productivity through the use of rice varieties suitable for non-flooded conditions. The rice variety used in this study was released and adopted for flood-irrigated conditions. As the morphological and physiological response of the same rice variety grown under flooded and non-flooded conditions differs (Senewiratne and Mikkelsen 1961), the rice variety for non-flooded aerobic conditions should be different. The author of this study is not aware of any published reports of rice varieties that consistently grow better and yield more under aerobic soil conditions. Thus, as described by Gupta and Seth (2007), rice production under WAD conditions may first require the development of high-yielding improved aerobic rice varieties with early seedling vigor, high tillering and fast canopy cover (Singh et al. 2003), tolerance to occasional drought and submergence, thick and deep-penetrating roots, and better input responsiveness (Farooq et al. 2009).

Yields in the RH treatments of WAD irrigated rice in 2009 were 34% and 15% higher and -3% lower compared to the average yield of rice in Central Asia, Uzbekistan and Khorezm, respectively (based on data from FAOSTAT 2009). Water application for early maturing varieties under wet-direct seeded conditions in arid regions exceeds 40,000 m^3 ha^{-1} (Aldaya et al. 2010) and 30,000 m^3 ha^{-1} under transplanted conditions (FAO 1997). All evidence combined shows that by growing rice under residue-harvested WAD conditions, it is possible to achieve 35-55% water saving while maintaining the average regional and national productivity.

3.5 Conclusions

In this study, water-saving irrigation methods combined with CA practices has large water saving potential (68-73%) compared to the present rice cultivation practices in Uzbekistan, but this could reduce yields considerably. The consequent reduction in growth, delayed phenological development, impaired root growth, reduction in number of spikelets and increase unfilled grains are the key causes for the yield decline under the water-saving irrigation and residue-retained treatments. This was largely due to the fact that the variety (Nukus-2) was unable to cope with the water stress imposed during the rice grain setting phase. This could be bypassed by flooding such varieties during this phase. As long as farmers in the study region do not pay directly for the water use, the incentives of water saving perhaps are insufficient to implement water-saving practices.

Furthermore, yield reductions were also caused by high levels of residue retention, which had caused shading. A certain N stress under alternate wet and dry irrigation was also observed. This calls for both increased knowledge on crop residue management and increased N management when introducing CA practices in rice-wheat rotations. Based on the comparisons among the RH treatments of BP and ZT, CT-II and CT-FI, the conventional method of tillage and field preparation did not have any beneficial effect on rice yield. Despite the lower yield, the concept of WAD rice combined with CA practices cannot be disregarded as it has a high water saving potential. But further studies are needed using suitable rice varieties to determine the success of improved agronomic practices with respect to preventing N loss, increasing radiation interception, and provoking faster canopy cover, e.g., proper residue management, optimized amount and time of irrigation, drilling of N to appropriate soil depths, strip-till transplanting in permanent raised beds and untilled ZT flats lands, and the use of improved aerobic rice varieties.

4 MINERAL NITROGEN DYNAMICS IN IRRIGATED RICE-WHEAT SYSTEM UNDER DIFFERENT IRRIGATION AND TILLAGE METHODS AND RESIDUE LEVELS IN ARID DRYLANDS OF CENTRAL ASIA

4.1 Introduction

Rice is an important part of the national diet particularly in Uzbekistan, Kazakhstan and Tajikistan, where it forms the basis for the national dish pilov (Nesbitt et al. 2010). The per capita consumption in this region is about 20 to 25 kg (Ismali 2006). Most of the present demand is met through imports. Rice is mostly cultivated in rice-wheat cropping systems in the irrigated lowland areas of the Amu Darya and Syr Darya river basins (Gupta et al. 2009). Although rice is a highly renumerative crop in the region, its area has been decreasing mostly due to the decreasing availability of irrigation water (Gupta et al. 2009; Christmann et al. 2009).

Nitrogen (N) is the most limiting nutrient for crop production in rice-based cropping systems (Thuy et al. 2008). Nitrogen dynamics in flood-irrigated rice have been extensively studied (De Datta and Buresh 1989; Buresh and De Datta 1991; George et al. 1992; Kundu and Ladha 1995). These studies have shown that N transformation processes, i.e., mineralization-immobilization, nitrification-denitrification, NH_4 fixation, NH_3 volatilization, leaching, and run-off, lead to high N losses. These processes are largely controlled by O_2 fluxes, soil-water content, NO_3-N content, carbon supply, temperature, pH, soil texture, etc. (Mikkelsen 1987; Scheer 2008). At a water-filled pore space (WFPS) above 80%, the oxygen content in the soil is low and nitrification ceases, whereas highest nitrification activity is expected at 30-60% WFPS (Firestone and Davidson 1989). Denitrification levels have been reported to increase with increasing soil moisture (Scholefield et al. 1997), and highest denitrification rates were found at a WFPS above 60% (Davidson 1991; Bouwman 1996; Linn and Doran 1984).

Conservation agriculture (CA) practices like minimum tillage, crop residue retention and proper crop rotation has become increasingly popular in rice cultivation in southern USA (Griggs et al. 2007) and have the potential to cover a large area in the Indo-Gangetic Plains (Saharawat et al. 2010). Direct seeded rice (DSR) and wheat on permanent raised beds and zero tillage flats have been proposed for rice–wheat cropping systems as a means to increase irrigation water productivity (Rejesus et al. 2011; Kukal et al. 2010), to avoid the deleterious effects of puddling on soil structure and fertility, to improve water- and nutrient-use efficiency (Timsina and Conner 2001), and to reduce production cost (Jat et al. 2009; Bhushan et al. 2007). Dry-direct seeded rice using water-saving frequent alternate wet and dry irrigation tends to reduce water application. This method leads to increased N loss mostly through denitrification due to the fluctuating soil moisture and soil redox potential. Several studies conducted in the past (O'Toole and Baldia 1982; MacRae et al. 1968; Patrick and Wyatt 1964) have reported a severe N loss when soil is subjected to alternate anaerobic (flooding) and aerobic (drying) conditions. A loss of 15 to 20% of the total soil N (Patrick and Wyatt 1964) and 24% of the total soil N in 2-by-2-day aerobic-anaerobic conditions (Reddy and Patrick 1976) has been reported.

Mineral nitrogen dynamics in dry-direct seeded rice under alternate wet and dry irrigation is different to continuously flood irrigated. In continuous flood-irrigated rice, as the soil is mostly under anaerobic conditions, ammonium nitrogen (NH_4-N) is mostly available (Vlek and Byrnes 1986), while under aerobic conditions N is available mostly in the form of nitrate nitrogen (NO_3-N) (George et al. 1992). Under frequent wet and dry irrigation, the drying phase of the soil favors aerobic-N transformation, resulting in nitrification and increased accumulation of NO_3 (George et al. 1992). Since conversion of NO_3 to NH_4 is negligible, the accumulated NO_3-N is prone to losses either by denitrification or leaching upon soil flooding unless roots are active in uptake (Ponnamperuma 1985; Buresh et al. 1989; George et al. 1992).

Intensive soil tillage accelerates N mineralization of crop residues and soil organic N (Sainju and Singh 2001) and increases accumulation of NO_3-N in the soil profile (Al-Kaisi and Licht 2004). Increased accumulation of NO_3-N in the soil profile increases the potential for N leaching to shallow water tables (Keeney and Follett 1991). Thus, availability of soil mineral N (NO_3- and NH_4-N) in the soil and the rate of uptake by rice and wheat crops may differ with tillage method. The addition of crop residue can affect the transformation and distribution of fertilizer N into different soil-N fractions (Chou et al. 1982), and higher N loss has been reported with residue retention or incorporation through denitrification (Aulakh et al. 1984) or immobilization (Quemada and Cabrera 1995).

Nitrogen dynamics of dry-direct seeded rice-(aerobic, anaerobic)-wheat (well drained, aerobic) rotation vary greatly because of the difference in soil management. Major inputs of N in rice-wheat systems include fertilizer, irrigation water, precipitation, N from residue decomposition, and biological N_2 fixation. Nitrogen losses or removals result from leaching, runoff, denitrification, NH_3 volatilization as well as from uptake by the crop plants. Diverse results are reported regarding the N loss from rice-wheat systems. In a study in Japan, (Ogawa 2000 as cited in Kyaw 2005) reported paddy fields as a site of N loss, as N inputs were higher (229 kg ha^{-1}) than N outputs (187 kg ha^{-1}), where N was mostly lost by downward leaching. The annual N balance is (34 to 93 kg ha^{-1} under rainfed and -17 to 9 kg ha^{-1} under irrigated condition) in rice-wheat system of northern Bangladesh (Timsina et al. 2001). Similarly, a positive N balance (77 to 308 kg N ha^{-1}) is reported in various rice-based cropping systems in India (Sadanandan and Mahapatra 1973). However, Pathak et al. (2006) reported negative N balance of (-19 to -71 kg N ha^{-1}) in Indo-Gangetic Plains which was attributed to higher N uptake and yield and reduction of total soil N. In all these studies, rice was grown under flood irrigated conditions. In a rice-wheat system in a semi-arid region in India, N losses through N_2O emissions as high as 58 kg N ha^{-1} from rice and 5-8 kg ha^{-1} from wheat with 120 kg N application were observed (Aulakh et al. 2001). In rice, 50% of the applied N can be unaccounted for and presumably lost via denitrification (Rekhi et al. 1982; Katyal et al. 1985; Panda et al. 1995).

Information on N dynamics and N balance are essential to increase the N use efficiency through minimizing N losses, to determine fertilizer recommendations, and to develop appropriate crop management practices for rice-wheat systems under different water saving irrigation methods combined with CA practices to make the system sustainable. Although much is known about the N losses in paddy rice, the N dynamics in rice grown under CA practices (tillage and residue retention) and water-saving practices have not yet been studied, particularly in Central Asia. This also applies to the N balance in a rice-wheat rotation. Thus, the objective of this study was to examine mineral N dynamics in a rice-wheat system seeded under water-saving wet and dry irrigation, residue retention and tillage methods in arid drylands of Central Asia.

4.2 Materials and methods

4.2.1 Experimental site

Experiments were carried out at the Cotton Research Institute, in the Khorezm region of northwest Uzbekistan (60.05°- 61.39° N and 41.13°-42.02° E, 100 m asl) from 2008-2009. The region has an average annual precipitation of less than 100 mm and the potential evapotranspiration (>1100 mm year^{-1}) always greatly exceeds precipitation (Forkutsa, 2006). For detail of the climate, see section 2.2.

The soil of the experimental site is calcaric gleysoils (FAO 2003) characterized by a shallow groundwater table often with elevated groundwater salinity and secondary salinization in the upper soil. Initial soil chemical parameters indicated a medium to high soil mineral N, low total soil N (0.04-0.05%), low soil organic carbon, and a moderate range of exchangeable potassium. For detail see section 2.3.

4.2.2 Experimental design and treatments

The experiment was designed as a randomized complete block with four replications. The individual plot size was 480 m^2. In the rice season, seven treatments in 2008 and eight in 2009 were implemented as a result of the combination of two irrigation methods, i.e., frequent wet and dry (WAD) and continuous flood irrigation (FI), and three tillage methods, i.e., raised bed planting (BP), zero tillage (ZT) planting on flat land, and conventional tillage (CT), and three levels of residue retention, i.e., residue harvested (RH), 50% residue retention (R50) and 100% residue retention (R100) (Table 4.1). For detail see section 3.2.2.

Table 4.1 Treatment details of rice-wheat system experiment in the Khorezm region of Uzbekistan 2008-2010.

Treatment	Rice	Wheat
BP-RH	Bed planting, residue harvested, drill seeded 2 rows rice in 67 cm bed, wet and dry irrigation	Surface seeded in permanent beds in standing rice, residue harvested
BP-R50	Bed planting, 50% residue retention, drill seeded 2 rows rice in 67 cm bed, wet and dry irrigation	Surface seeded in permanent beds in standing rice, 50% residue retention
BP-R100	Bed planting, 100% residue retention, drill seeded 2 rows rice in 67 cm bed, wet and dry irrigation	Surface seeded in permanent beds in standing rice, 100% residue retention
ZT-RH	Zero tillage, residue harvested, drill seeded rice in 20 cm spacing, wet and dry irrigation	Surface seeded in zero-till flat in standing rice, residue harvested

Table 4.1 continued

Treatment	Rice	Wheat
ZT-R50	Zero tillage, 50% residue retention, drill seeded rice in 20 cm spacing, wet and dry irrigation	Surface seeded in zero-till flat in standing rice, 50% residue retention
ZT-R100	Zero tillage, 100% residue retention, drill seeded rice in 20 cm spacing, wet and dry irrigation	Surface seeded in zero-till flat in standing rice, 100% residue retention
CT-FI	Conventional tillage and field preparation, chiseling, levelling and wet-direct seeding of rice, broadcast seeded, continuous flood irrigation	Surface seeded into standing rice
CT-II	Conventional tillage and field preparation, chiseling, levelling and wet-direct seeding of rice, broadcast seeded, intermittent irrigation	Surface seeding into standing rice

4.2.3 Crop management

Rice was dry-direct seeded with a tractor-drawn Indian Planter in BP and ZT tillage treatments, while under conventional tillage (CT-II and CT-FI), 24-h water-soaked, pre-germinated rice seed was wet-direct seeded into the standing water in a field that had been ploughed and leveled 2-3 times (Table 4.2). For detail cultivation practices see section 3.2.3.

Table 4.2 Time of seeding and harvesting and input use in rice-wheat system 2008-2010.

Item	Rice 2008	Wheat 2009	Rice 2009	Wheat 2010
Seeding	18 June	23 September 2008	21 June	1 October 2009
Harvesting	8 October	13 June	22 October	22 June
Seed rate (kg ha^{-1})	140	200	140	200
Fertilizer dose (NPK kg ha^{-1})	257:120:80	124:100:70	250:120:80	233:140:70
Residue in R50 (kg ha^{-1})	1500	2922	4146	2926
Residue in R100 (kg ha^{-1})	3000	4657	6689	3139

Wheat was surface-broadcast seeded into the standing rice in all treatments at 17 days before rice harvest in 2009. In wheat, phosphorus and potassium fertilizers were broadcast applied in the first week of November, while N was applied in two equal splits in March and April; N was applied as urea granules. In wheat, weed control was carried out through the application of the herbicide Granstar 75 DF (75% Tribenuron methyl) at the rate 25 g ha^{-1} in the last week of March. Wheat was irrigated eight times during the crop-growing period, i.e., before fertilizer application and at the major growth stages.

4.2.4 Soil and plant sample collection and analysis

Initial soil samples were collected before the start of the experiment to determine the initial fertility status of the experimental site. Soil samples for mineral N content were collected at the main growth stages from three different points of each plot from 0-10, 10-20, 20-30, 30-50 and 50-80 cm soil depths; the samples were composited. Plant and soil samples were analyzed for N at the Soil Science Institute, Tashkent, using the standard procedures applied at this institute (Kuziev 1977). Total plant N was analyzed by the Kjeldahl method (Bremner and Mulvaney 1982). Soil NO_3-N content (mg kg^{-1}) was examined using the Granvald-Ljashu method, while the NH_4-N content (mg kg^{-1}) was determined by colorimetric analysis using the Nessler reagent (Protasov 1977).

4.2.5 Groundwater nitrate

Groundwater nitrate content was measured in collaboration with Ph D student Oksana Forkutsa. It was measured before and after irrigation and fertilizer application during entire crop-growing period in 2009. A total of 15 piezometers (3 in the CT-FI and 12 in the WAD treatments) were installed randomly in up to 2.5 m soil depths. Water samples were collected from each piezometer and analyzed immediately for NO_3-N concentration using nitrate test sticks (color scale in steps of 10-25-50-100-250-500 mg NO_3 l^{-1} (Merkoquant®, Merk® KGAA) and photometrically with a calibration solution (0.5-20 mg l^{-1}) (Spectroquant®, Merk® KGAA).

4.2.6 Mineral nitrogen dynamics

Mineral N dynamics were determined in two steps, i.e., at harvest of each crop and at different crop growth stages (sampling dates). N dynamics at crop harvest was determined based on the total soil mineral N content before crop seeding, soil mineral N remained at crop harvest, total N uptake by the crop, and total amount of N added from fertilizer during the crop growing period. Similarly, N dynamics at different crop growth stages was determined based on the total soil mineral N content in the earlier sampling date (initial soil mineral N), total mineral N remained at the sampling date, N added from fertilizer, and N uptake by the crop from earlier to this sampling date. Total plant N uptake was determined from the sum of root, leaf, stem, senesenced leaf and panicle by multiplying biomass with N concentration (%) of the respective plant part. The N input was calculated by adding the initial soil mineral N content at 0-80 cm soil depth to the amount of N from added N fertilizer (Liu et al. 2003). Similarly, N output was calculated by adding plant N uptake to the mineral N content remained in the soil.

$$\text{N input} = \text{Initial soil soil mineral N} + \text{N added from fertilizer} \tag{4.1}$$

$$\text{N output} = \text{Soil mineral N remained at harvest/soil mineral N remained at Sampling} + \text{crop N uptake} \tag{4.2}$$

$$\text{Unaccounted mineral N} = \text{N Input} - \text{N Output} \tag{4.3}$$

The difference between N input and output is considered as unaccounted mineral N or N possibly lost via any mechanism. Nitrogen not measured directly includes N input from rainfall and irrigation water, N mineralization from the organic N pool, gaseous N losses from ammonia volatilization and denitrification and leaching, N immobilized by the crop residue, and N released from residue decomposition.

The NH_4- and NO_3-N contents (kg ha^{-1}) at a particular depth were determined by multiplying N concentrations with the respective bulk density.

4.2.7 Water-filled pore space and relative aerobic activity

Water-filled pore space (WFPS) was calculated from the volumetric moisture content of soil measured at 10, 30, 50 and 70 cm depths. Volumetric moisture content was measured at hourly intervals during the entire crop growing period in two replications by ThetaProbe ML2X FDR sensors. Sensor data were validated using the volumetric moisture content measured manually at 10 sampling dates in rice 2008, 23 sampling dates in rice 2009, and 11 sampling dates in wheat 2009 in the respective soil depths.

The water-filled pore space was calculated using the measured volumetric moisture content, soil porosity, bulk density, and particle density of the soil using the equation given by Linn and Doran (1984);

$$\text{WFPS (mL mL}^{-1}\text{)} = \frac{\text{Percent volumetric water content}}{\text{Percent total soil porosity}} \text{X } 100 \qquad (4.4)$$

$$\text{Porosity (\%)} = \left(1 - \frac{\text{Bulk density}}{\text{Particle density}}\right) \text{X } 100 \qquad (4.5)$$

A soil particle density of 2.65 g cm^{-3} was used when calculating porosity (Scheer 2008).

Similarly, relative aerobic activity in different soil depths during the rice and wheat growing period was calculated using the equation given by Linn and Doran (1984) for WFPS higher than 60% as:

$$\text{Relative aerobic activity} = \frac{60\%}{\text{Percent water filled pore space}} \qquad (4.6)$$

4.2.8 Statistical analysis

Dependent variables were subjected to analysis of variance using PROC GLM (SAS Institute 2008) for randomly complete block design. Repeated measure analysis was performed for those observations recorded over time. As the method and time of N application in rice was different, data were analyzed and presented year-wise. When the interaction between BP and ZT with three levels of residue retention was non-significant, data over tillage and residue were pooled. Individual treatments were compared using Fisher's Protected Least Significant Difference (LSD), and the treatment differences were considered statistically significant at $p<0.05$.

4.3 Results

4.3.1 Mineral nitrogen dynamics in rice-wheat system

At crop harvest

Rice

At rice harvest, 32-43% (122-163 kg ha^{-1}) in 2008 and 38-70% (125-236 kg ha^{-1}) in 2009 mineral N was unaccounted (lost) (Figures 4.1A and 4.1B). The unaccounted mineral N was affected by the irrigation method, and was higher ($p<0.05$) in the WAD treatments by 21% in 2008 and by 41% in 2009 than under CT-FI. The unaccounted mineral N was not affected by residue retention in 2008, while in 2009, residue retention increased ($p=0.001$) the unaccounted mineral N by 38% under R100 compared to RH. Irrespective of residue level, no significant difference in unaccounted mineral N among BP, ZT and CT-II indicates tillage method has no effect on N loss. Among the different tillage methods, ZT-R100 followed by BP-R100 had the highest, while CT-FI followed by CT-II and ZT-RH had the lowest amount of unaccounted mineral N in 2009. The unaccounted mineral N was mainly affected ($p<0.05$) by the plant N uptake in 2008, and by both plant N uptake and soil mineral N content in 2009. Both plant N uptake and soil mineral N content were significantly lower in ZT-R100 than in the other treatments in 2009.

Wheat

During the wheat season, unaccounted mineral N was not observed, and the averaged N output (243 kg ha^{-1}) was higher by 6% than input (229 kg ha^{-1}) (Figure 4.1C). A residual effect of WAD treatments of rice was observed in wheat, where N output was higher by 9% in the WAD than under CT-FI. Among the WAD treatments, there was no significant difference in N input and output.

Rice-wheat system

Combined over two seasons rice and one season wheat, the total amount of unaccounted mineral N was significantly higher under ZT-R100 (403 kg ha^{-1}) followed by BP-R100 (354 kg ha^{-1}) and the lowest under CT-FI (261 kg ha^{-1}). In the rice-wheat system, mineral N dynamics were affected by irrigation method, and the unaccounted mineral N content was higher under WAD treatments than under CT-FI by 26% ($p=0.001$). It was also affected by residue retention, and was higher under R100 than under RH by 28% ($p<0.001$), and by tillage method, where the values were higher under ZT than under BP by 6% ($p=0.17$).

.

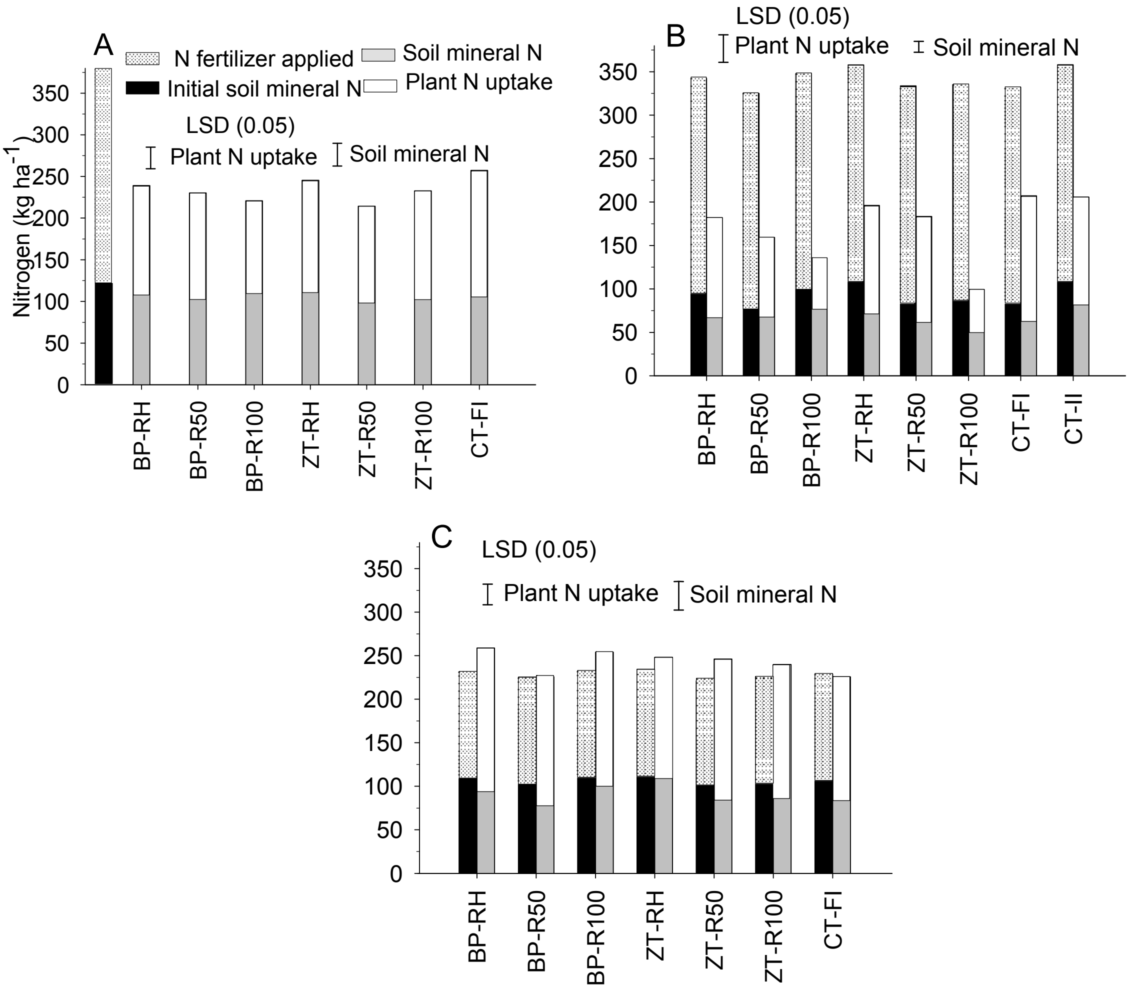


Figure 4.1 Nitrogen from fertilizer, initial soil mineral N, plant N uptake, and mineral N remained in soil at harvest (kg ha^{-1}) in rice 2008 (A), rice 2009 (B) and wheat 2009 (C) as affected by different irrigation and tillage methods and residue levels; LSD (0.05) is least significant difference between treatments; BP-RH=bed planting residue harvested, BP-R50=bed planting 50% residue retention, BP-R100=bed planting 100% residue retention, ZT-RH=zero tillage residue harvested, ZT-R50=zero tillage 50% residue retention, ZT-R100=zero tillage 100% residue retention, CT-FI=conventional tillage continuous flood irrigation, CT-II=conventional tillage intermttent irrigation.

At different crop growth stages

Rice

In 2008, the largest amount of mineral N (43-58%; 127-169 kg ha^{-1}; Figure 4.2) was unaccounted in the rice field from seeding to panicle initiation (PI), while during PI to flowering, it was negligible (0-12%). At both measurements, N output was significantly higher in the CT-FI than in the WAD treatments, mostly due to higher N uptake. Total mineral N content in the soil profile was not significantly different among treatments at both stages.

In 2009, unaccounted mineral N content was affected by irrigation method and residue level, except from seeding to tillering, where 35 kg N ha^{-1} was unaccounted with both WAD and CT-FI irrigation methods (Figure 4.3). The unaccounted mineral N in the WAD treatments was 66 kg ha^{-1} from tillering to PI and 46 kg ha^{-1} from PI to flowering, but unaccounted N was not observed in CT-FI at both measurements. In the WAD treatments, unaccounted mineral N did not differ between BP and ZT but was comparatively lower in CT-II at all growth stages. Averaged over tillage method, a higher ($p<0.05$) amount of unaccounted mineral N was observed in the R100 treatment followed by the R50 and RH treatments.

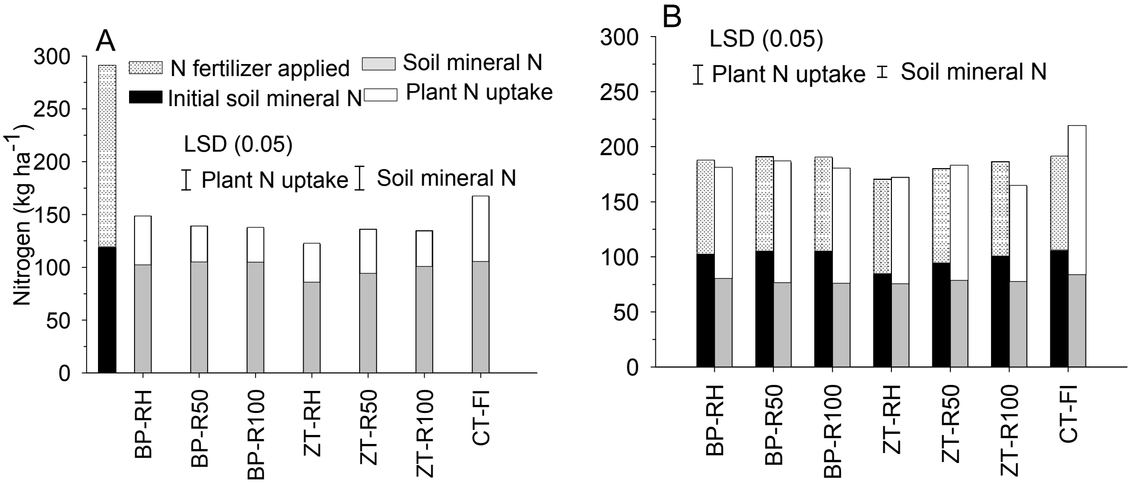


Figure 4.2 Nitrogen from fertilizer, initial soil mineral N, plant N uptake, and mineral N remained in soil (kg ha^{-1}) from seeding to PI (A) and PI to flowering (B) stages of rice as affected by different irrigation and tillage methods and residue levels in 2008; LSD (0.05) is least significant difference between treatments (for legend see Figure 4.1).

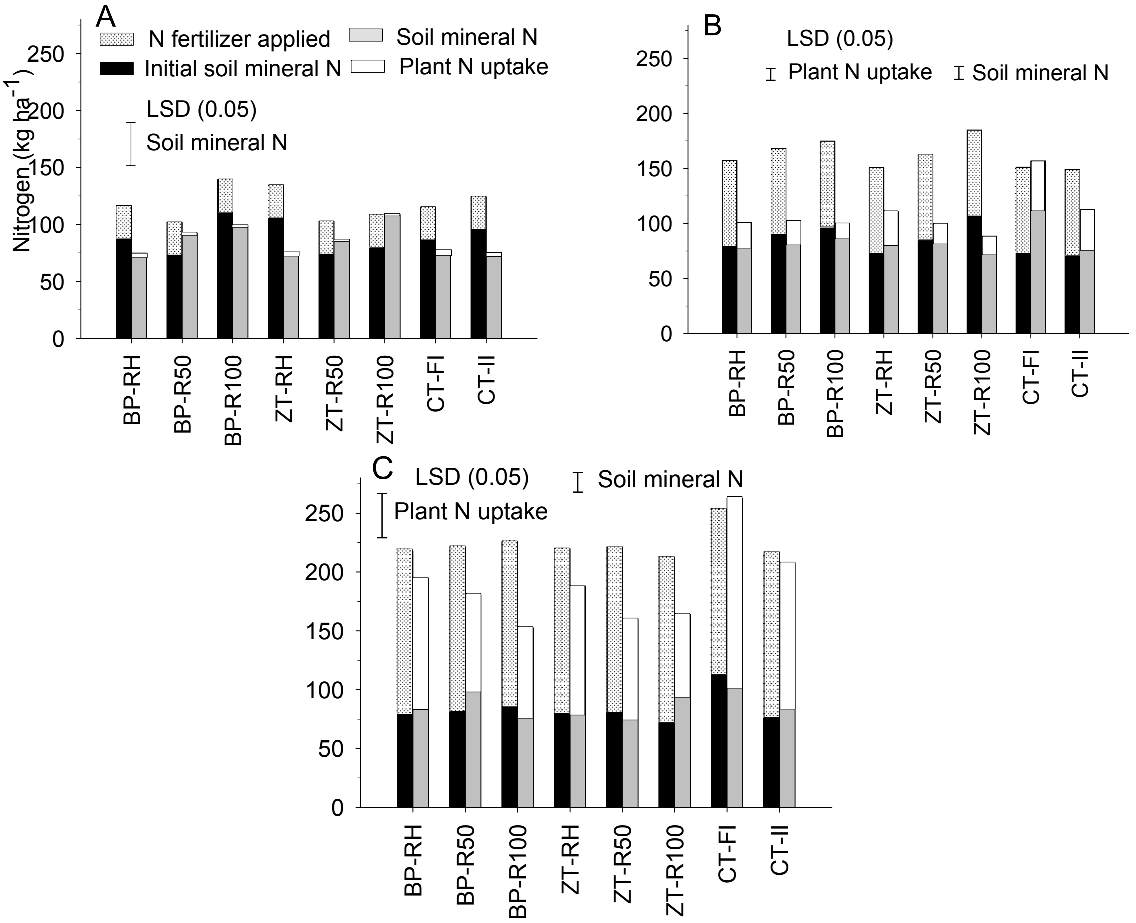


Figure 4.3 Nitrogen from fertilizer, initial soil mineral N, plant N uptake, and mineral N remained in soil (kg ha^{-1}) from seeding to tillering (A), tillering to PI (B) and PI to flowering (C) stages of rice as affected by different irrigation and tillage methods and residue levels in 2009; LSD (0.05) is least significant difference between treatments (for legend see Figure 4.1).

Wheat

At all growth stages, N output was higher than N input, except in ZT-RH and CT-FI at spike initiation where N output was slightly lower than N input, and there was no unaccounted mineral N in any treatment. A residual effect of the WAD treatments of rice was observed in wheat on soil mineral N content and N uptake. Total soil mineral N content was higher by 7% from seeding to spike initiation, by 19% from spike initiation to flowering, and by 10% from flowering to physiological maturity in WAD treatments than under CT-FI (Figure 4.4). Plant N uptake was higher ($p<0.05$) in the WAD treatments than in the CT-FI. Irrespective of tillage method, R100 had higher mineral N availability by 10% from seeding to spike initiation and by 21% from spike initiation to flowering than RH.

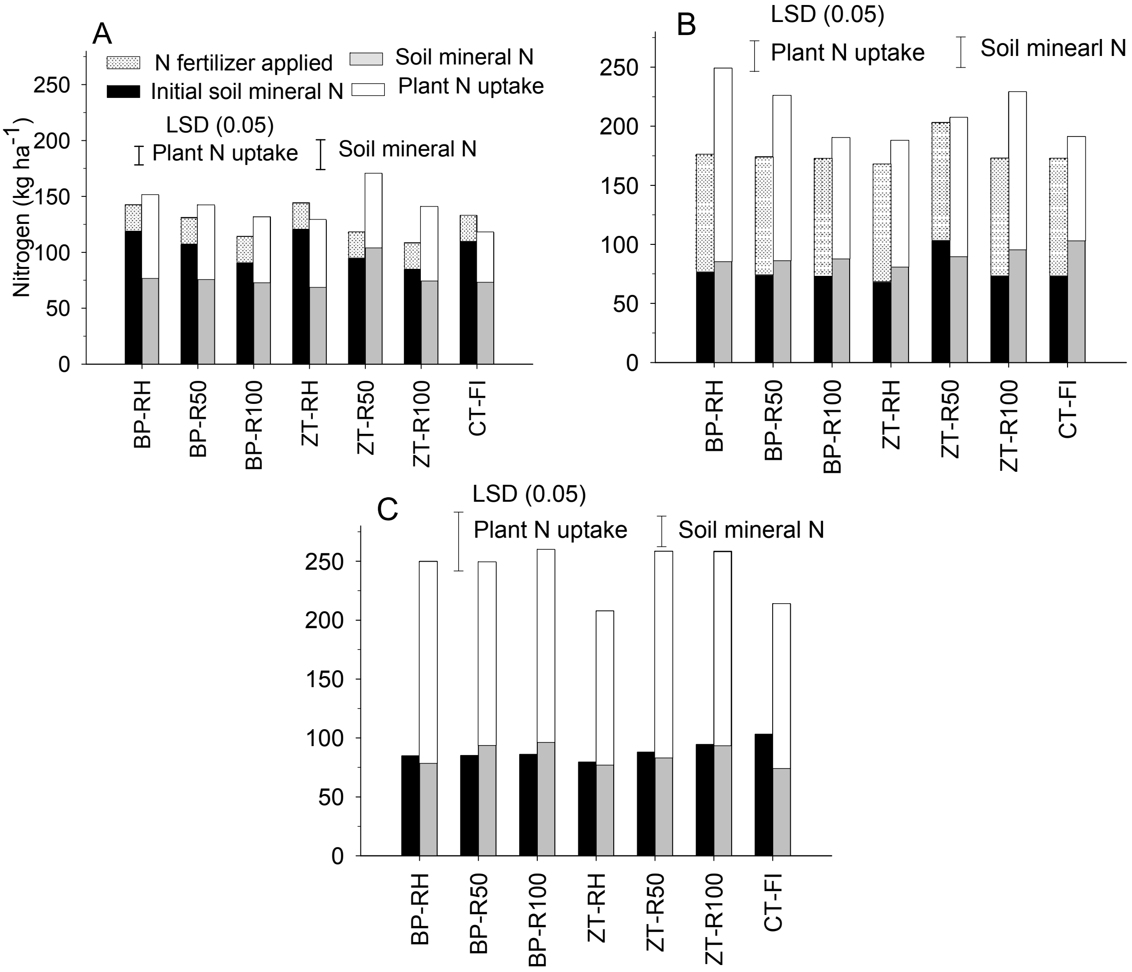


Figure 4.4 Nitrogen from fertilizer, initial soil mineral N, plant N uptake, and mineral N remained in soil (kg ha^{-1}) from seeding to spike initiation (A), spike initiation to booting (B), and booting to flowering (C) stages of wheat as affected by different tillage method and residue level 2009; LSD (0.05) is least significant difference between treatments (for legend see Figure 4.1).

4.3.2 NH_4- and NO_3-N dynamics in soil as affected by irrigation and tillage methods and residue level in rice-wheat system

In both the rice and wheat season, NH_4-N and NO_3-N concentration consistently decreased ($p<0.001$) from 0- to 80-cm soil depth in all treatments.

NH_4-N dynamics

Rice

In rice, NH_4-N content in the top 80 cm soil profile was affected ($p<0.05$) by irrigation method, and was higher under CT-FI by 28 and 46% at PI and 12 and 27% at flowering in 2008 and 2009, respectively, than in WAD treatments (Figure 4.5A). In contrast, at maturity NH_4-N was lower by 10% in 2008 and by 6% in 2009 under CT-FI than in the WAD treatments. NH_4-N was affected by residue level, and the values were higher under R100 than under RH by 18% in 2008 and by 44% in 2009 at tillering. After tillering, NH_4-N was not significantly different among residue levels in both years.

Among the WAD treatments, the non-significant difference in NH_4-N content between BP-RH and ZT-RH in 2008 and BP-RH, ZT-RH and CT-II in 2009 indicates that tillage method has no effect on NH_4-N dynamics in the soil profile (Figure 4.5B).

The NH_4-N concentration was higher in the CT-FI than in the WAD treatments in all 0- to 80-cm soil depths at all growth stages (data not shown).

Wheat

In wheat, NH_4-N content in the top 80 cm soil profile was not affected by tillage method and residue treatments at all growth stages (Figure 4.5). Averaged NH_4-N content was higher ($p>0.05$) under WAD than under CT-FI. Irrespective of tillage method, NH_4-N was higher under R100 than under RH by 11% at booting, and by 27% at flowering.

NO_3-N dynamics

Rice

In 2008, NO_3-N content in the top 80 cm soil profile was affected ($p<0.05$) by irrigation and tillage method and residue level only in the early crop growth stage (Figure 4.5). Averaged over residue and tillage methods, WAD treatments showed 54% higher NO_3-N than CT-FI at PI. Similarly, irrespective of residue level, BP had 26% higher NO_3-N content than ZT. Across tillage methods, R100 had 19% higher NO_3-N content than RH.

However, in 2009, NO_3-N content was not affected by irrigation, tillage method and residue level at all growth stages (Figure 4.5). The averaged NO_3-N content combined over different growth stages was 12 kg ha^{-1} in the top 80 cm soil profile.

Wheat

During the wheat season, NO_3-N content in soil profile was not significantly different among tillage method and residue level at all growth stages, and the averaged value was 12 kg ha^{-1} (Figure 4.5).

During winter freezing, i.e., October-March, NH_4-N increased by 23% from October 10 (19 DAS) to March 24 (183 DAS). In contrast, NO_3-N content decreased by 73% in the same period (Figure 4.5).

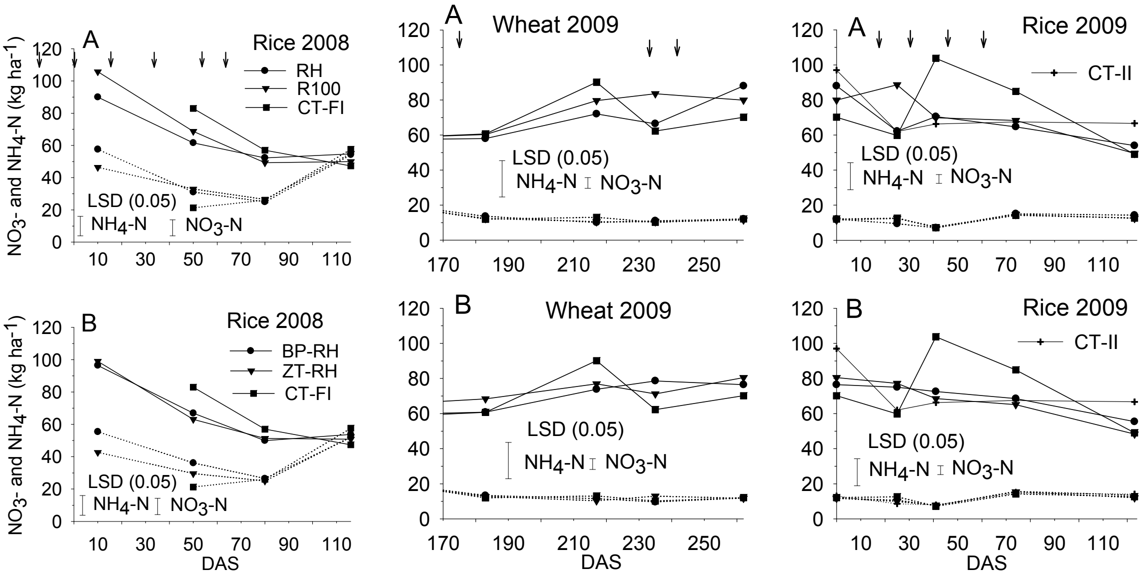


Figure 4.5 Total NO_3- and NH_4-N content (kg ha^{-1}) in top 80 cm soil profile under different residue levels (A) and tillage methods (B); solid lines indicate NH_4- and dotted lines NO_3-N; down arrows are date of N fertilizer application; LSD (0.05) is least significant difference between treatments over time; RH=residue harvested, R100=100% residue retention, CT-FI=conventional tillage with continuous flood irrigation, CT-II=conventional tillage intermittent irrigation, BP-RH=bed planting residue harvested and ZT-RH=zero tillage planting residue harvested; DAS=days after sowing; lines are connected for better visualization.

4.3.3 Groundwater nitrate content

Groundwater NO_3-N concentration in WAD (1.86±0.05 mg l^{-1}) treatments was higher by 52% than under CT-FI (1.22±0.07 mg l^{-1}; Figure 4.6; data source: Forkutsa, 2011 forthcoming).

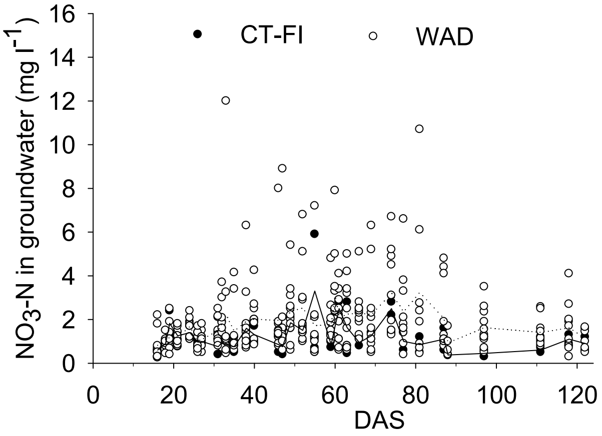


Figure 4.6 Groundwater NO_3-N concentration (mg l^{-1}) in CT-FI and WAD treatments, 2009. Dotted line indicates mean NO_3-N concentration in WAD treatments and solid line in CT-FI; CT-FI=conventional tillage with flood irrigation, WAD=frequent intermittent wet and dry irrigation; DAS=days after sowing; lines are connected for better visualization.

4.3.4 Water-filled pore space and relative aerobic activity

During the rice growing season, soil pores under CT-FI were filled with water, thus the soil was continuously under anaerobic conditions. In the WAD treatments, averaged water-filled pore space (WFPS) was 64, 74, 88, and 104% in 10, 30, 50 and 70 cm soil depths, respectively; the soil in the top 30 cm was mostly under aerobic conditions (Figure 4.7A, B). However, the continuously fluctuating WFPS during the rice season indicates that the soil in the WAD treatments was under frequent aerobic-anaerobic transformation. During the wheat season, WFPS was 57, 68, 79, and 95% in 10, 30, 50 and 70 cm soil depths, respectively (Figure 4.7C).

The calculated microbial aerobic activity under WAD treatments during the rice growing season was 93% in the top 10 cm soil followed by 82, 69 and 57% in 30, 50 and 70 cm soil depths, respectively. Similarly, during the wheat season, the microbial aerobic activity was 107, 89, 78 and 63% in 10, 30, 50 and 70 cm soil depths, respectively.

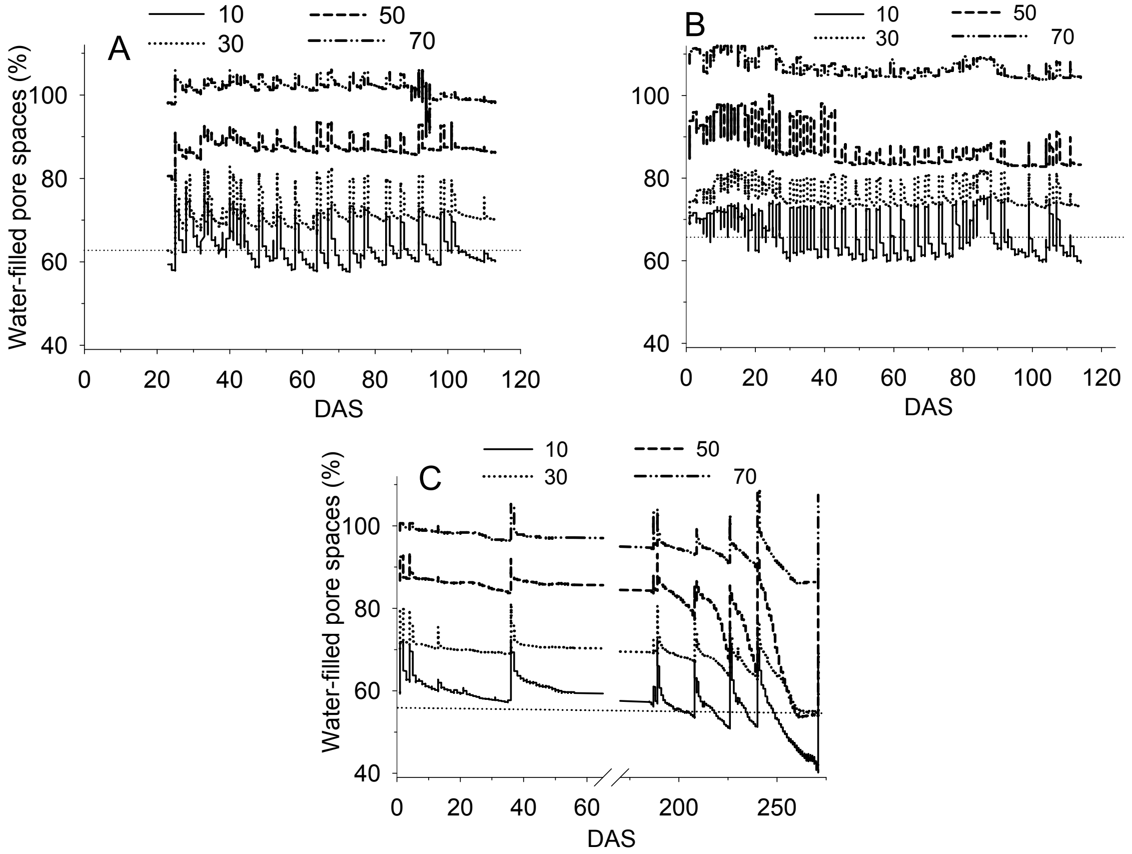


Figure 4.7 Water-filled pore spaces (%) at different soil depths (cm) in WAD treatments under rice-wheat system, 2008-2009; Rice 2008 (A), Rice 2009 (B) and Wheat 2009 (C); horizontal dotted line indicates mean water-filled pore space at 10 cm soil depth; DAS=days after sowing.

4.4 Discussion

Information on mineral N dynamics is essential before a wider scaling-out and adoption of CA practices in rice-wheat cropping systems. As these practices involve water saving irrigation and residue retention, they may change mineral N dynamics more than conventional methods. Thus, the objective of this study was to examine mineral N dynamics in a rice-wheat system seeded under different irrigation and tillage methods and residue levels in the irrigated drylands of Central Asia.

4.4.1 Effect of irrigation method

Rice

Nitrogen depletes from rice field under frequent wet and dry irrigation and with high residue retention. As previously observed in other regions, e.g., by Becker et al. (2007) in Nepal, Timsina et al. (2001) in Bangladesh, Pathak et al. (2006) in India, and Sadanandan and Mahapatra (1973) in India, the unaccounted mineral N from the rice field is higher in arid regions. The higher unaccounted mineral N in the WAD treatments compared to the CT-FI could be related to the low plant N uptake and low soil mineral N availability, and to higher N losses through various pathways. The lower N uptake under WAD irrigation could be due to slow early crop growth and development rates, which lead to reduced above- and belowground biomass accumulation (section 3.3.3). This has previously been associated with the water stress under wet and dry irrigation (Bouman and Tuong 2001) and the higher N losses through denitrification, leaching, and volatilisation (Philips et al. 1980; Rice and Smith 1982; Patra et al. 2004) with WAD irrigation.

The largest amount of unaccounted mineral N in WAD treatments was from seeding to the panicle initiation stage in both years. As wet and dry irrigation had already been started before panicle initiation in the WAD treatments, the higher unaccounted mineral N was due to poor plant N uptake as a result of slow growth rate and poor root development (section 3.3.10). As stated by Belder et al. (2005b) and Beyrouty et al. (1994), this could be for two reasons (i) water stress in the WAD treatments reduced crop growth and N demand, and (ii) soil conditions led to increased N losses via nitrification-denitrification and/or ammonia volatilization and/or leaching.

The higher amount of unaccounted mineral N in the WAD treatments in this study could be due to the occurrence of frequent aerobic-anaerobic phases (Figure 4.7), which could have accelerated the significant amount of N loss through denitrification. In treatments with wet and dry irrigation, the higher N_2O and lower CH_4 fluxes than in CT-FI (Forkutsa 2011, forthcoming) indicates that the soil was mostly under aerobic conditions, while the frequent application of 4-5 cm flood irrigation (section 3.3.2) indicates the occurrence of temporary anaerobic conditions in the WAD treatments. Frequent aerobic-anaerobic phases could change the soil redox potential frequently and thus the NO_3- and NH_4-N transformations, which influence ammonification, nitrification, and denitrification processes in the soil (Vlek and Byrnes 1986; Reddy and Patrick 1976). Furthermore, as the average WFPS in the top 30 cm soil was 57-82% during the rice-growing period, and the microbial aerobic activity was more than 80%, a significant amount of unaccounted N in the WAD treatments through denitrification loss can be assumed. A significant N loss occurs through N_2O emission in WFPS of between 60-70% (Linn and Doran 1984; Bateman and Baggs 2005; Clayton et al. 1997). Higher N_2O losses (more than 50µg N_2O-N m^{-2} h^{-1}) at a WFPS greater than 60%, while generally low losses (<10 µg N_2O-N $m^{-2}h^{-1}$) under continuously flood irrigated condition in the Khorezm region have been reported by Scheer (2008).

Furthermore, the higher NO_3-N concentration in the groundwater in the WAD than in the CT-FI treatments in 2009 (Figure 4.6) indicates that a considerable amount of N could have been lost through leaching. Below a depth of 45 cm, the soil at the study site mostly consists of sand and has a high infiltration rate of 0.5-1.0 cm h^{-1} (section 5.3.2). Rapid loss of irrigation water (4-5 cm applied water within 5-6 hours) is a situation conductive to NO_3-N leaching (Bergstorm and Johansson 1991). Alternate wetting and drying is associated with increased NO_3-N during the aerobic phase (Ventura and Watanabe 1978; Linn and Doran 1984; George et al. 1993). As frequent wet and dry irrigation was applied in the WAD treatments in this study, the accumulated NO_3-N during the aerobic phase could have been lost through leaching during the subsequent irrigation. Thus, although the actual leaching loss of N from the soil profile was not measured, due to the high permeability of the soil layer and the application of frequent dry and wet flood irrigation, a significant amount of unaccounted mineral N in the WAD treatments could also be expected through the leaching loss of NO_3-N.

NH_4-N in soil profile remained significantly higher in the CT-FI than in the WAD treatments during the active crop growth stages, i.e., panicle initiation to flowering in both years (Figure 4.5). The applied N remained absorbed in the form of NH_4-N under flood-irrigated conditions. NH_4-N is the predominant and preferred form of N in flooded soil (George et al. 1992); it absorbs on soil colloids, stays longer and leads to lower percolation loss (Cassman et al. 1998). There is also less possibility of NH_4-N changing to NO_3-N under flooded conditions (Vlek and Byrnes 1986). In contrast, the consistently lower NH_4-N in the WAD than in the CT-FI, and also no differences in NO_3-N concentration between the WAD and CT-FI irrigation method, indicates that the applied N in the WAD treatments neither remained longer in the form of NH_4-N nor in NO_3-N in soil profile and possibly could have been lost.

The NO_3-N during rice growing season 2009 was consistently low due to (1) low NO_3-N content in soil at the time of rice seeding and N fertilizer was applied only after 27 DAS, (2) there could have been a greater flux of NO_3-N in the soil but it may not have been captured in the soil samples, as these had been collected only at 3-week intervals and always before fertilizer application, and (3) due to the frequent wetting and drying irrigation cycle, NO_3-N could have been lost through denitrification or leaching. The increased accumulation of NO_3-N in rice 2008 at harvest in all treatments could be due to no further irrigation around maturity; this was not observed in 2009, as the field was intermittently irrigated up to the rice harvest to allow germination of the wheat.

Wheat

The higher N output than N input during the wheat growing season suggests no loss of N from the wheat field. The exhausted soil fertility during the wheat growing period, i.e., reduction of soil total N at wheat harvest compared to seeding (0.031 vs. 0.044%, 29%) and available phosphorus (18.2 vs. 22.4 mg kg^{-1}, 19%) may explain the higher N output than input during the growing season. Some N could also have been added from residue decomposition and irrigation water, which was not included in the calculation of unaccounted mineral N. Hu et al. (1999) also found higher N output than input during the wheat season due to an 8% reduction of total N in China.

As the soil was continuously under aerobic conditions during the wheat growing season (Figure 4.7), predominantly NO_3-N should have been present in the soil profile. In contrast, the consistently lower NO_3-N compared to NH_4-N in the top 80 cm soil profile could be due to the fact that NO_3-N is the preferred form of N for uptake by wheat (Hamid 1972). The higher plant population (750 plants m^{-2}), more vigorous crop growth with more than 7.0 t ha^{-1} grain yield (section 5.3.1), N uptake of more than 145 kg ha^{-1}, no moisture stress during growing period (section 4.3.4), average temperature between 16-28 °C during March-May (main period of fertilizer application; Figure 2.2), deep wheat roots (up to 1.54 m), and no unaccounted mineral N during the growing period (section 4.3.1) possibly justifies the consistently lower NO_3-N content in the soil due to uptake by the crop neither the loss. Alternately, there could have some fluxes of

NO_3-N in the soil, but these may not have been captured in the soil samples as these had been collected at 3-week intervals and always before fertilizer application. Scheer et al. (2008a) found N_2O fluxes of 0.6 - 6.5 kg N_2O-N ha^{-1} season^{-1} in winter wheat in the same study region.

The nearly equal net N input of 129 kg ha^{-1} before freezing (10 October 2008) and N output 136 kg ha^{-1} after freezing (23 March 2009) indicates that there was no unaccounted mineral N during the winter freezing. The small difference (7 kg ha^{-1}) before and after freezing is due to the uptake by the wheat. Due to the low temperatures at that time, there was only a small possibility for mineralization of organic N.

The consistently high NH_4-N than NO_3-N during both rice and wheat growing season could be attributed to the NH_4-N from the irrigation water and groundwater. The 4-6 mg l^{-1} NH4-N in irrigation water, more than 5 mg l^{-1} NH_4-N in groundwater, shallow groundwater table (1.12 m during rice 2008, 1.84 m during wheat 2009 and 0.94 m during rice 2009) and the frequent irrigation in both crops may explain for this. Devkota (2011, forthcoming) also reported consistently high NH_4-N in cotton-wheat cropping system research in just adjacent to this experimental field.

4.4.2 Effect of tillage and residue

In the rice season, the higher unaccounted mineral N in the residue-retained treatments could be related to the reduced plant N uptake and soil mineral N availability. The lower N uptake in the residue-retained treatments could be due to slow early crop growth and development rates, which lead to reduced above- and belowground biomass accumulation (section 3.3.10). This has previously been associated with the decreased soil temperature under residue retention (Sandhu et al. 1980; Zhang et al. 2009), N immobilization by residues (Quemada and Cabrera 1995; Rao and Mikkelsen 1976), reduced light interception due to the shading effect of the standing residue (Yoshida 1981), and higher amount of N loss through N_2O denitrification and NH_4 volatilization (Mkhabela et al. 2008; Rochette et al. 2009; Philips et al. 1980; Rice and Smith 1982; Patra et al. 2004).

The higher amount of unaccounted mineral N in rice 2009 compared to rice 2008 in the R100 and R50 treatments could be related to some of the above reasons, as more than >14 t ha^{-1} residue in R100 and >8 t ha^{-1} in R50 were retained. As 2008 was the first year of the experiments, and the residue was applied externally, the amount was not sufficient to cover the soil surface. Rice and wheat residue can immobilize up to 34% of the applied N (Quemada and Cabrera 1995), and the N rate should be increased by 15% under residue-retained zero-till direct-seeded conditions (Ladha et al. 2009a). Further, the narrower difference of unaccounted mineral N between WAD and CT-FI rice in 2008 could possibly be due to drilling of N during planting in the WAD treatments. In 2009, N was not drilled, as the field was too dry and hard to drill, and all N was broadcast applied in 4 splits after rice emergence. The broadcast application in the WAD treatments could have further contributed to lowering the mineral N availability through increasing N loss through various pathways. The possible leaching and denitrification losses of N can be minimized by proper drilling of N fertilizers (Balasubramanian and Krishnarajan 2003; Raun and Johnson 1999).

The non-significant difference in amount of unaccounted mineral N, and NO_3- and NH_4-N content among the CT-II, BP-RH and ZT-RH treatments during the rice growing season in 2009 indicates that availability of soil mineral N is not affected by tillage method.

4.5 Conclusions

As the unaccounted mineral N in rice is higher under WAD irrigation and residue retention than in conventional systems, there is an urgent need to develop strategies for appropriate N fertilization, irrigation scheduling and residue management to increase mineral N availability in rice under WAD irrigation and CA practices before these practices can be adopted. Better understanding of appropriate time, method, dose, and placement of N fertilizer application can increase availability of N and thus may help to make CA-based rice-wheat systems sustainable in the arid regions of Central Asia. Furthermore, suitable rice cultivars with high N uptake need to be developed for these systems.

5 LAND AND ECONOMIC PRODUCTIVITY OF RICE-WHEAT ROTATION SYSTEMS UNDER DIFFERENT IRRIGATION, TILLAGE AND RESIDUE MANAGEMENT PRACTICES IN ARID DRYLANDS OF CENTRAL ASIA

5.1 Introduction

Rice and wheat are the major food crops in Central Asia. They are grown on 0.19 and 17.3 million ha, respectively (FAOSTAT 2010). In the region, rice is mostly cultivated in rice-wheat systems in the Amu Darya and Syr Darya river basins (Gupta et al. 2009). In rice-wheat rotation systems, rice is flood-irrigated wet-direct seeded or transplanted from June to October, while winter wheat is surface-seeded into the standing rice or under conventional tillage from October to June (Djanibekov 2008).

Most of the irrigated cropland in Central Asia is irrigated through a highly water wasteful surface irrigation (Bucknall et al. 2003), where farmers apply 4200-7000 m^3 t^{-1} irrigation water for rice and 1400-4000 m^3 t^{-1} for wheat (Aldaya et al. 2010). Continuous flood irrigation keeping a 15-20 cm standing water collar throughout the rice-growing season is commonly practiced by farmers in Uzbekistan (Christmann et al. 2009). Over-irrigation, ineffectively managed irrigation, water quality deterioration, water logging, and raising groundwater tables are leading to soil degradation (Ibrakhimov 2005; Conrad 2007; Cai et al. 2003; Kitamura et al. 2006) and desertification of the irrigated agricultural lands in the Aral Sea Basin. The rapidly expanding irrigated agriculture in Central Asia (2.0 to 7.9 million ha between 1925 and 2005) is using practically the entire available flow of the two main rivers, i.e., the Amu Darya and the Syr Darya (UNEP 2005). Thus, water management is a most important issue constraining and threatening crop productivity and sustainability in the region (Gupta et al. 2009), and farmers are compelling to develop and adopt water-saving technologies for crop production.

Conservation agriculture (CA) practices like zero tillage (ZT) and bed planting (BP) combined with residue retention and proper crop rotation, is the most sustainable cultivation system for the future (Hobbs et al. 2008). Such alternative crop production methods have increased water productivity (Rejesus et al. 2011; Kukal et al. 2010), soil quality and water- and nutrient-use efficiency (Timsina and Conner 2001), crop production and farmers' incomes in tropical regions of Southeast Asia (Bhushan et al. 2007; Gupta and Sayre 2007; Gupta and Seth 2007). Direct-seeded mulch-based cropping systems, involving various crops including rice, are currently being adopted in large areas throughout the world, most notably in countries such as the USA, Canada, Australia, Brazil, Paraguay, and Argentina, to obtain a sustainable production of grain and to increase agronomic and environmental efficiency (Scopel et al. 2004). Minimum tillage is becoming increasingly popular in rice cultures in southern USA (Griggs et al. 2007), and is becoming an increasingly accepted management technology for rice-wheat systems in parts of the Indo-Gangetic Plains (Hobbs and Gupta 2002; Singh and Ladha 2004). However, to achieve the full benefits of minimum tillage, both rice and wheat need to be grown in a double zero-tillage system (Bhushan et al. 2007).

In rice-wheat systems, rice consumes more than 85% of the total water applied. Therefore, much water could be saved if tillage and crop establishment practices of wheat were adopted in rice. However, the extension of tillage and crop establishment practices followed in wheat to rice without yield reduction has always been a major challenge for researchers. For example, Borrell et al. (1997) reported 34% water saving and 16-34% yield losses under BP in Australia. Similarly, Sharma et al. (2002) reported 49-55% water saving and 52% yield reduction in BP, and 49-43% water saving and 36-46% yield reduction under ZT compared to flood-irrigated rice in India. Although it is often claimed that reduced tillage operations such as direct seeding on flat land and raised beds can result in significant water savings (Gupta et al. 2003), systematic studies evaluating the effects of these practices on yield and water requirement of the rice-wheat systems under irrigated arid climatic conditions are lacking. It is the overall system productivity and system water use that should be considered when judging the suitability of a practice, and not just the individual crop productivity and water application.

Information on water balance components in cropped soils is crucial for irrigation planning at a field scale (Jalota and Arora 2002). Straw mulching helps to conserve moisture in the soil profile (Cabangon and Tuong 2000), direct-seeded rice reduces water application better than puddled transplanted (Bhuiyan et al. 1995; Cabangon et al. 2002), and raised beds can save 16-43% of the irrigation water compared to flat fields (Borrell et al. 1997). Thus, combining straw mulch (residue retention) and dry-direct seeding with bed planting using water-saving irrigation may save a significant amount of water application in rice-wheat systems.

Salinity is associated with heavily irrigated areas of the world that also have arid or semi-arid climates (Letey 1984; Rhoades and Loveday 1990). Rice is a salt-sensitive crop and yield reduction starts in soil salinity at 3 dS m^{-1}, going up to 50% at 6 dS m^{-1}, and 90% at 10 dS m^{-1} (Shannon 1997), while in wheat yields declines at 6 dS m^{-1}. Rice is relatively tolerant to salinity during germination, active tillering, and toward maturity, but is sensitive during the early seedling and reproductive stages (Bouman et al. 2007). In general, the cultivated soil in the arid region has high soil salinity (2-16 dS m^{-1}) mainly due to secondary soil salinization (Forkutsa et al. 2009). Both rice and wheat crops can be affected by the existing salinity levels. Rice can be used as a desalinization crop because the continuously percolating water leaches salts from the topsoil (Bhumbla and Abrol 1978). However, flooded rice can locally raise groundwater tables with subsequent risk of salinization if the groundwater carries salts (Bouman et al. 2007), but the better management of irrigation water can reduce the rate of rise. However, salinity dynamics under different irrigation and tillage methods and residue levels in rice-wheat systems of arid region are not yet understood.

Direct seeding in rice and wheat is also cost effective (Ladha et al. 2003). Puddling, transplanting and continuous submergence in conventional systems are highly labor, capital, water, time and energy intensive (Sharma et al. 2003). In direct-seeded rice-wheat systems, 40-60 l of diesel fuel can be saved, because farmers can forego the practice of plowing many times (Hobbs and Gupta 2004). However, these benefits can be slightly offset by increased cost for chemical weed control (Harmon et al. 1989). Thus, the objectives of this study were to evaluate the effects of water-saving irrigation combined with different tillage methods and residue levels on the system productivity, water application and balance, soil salinity dynamics, and gross margin of a rice-wheat system in arid drylands of Central Asia.

5.2 Materials and methods

5.2.1 Description of the experimental site

Experiments were carried out at Cotton Research Institute, Khorezm region of northwest Uzbekistan (60.05°- 61.39° N and 41.13°-42.02° E, 100 m asl) from 2008-2009. The area has a continental, arid climate with short, hot and dry summers and long, cold dry winters (Kottek et al. 2006), a mean annual temperature of 13.4 °C with a minimum in February (-9 °C) and a maximum in June/July (40 °C) (Glavgidromet 2003 as cited by Kinzler, 2010). For detail see section 2.2.

The soil of the experimental site is calcaric gleysoils (FAO 2003) characterized by a shallow groundwater table often with elevated groundwater salinity and secondary salinization in the upper soil. Soil texture is silty clay loam, with a bulk density 1.35-1.57 g cm^{-3} at the top 0-80 cm soil depth. For details on field history, climatic conditions, and soil physical and hydraulic properties see section 2.2.

5.2.2 Experimental design and treatments

The experiment was designed as a randomized complete block with four replications. The individual plot size was 480 m^2. In the rice season, seven treatments in 2008 and eight in 2009 were implemented as a result of the combination of two irrigation methods, i.e., frequent wet and dry (WAD) and continuous flood irrigation (FI), and three tillage methods, i.e., raised bed planting (BP), zero tillage (ZT) planting on flat land, and conventional tillage (CT), and three levels of residue retention, i.e., residue harvested (RH), 50% residue retention (R50) and 100% residue retention (R100). For detail see section 4.2.2.

5.2.3 Crop management

Rice was dry-direct seeded with a tractor-drawn Indian planter in the BP and ZT treatments, while in the conventional treatments, i.e., CT-II and CT-FI, 24-h water-soaked, pre-germinated rice seed was wet-direct-seeded into the standing water fields that had been ploughed and leveled 2-3 times. For details see sections 3.2.3 and 4.2.3.

5.2.4 Laboratory analysis of leaf samples

In 2009, wheat leaf samples from the RH and R100 treatments were analyzed for different plant nutrients using the standard procedure followed in the laboratory at Sabanci University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey, and the Center for Soil Plant Water Analysis Division of Soil Science and Agricultural Chemistry, IARI, New Delhi, India.

5.2.5 Crop harvest

For both crops, grain and straw yield was determined by harvesting plants from three randomly selected 2.25 m^2 areas, i.e., 6.75 m^2 per plot. Grains were threshed manually, dried and the yield was expressed on a 12% moisture level basis. Straw weight was determined after oven drying at 70 °C to a constant weight and expressed on an oven-dry weight basis. System productivity was calculated by adding grain yield of rice and wheat in each year (Bhushan et al. 2007).

5.2.6 Irrigation water application and measurements

Standard tensiometers (Eijkelkamp, EcoTech GmBh) were installed at 20 and 50 cm soil depths in two replicates for scheduling irrigation in the WAD treatments. In all WAD treatments, rice was irrigated almost every day during the first 15 DAS. After 15 DAS, fields were irrigated using flood irrigation when volumetric soil moisture content at 20 cm soil depth dropped 5-10% below the field capacity, i.e., soil metric potential around -20 kPa. The CT-FI rice was irrigated as in farmers' practice, and continuous flood irrigation was applied to maintain a 5-15 cm standing water level until one week before crop harvest. For detail method of irrigation water measurement and calculation, see section 3.2.4.

Irrigation water input was also measured in one of the farmer's fields (7.4 ha block) through a Standard Trapezoidal Cipolletti weir (0.75 m crest width) with an automated data logger (DL/N-70) for level measurement.

5.2.7 Water balance

The water balance was calculated for the BP, ZT and CT treatments and also for the farmer's field. Potential evapotranspiration was calculated using the Penmen Monteith equation with daily climatic data (Allen et al. 1998). The water balance for the residue levels in the BP and ZT treatments was not calculated, as the same amount of irrigation water was applied for all residue levels. Combined percolation and seepage losses were calculated, as it is difficult to separate them. Runoff was not included, as runoff never occurred because of the sufficient bund height. The water balance was calculated as:

$$\text{Water balance} = [\text{irrigation} + \text{rainfall}] - [\text{PET} - \text{SP} + \text{dW (mm)}] \qquad (5.1)$$

$$\text{SP} = \text{irrigation} + \text{rainfall} - \text{evapotranspiration} - \text{dW} \qquad (5.2)$$

where, PET is potential evapotranspiration, SP is seepage and percolation, and dW is change in soil-water storage in the root zone.

The infiltration rate of the soil was measured with a double-ring infiltrometer (19 cm inner and 38 cm outer diameter) using the methodology as described by Brouwer et al. (1988).

5.2.8 Soil sampling and analysis of soil salinity

To study the salt dynamics in the rice-wheat system, measurements were taken from all treatments in both years. Salinity was assessed in soil samples from predetermined points with 5-12 replications for each treatment. The soil samples were collected at 19 dates in rice 2008, 15 dates in wheat 2009, and 26 dates in rice 2009. In BP, soil samples were collected from both the top of the bed and the center of the furrow to obtain the average salinity of the bed. Soil samples were collected from 0-10, 10-20, 20-30, 30-50, and 50-80 cm depths before irrigation using a tube augur. The soil samples were analyzed for electrical conductivity (EC_p), which is the EC, dS m^{-1} of 1:1 water:soil paste, and was measured according to Chernishov and Shirokova (1999) as cited by Forkutsa et al. (2009). The measured EC_p was converted to the international standard EC value of the saturated soil extract (ECe; Rhoades et al. 1999), and was derived from the equation $EC_e = (2.02 \times EC_p) + 0.14$ ($R^2 = 0.90$) (Akramkhanov 2010).

To measure the groundwater salinity and depth, 15 piezometers, i.e., 12 in the WAD and 3 in the CT-FI treatments were installed and the observations were collected in collaboration with Ph D student Oksana Forkutsa. Water samples were taken from each piezometer before and after irrigation in both crops and analyzed for ECe with a

Hanna instrument (HI 98312) in dS m^{-1}. Groundwater depth is the averaged value from 9-12 observation wells in the WAD and from 2-3 wells in the CT-FI rice treatments in 2008. In 2009 in the wheat and rice treatments, it is the value measured at one-hour intervals by level measurement (DL/N-70) divers and validated based on manual measurements.

5.2.9 Costs and economic analysis

Total variable cost was calculated by adding up the cost of seed, fertilizers, herbicides and other biocides, machinery, human labor, and irrigation water. Human labor for tillage, seeding, irrigation, fertilizer and pesticide application, weeding and harvesting of different treatments of rice and wheat were recorded. The price of human labor, machinery, diesel, rice and wheat grain, and straw were collected through a market survey (Table 5.1). Machinery cost was calculated by adding the cost of fuel consumption for various operations like bund and irrigation canal preparation, ploughing, chiseling, leveling, planting, harvesting and threshing, and transport of various inputs, and the charge for hiring the machines.

The cost of irrigation water was calculated based on the electricity power used by the water pump. The pump required 110 kWatt electricity h^{-1}, i.e., 110 units h^{-1} with a pumping capacity of 500 l water sec^{-1}. A conveyance loss of 30% irrigation water was added in all treatments. The residue was externally applied at the start of the experiment in rice 2008, where the cost of residues was US\$ 86 ha^{-1} for R50 and US\$ 172 ha^{-1} for R100. In the following seasons, the cost of 40% and 70% of the total residue produced was added in R50 and in R100, respectively (Table 5.1). The cost of 10 l diesel ha^{-1} to prepare the beds was added in BP in rice 2008. In CT-II, costs for field preparation as incurred in CT-FI and the cost for other operations as in WAD treatments are considered.

Table 5.1 Cost and revenue variables used to calculate total variable cost and gross revenue in rice-wheat system.

Item	Rice 2008	Wheat 2009	Rice 2009	Wheat 2010
Total variable cost				
Urea (\$ kg^{-1})	0.273	0.236	0.236	0.258
Ammonium phosphate (US\$ kg^{-1})	0.330	0.414	0.414	0.378
Muriate of potash (U\$ kg^{-1})	0.256	0.580	0.580	0.580
Seed (U\$ kg^{-1})	0.933	0.232	1.072	0.251
Labor (U\$ a person day^{-1})	3.589	3.308	3.308	3.308
Diesel (U\$ l^{-1})	0.592	0.716	0.716	0.716
Electricity (U\$ unit^{-1})	0.05	0.046	0.046	0.046
Gross revenue				
Grain (U\$ kg^{-1})	0.359	0.205	0.417	0.232
Straw (U\$ kg^{-1})	0.054	0.033	0.050	0.033

1 \$=1393 Uzbek Soum in 2008, 1511.4 in 2009 and 1630 Uzbek Soum in 2010.

Gross revenue was calculated by adding the revenue from grain and straw. Straw yield on a dry-weight basis was used in the calculation. The gross margin was calculated by deducting the total variable cost of cultivation from the gross revenue. The benefit:cost (B:C) ratio was calculated by dividing gross margin with total variable cost of cultivation. Cost kg^{-1} grain was calculated by dividing total variable cost by total grain yield of the respective treatment. The relationship between the gross margin and the variable price of irrigation water (US\$ m^{-3}) was determined for the CT-FI and RH treatments.

5.2.10 Statistical analysis

Dependent variables were subjected to analysis of variance using PROC GLM (SAS Institute, 2002-2008) for randomized complete block design. Repeated measure analysis was performed for the measurements over time. For detail statistical analysis, see section 3.2.5.

5.3 Results

5.3.1 Rice, wheat and system productivity

Rice

The averaged grain yield of rice was lower ($p<0.001$) by 33% in 2009 (3293 kg ha^{-1}) than in 2008 (4916 kg ha^{-1}). The WAD rice treatments yielded less ($p<0.001$) than the CT-FI and showed an average yield loss of 30% in 2008 and 56% in 2009 (Table 5.2).

Irrespective of residue level, rice yield was not different (p=0.21) between BP and ZT in both years. Yield reduction in the WAD treatments increased with increasing amount of standing residue. For details see section 3.3.7.

Table 5.2 Rice, wheat, and system productivity (kg ha^{-1}) under different irrigation and tillage methods and residue levels in rice-wheat system.

Treatment[a]	Rice		Wheat		System productivity	
	kg ha^{-1}					
	2008	2009	2009	2010	2008/09	2009/10
BP-RH	5368b	3954bc	8253a	6823	13621ab	10777bc
BP-R50	5398b	3494bc	7632abc	7010	13030bc	10504bc
BP-R100	4751b	1945d	7585abc	6353	12337c	8298de
ZT-RH	5099b	4354b	6932c	7349	12031c	11703b
ZT-R50	4773b	3067c	7565abc	6752	12338c	9818cd
ZT-R100	4625b	1468d	7817ab	5895	12442c	7364e
CT-FI	7230a	6900a	7007bc	7804	14238a	14703a
CT-II	-	4218b	-	6630	-	10848bc
Gross mean	5321	3675	7542	6827	12862	10502
P value	^{d}	^{d}	0.057	ns	^{d}	^{d}
LSD (0.05)	947	963	844	1318	1172	1661
Contrast¶	P>F					
WAD vs. CT-FI	^{d}	^{d}	^{b}	^{b}	^{d}	^{d}
PB vs. ZT	Ns	Ns	ns	ns	^{b}	ns
RH vs. R50	Ns	^{b}	ns	ns	ns	^{b}
R50 vs. R100	Ns	^{d}	ns	ns	ns	^{c}
RH vs. R100	Ns	^{d}	ns	^{b}	ns	^{d}
RH vs. CT-II	-	Ns	-	ns	-	ns

[a] BP-RH=bed planting residue harvested, BP-R50=bed planting 50% residue retention, BP-R100=bed planting 100% residue retention, ZT-RH=zero tillage residue harvested, ZT-R50=zero tillage 50% residue retention, ZT-R100=zero tillage 100% residue retention, CT-FI=conventional tillage continuous flood irrigation, CT-II=conventional tillage intermittent irrigation, BP=bed planting, ZT=zero tillage, WAD=frequent wet and dry irrigation, RH=residue harvested, R50=50% residue retention, R100=100% residue retention; ns=nonsignificant (P>0.05), ^{b} P<0.05, ^{c} P<0.01 and ^{d} P<0.001; Contrast is shown as difference in mean values of the treatments. Figures within each column followed by the same letter are not significantly different at p=0.05.

Wheat

Wheat yield decreased (p>0.05) by 10% in 2010 (6827 kg ha^{-1}) compared to 2009 (7542 kg ha^{-1}) (Table 5.2). In 2009, the yield was higher (p=0.05) by 9% in the WAD treatments (wet and dry irrigation applied in rice season) than in the CT-FI, while in 2010, it was lower (p=0.03) by 14% in the WAD treatments. In 2009, BP-RH had a significantly higher yield than ZT-RH and CT-FI, while this was not significantly different with the residue retained treatments of BP and ZT tillage methods. With residue retention, wheat yield was not significantly different between BP and ZT.

In 2010, a more significant yield reduction was observed in the R100 than in the RH treatments of BP and ZT. Grain yield of wheat decreased by 3% with R50 and by 16% with R100 compared to the RH treatments. The residue-harvested treatments of BP and ZT showed higher yields than CT-II of 3 and 10%, respectively.

Rice-wheat system productivity

A significant treatment effect was observed in rice-wheat system productivity in both years (Table 5.2). In CT-FI, system productivity was higher by 13% in 2008/09 and by 51% in 2009/10 than in WAD. The CT-FI treatments showed a higher system productivity of 11% in 2008/09 and 31% in 2009/10 than the RH treatments of BP and ZT. Among the WAD treatments, system productivity was not different between residue levels in 2008/09, while in 2009/10, residue retention decreased the system productivity by 11% with R50 and by 44% with R100 compared to the RH treatments. Irrespective of residue level, system productivity was not different ($p>0.05$) among BP, ZT and CT-II in both years.

In 2010, the wheat leaf samples before flowering showed a low N and high manganese concentration in the treatments with a higher amount of residue retention (R100) than in the RH (Table 5.3). Major plant nutrients like phosphorus, potassium, and zinc were lower in R100 than in RH.

Table 5.3 Wheat leaf nutrient concentration before flowering stage 2010 analyzed at Turkey and India.

Nutrient	Turkey		India	
	R100[a]	RH	R100	RH
Nitrogen (%)	2.69±0.10	4.61±0.52	-	-
Phosphorus (%)	0.27±0.01	0.32±0.03	0.26	0.29
Potassium (%)	2.28±0.19	2.82±0.06	2.0	3.15
Manganese (mg kg^{-1})	34.9±5.60	30.6±1.7	26.0	18.8
Zinc (mg kg^{-1})	10.3±0.7	14.4±1.7	11.6	12.4

[a] R100=100% residue retention, RH=residue harvested.

5.3.2 Water application and balance in rice-wheat system

Water application

The amount of irrigation water applied in both rice and wheat was affected ($p<0.001$) by tillage method (Table 5.4). In rice, the amount of water was significantly higher in CT-FI than in WAD in both years. The amount of water in the WAD treatments was 30% of the total amount applied in CT-FI in both years. Among the WAD treatments, BP showed a higher water-saving potential than ZT, where 19% more irrigation water was saved than under ZT in both years.

In wheat, the amount of irrigation water applied in BP was 19% less in 2009 and 13% less in 2010 compared to ZT (Figure 5.1). In the rice-wheat system, BP saved 15 and 67% irrigation water compared to ZT and CT-FI, respectively (Table 5.4).

Table 5.4 Amount of water applied (mm) under different tillage methods in rice-wheat system 2008-2010.

Treatment[a]	Rice 2008	Wheat 2009	Rice 2009	Wheat 2010	System 2008/09	System 2009/10
CT-FI	6691	627	5906	668	7318	6574
BP	1736	461	1768	584	2197	2352
ZT	2065	548	2088	668	2613	2756
CT-II	-	-	2171	668	-	2839
Farmer’s field	-	-	9650	-	-	-

[a] CT-FI=conventional tillage flood irrigation, BP=bed planting, ZT=zero tillage, CT-II=conventional tillage intermittent irrigation.

Water balance

In the rice-growing season, potential evapotranspiration (PET) was 525 mm in 2008 and 487 mm in 2009. The irrigation water loss through seepage and percolation was higher (more than 90%) in the CT-FI than in the WAD treatments (67%; Figure 5.1). Under similar conditions in farmers’ fields, a seepage and percolation loss of more than 95% of the applied irrigation water was observed. During seedling establishment (June), losses in the WAD treatments were higher than under CT-FI in both years, while after seedling establishment, losses were higher under CT-FI.

In the wheat growing season, PET was 495 mm in 2009 and 530 mm in 2010. In both years, water loss from seepage and percolation was negligible from the wheat field except in October in all treatments (Figure 5.1).

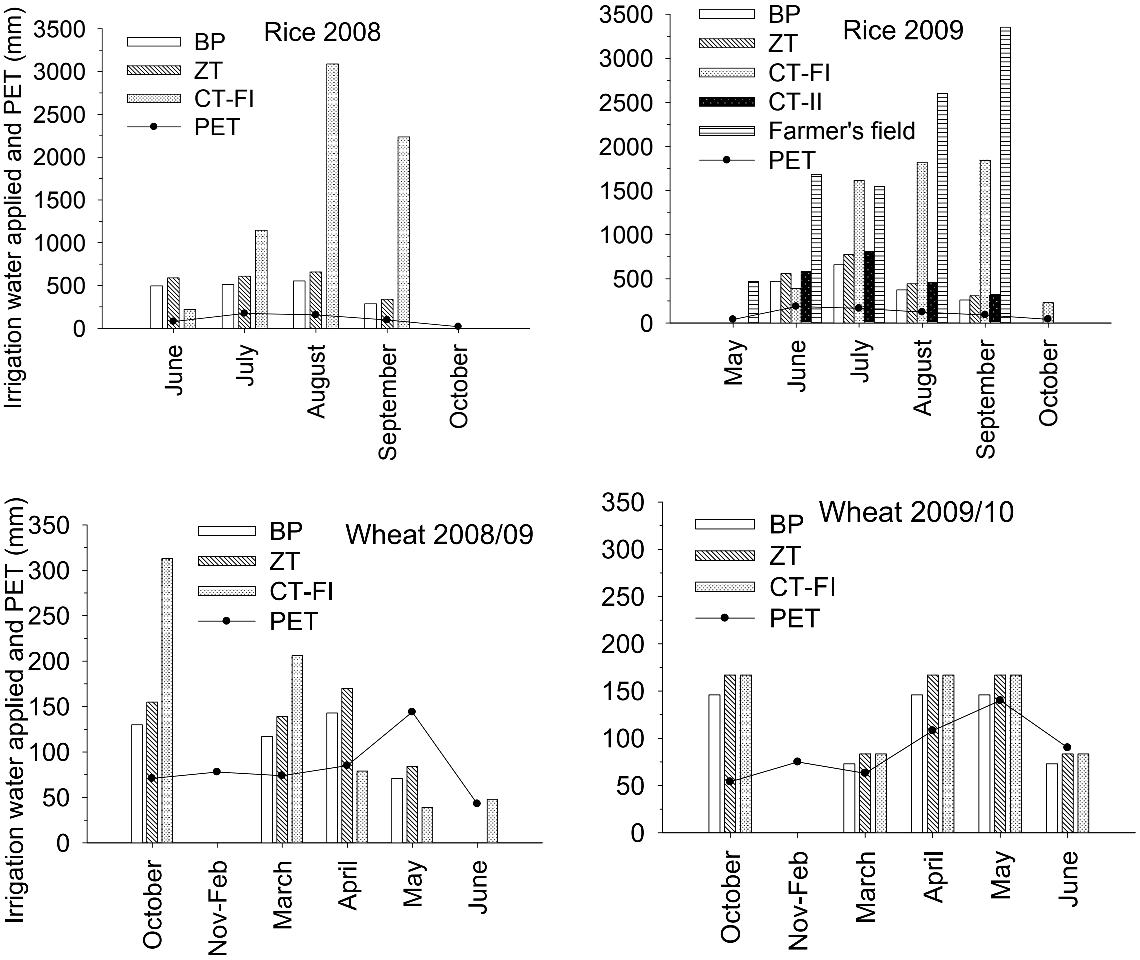


Figure 5.1 Amount of irrigation water applied and potential evapotranspiration (PET) (mm) during rice- and wheat-growing season, 2008-2010; BP=bed planting, ZT=zero tillage, CT-FI=conventional tillage flood irrigation, CT-II=conventional tillage intermittent irrigation, PET=potential evapotranspiration; connecting lines are added for better visualization.

The infiltration rate of the top 10 cm soil was 1 cm h^{-1} in the WAD rice field, while it was 0.5 cm h^{-1} in the unirrigated fallow land adjacent to the experimental field (Figure 5.2).

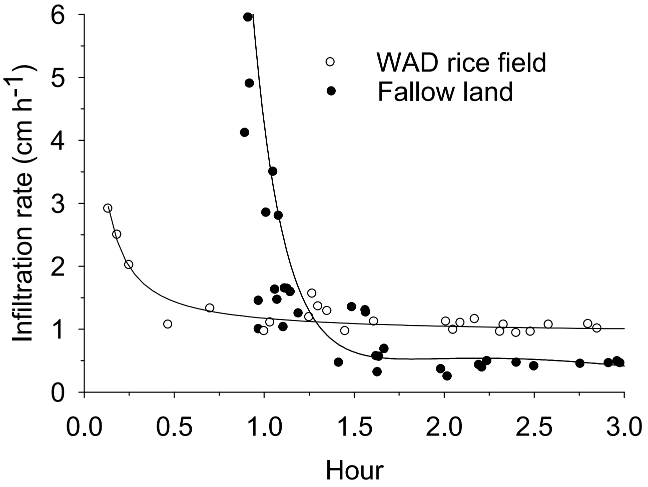


Figure 5.2 Infiltration rate (cm h^{-1}) of the soil of the WAD irrigated rice field and fallow land adjacent to the experimental area.

5.3.3 Soil salinity in rice-wheat system

Soil salinity was reduced with increased soil depth in all treatments, and the effect was significant up to the top 30 cm depth (Figure 5.3). The initial soil salinity, i.e., after leaching and laser leveling in 2008, was 4.0 dS m^{-1} in the top 30 cm soil. Compared to the initial level, salinity in the top 30 cm decreased by 48% in the WAD treatments and by 61% in the CT-FI treatments in rice 2008. Soil salinity during the wheat-growing season was not significantly different to that of rice 2008. In rice 2009, salinity in the top 30 cm further decreased by 48% in the WAD treatments and by 34% under CT-FI compared to the wheat season. In all crop-growing seasons, BP-RH had the highest ($p<0.001$) salinity level in all soil depths followed by BP-R100, ZT-RH, ZT-R100 and CT-FI.

Soil salinity in the rice-wheat system in the top 30 cm soil was affected ($p<0.001$) by tillage method and remained consistently higher in BP followed by ZT and CT-FI (Figure 5.3). BP-RH showed a significantly higher salinity of 55% in rice 2008, of 70% in wheat 2009, and of 51% in rice 2009 compared to ZT-RH. Salinity under ZT-RH and CT-FI was not significantly different at all soil depths.

Among the WAD treatments, soil salinity was significantly affected by the interaction between tillage method and residue level. The higher salinity in BP-R100 than in ZT-RH indicates that soil salinity was more affected by the tillage method than by the residue level. Irrespective of the tillage method, salinity was not affected by residue level in rice 2008. However, soil salinity was consistently higher in RH than in R100 in wheat 2009 and rice 2009 (Figure 5.3). In wheat, RH treatments had an 8% higher salinity than R50, and 18% higher than R100 in the top 30 cm soil. Similarly, in rice 2009, soil salinity in the RH treatments was 15% higher than in the R50, and 19% than in the R100 treatments in the top 30 cm soil. Overall, in the rice-wheat system, irrespective of tillage method, RH treatments had an 8-19% higher soil salinity than the treatments with residue retention.

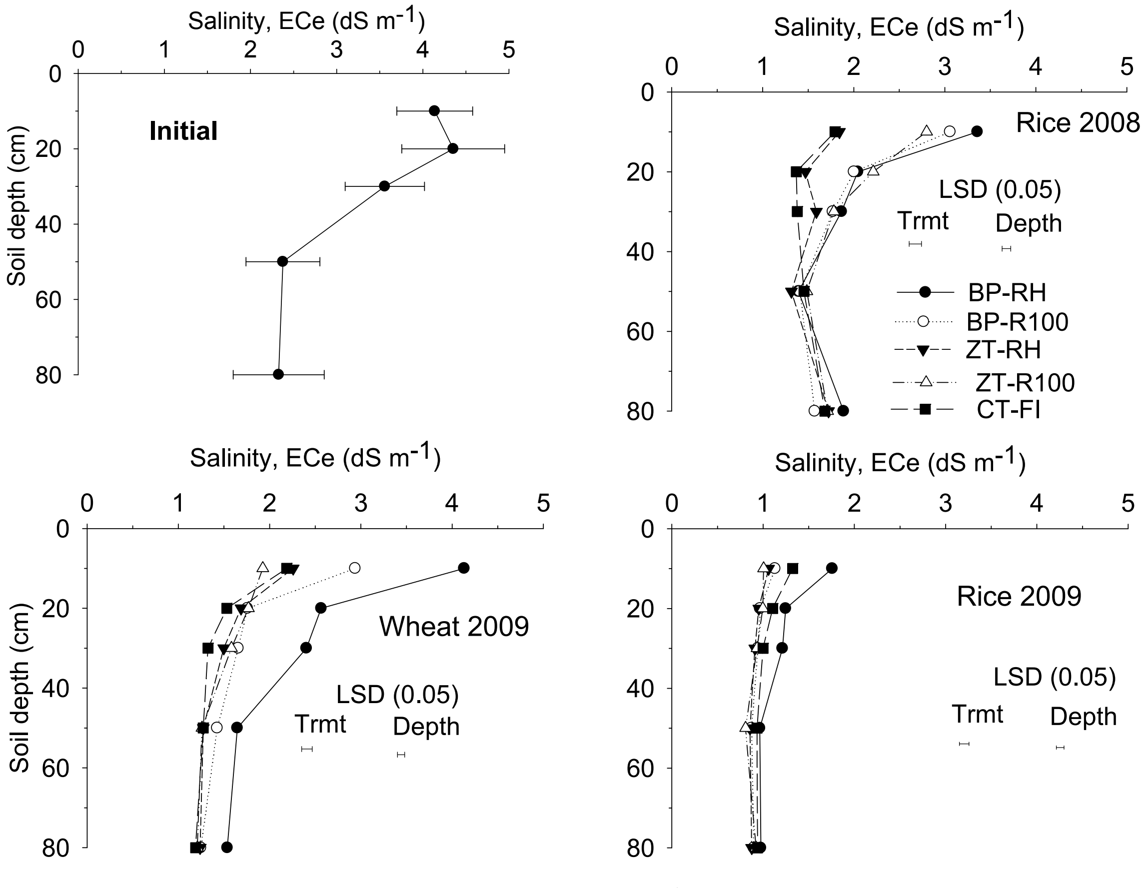


Figure 5.3 Averaged soil salinity (ECe, dS m^{-1}) during rice- and wheat-growing season in different soil depths as affected by tillage and irrigation methods and residue level in 2008 and 2009; LSD (0.05) is difference between treatment over time at P=0.05; BP-RH=bed planting residue harvested, BP-R100=bed planting 100% residue retention, ZT-RH=zero tillage residue harvested, ZT-R100=zero tillage 100% residue retention, CT-FI=conventional tillage flood irrigation.

5.3.4 Groundwater salinity and dynamics in rice-wheat system

The average groundwater salinity was 2.3 dS m^{-1}during the rice season 2008, 2.2 dS m^{-1} during the wheat season 2009, and 1.5 dS m^{-1}during the rice season 2009 (Figure 5.4).

Irrespective of tillage method and residue level, groundwater salinity was affected by irrigation method ($p<0.05$). In rice 2008, groundwater salinity was higher by 38% in the WAD (2.42 dS m^{-1}) than in the CT-FI treatments (1.75 dS m^{-1}). Similarly, during the wheat season, groundwater salinity was higher by 13% in the WAD treatments (2.20 dS m^{-1}) than in CT-FI (1.94 dS m^{-1}). In contrast, during the rice season 2009, groundwater salinity was higher by 17% in the CT-FI (1.68 dS m^{-1}) than in the WAD treatments (1.43 dS m^{-1}; data source: Forkutsa, 2011 forthcoming).

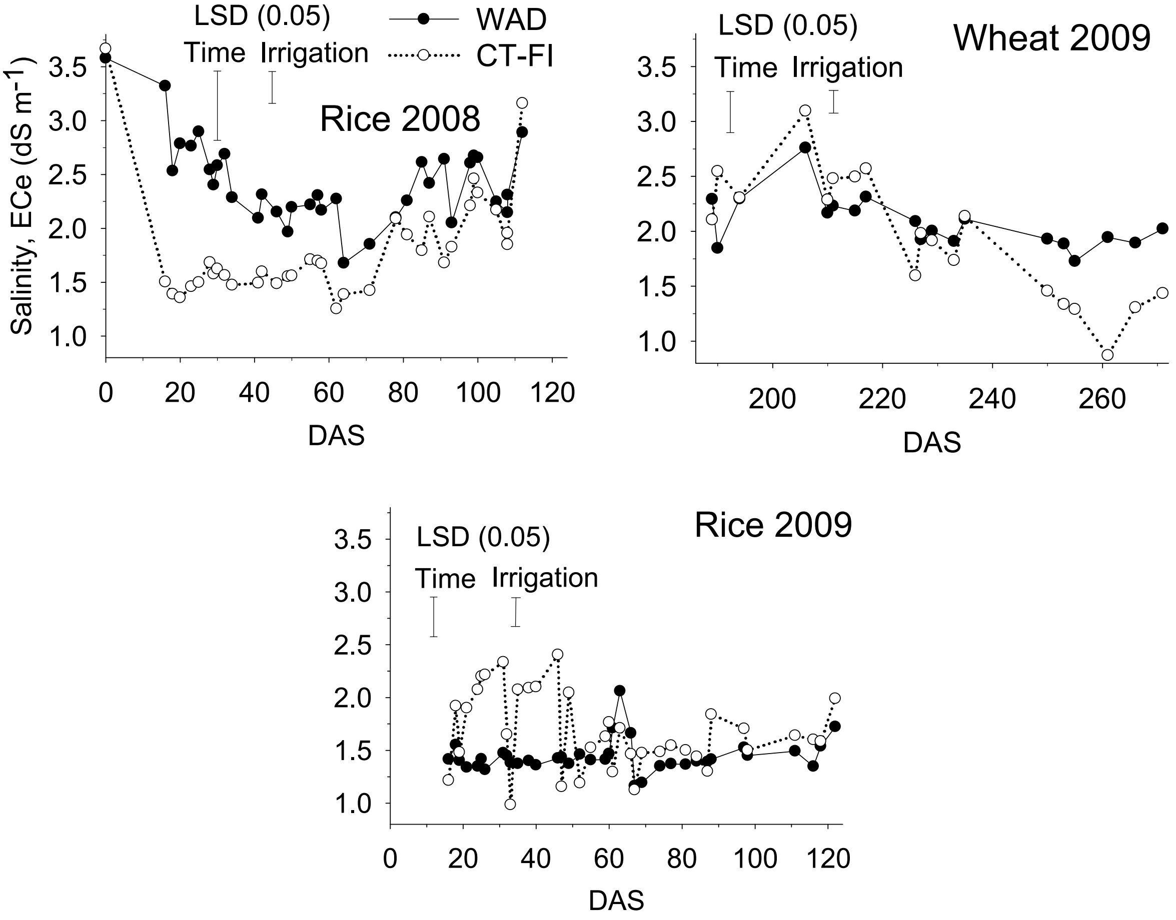


Figure 5.4 Groundwater salinity (ECe, dS m^{-1}) in rice-wheat system as affected by irrigation method; LSD (0.05) values are difference between time and irrigation method; WAD=frequent intermittent wet and dry irrigation, CT-FI=conventional tillage flood irrigation; DAS=days after sowing.

At the start of cropping season, the depth of the groundwater table was 1.97 m (Figure 5.5). During rice growing period in both 2008 and 2009, the averaged groundwater table in the WAD treatments was deeper ($p<0.001$) than in the CT-FI. During the wheat-growing period, groundwater depth was not different ($p< 0.001$, 6 cm difference) between WAD and CT-FI. In 2008, the rice-growing period was fairly dry compared to 2009.

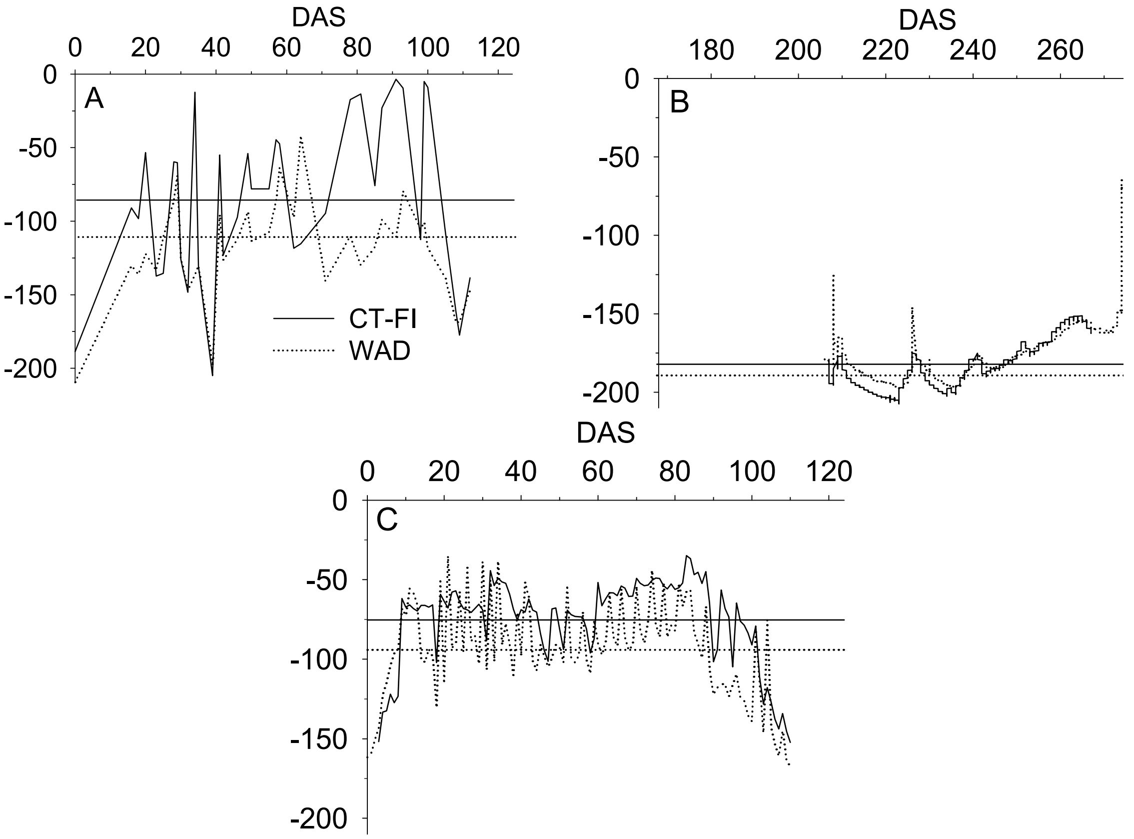


Figure 5.5 Groundwater dynamics in WAD and CT-FI irrigation treatments in rice 2008 (A), wheat 2009 (B) and rice 2009 (C) in Khorezm region of Uzbekistan; DAS=days after sowing; horizontal lines indicate mean groundwater depth during crop-growing season in CT-FI and WAD treatments.

5.3.5 Economic performance of rice and wheat under different irrigation and tillage methods and residue levels

Total variable cost of production

Precision land leveling included deep ploughing, chiseling, flat leveling and laser leveling. For the undulated topography (15-25 cm) of the experimental field, including the cost of 80 l diesel ha^{-1} plus the cost for hiring the tractor and laser level equipment, the cost was US$ 97 ha^{-1} (Table 5.5).

Table 5.5 Cost of cultivation (US$ ha^{-1}) of rice and wheat under different irrigation methods.

Item[a]	Rice 2008		Wheat 2009		Rice 2009		Wheat 2010	
	WAD†	CT-FI	WAD	CT-FI	WAD	CT-FI	WAD	CT-FI
Precision land leveling	97	97	-	-	-	-	-	-
Fertilizer	257	257	239	239	299	299	274	274
Seed	121	121	46	46	139	139	47	47
Herbicide	77	36	6	6	83	45	22	22
Machinery	71	88	59	59	79	105	64	64
Labor	82	65	57	57	79	77	64	64
Irrigation	82	267	18	23	77	217	22	25
Residue								
R50	86	-	126	-	110	-	116	-
R100	172	-	219	-	194	-	136	-
Total variable cost	787	931	425	430	756	882	493	496

[a]WAD=frequent intermittent wet and dry irrigation, CT-FI=conventional tillage flood irrigation; [b]R50= 50% residue retention, R100= 100% residue retention.

For rice, the cost of fertilizer and seed in both years was same for all treatments. Herbicide use for weed control was higher in the WAD than in the CT-FI treatments (Table 5.5). Total diesel consumption during planting, preparation of bund and irrigation canals, combined harvesting and threshing, and transportation of grain and straw was higher in the CT-FI (106 l ha^{-1} in 2008 and 110 l ha^{-1} in 2009) than in the WAD treatments (78 l ha^{-1} in 2008 and 73 l ha^{-1} in 2009). The total machinery cost combined with the fuel and the rent for the above operations was higher in the CT-FI than in the WAD treatments. Despite the use of herbicide, labor used for weed control was higher in the WAD treatments than in the CT-FI. The cost of irrigation water in rice was higher in the CT-FI than in the WAD treatments in both years. Thus, the total variable cost for rice was higher in the CT-FI (US$ 931 ha^{-1} in 2008 and US$ 882 ha^{-1} in 2009) than in the RH treatments of WAD irrigation (US$ 787 ha^{-1} in 2008 and US$ 756 ha^{-1} in 2009).

For wheat, as it was broadcast seeded with the same seed rate and fertilizer dose in all treatments, total variable cost (except the cost of irrigation water) was same in all treatments in both years (Table 5.5).

Economic analysis

For rice, total variable cost, gross revenue, gross margin, B:C ratio, and cost kg^{-1} grain were affected ($p<0.01$) by tillage methods, residue levels and irrigation methods in both crops and in both years (Table 5.6). Significantly higher gross revenue, gross margin, B:C ratio, and the lowest cost of production kg^{-1} grain were observed in CT-FI rice in both years followed by BP-RH and ZT-RH, and the lowest under ZT-R100 and BP-R100 (Figure 5.6 and Table 5.6).

For wheat, gross revenue, gross margin and B:C ratio were higher in the BP-RH and lowest in the CT-FI treatments in 2009. In contrast, in 2010, CT-FI followed by the residue-harvested treatments of BP and ZT showed higher gross revenue, gross margin and B:C ratio than the residue-retained treatments (Figure 5.6).

In the rice-wheat system, gross margin and B:C ratio were not significantly different between CT-FI and BP-RH, while they were lower ($p<0.05$) under BP-R100 and ZT-R100 in 2008. In 2009, gross margin and B:C ratio were significantly higher in the CT-FI than in the WAD treatments. Irrespective of tillage method, among the WAD treatments, gross margin and B:C ratio were reduced in the residue-retained treatments.

The gross margin in the CT-FI treatments is higher than in the RH treatments under the current price for pumping the irrigation water (US$ 0.0038 m^{-3}; Figure 5.7). When the price increased, cost of irrigation water goes up and the gross margin declined faster for the CT-FI than for the RH treatments. Rice cultivation can still be profitable when the current pumping price is 5 times higher (US$ 0.019) in the CT-FI treatments and 10 times higher (US$ 0.038) in the RH.

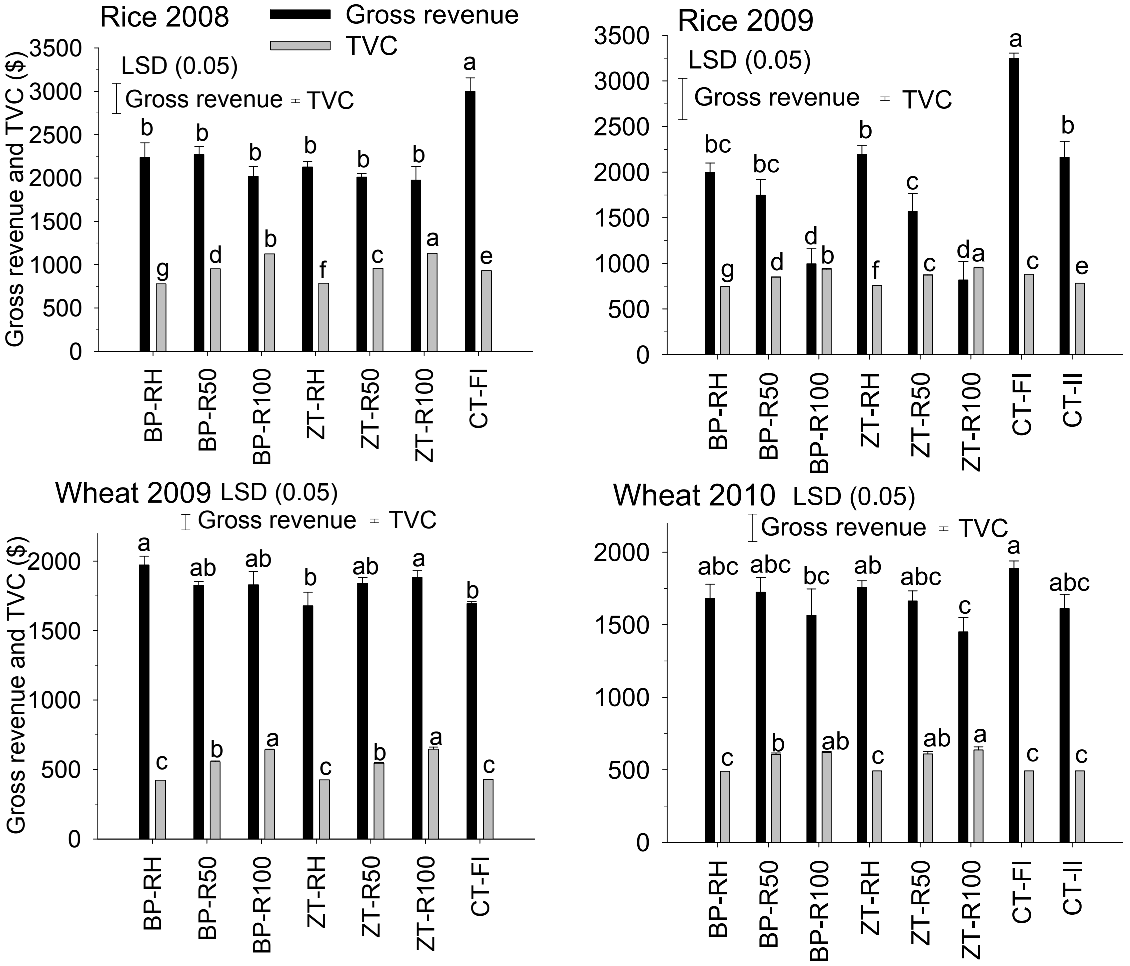


Figure 5.6 Gross revenue and total variable cost (TVC) of cultivation for rice and wheat grown under different irrigation and tillage methods and residue levels in rice-wheat rotation during 2008-2010, Khorezm, Uzbekistan.

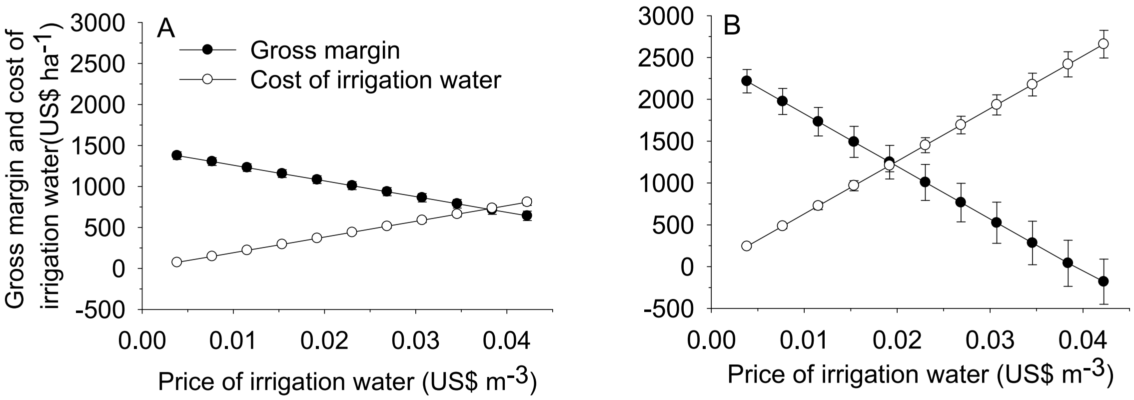


Figure 5.7 Gross margin and cost of irrigation water (US$ ha^{-1}) under increased price of irrigation water (US$ m^{-3}) in residue harvested (RH) (A) and conventional tillage flood irrigation (CT-FI) (B) for rice in 2008-2009 in Khorezm, Uzbekistan.

Table 5.6 Economic return (US\$ ha^{-1}) from rice and wheat under water-saving and different irrigation and tillage methods and residue levels 2008-2010.

Item	**BP-RH**	**BP-R50**	**BP-R100**	**ZT-RH**	**ZT-R50**	**ZT-R100**	**CT-FI**	**CT-II**	**Mean**	**P-value**	**LSD (0.05)**
Rice 2008											
Revenue from grain	1927b	1937b	1705b	1830b	1713b	1660b	2595a	-	1910	<0.001.	340
Revenue from straw	308b	333b	312b	296b	297b	315b	402a	-	323	<0.001	39.5
Gross revenue	2235b	2270b	2018b	2126b	2010b	1975b	2997a	-	2233	<0.001	365
Total variable cost	780g	952d	1124b	787f	959c	1131a	931e	-	952	<0.001	0
Gross margin	1455b	1318bc	894d	1340bc	1051cd	844d	2066a		1281	<0.001	365
B:C ratio	1.87ab	1.39cd	0.80d	1.70bc	1.10de	0.75d	2.22a		1.40	<0.001	0.38
Cost kg^{-1} grain	0.15cd	0.18bc	0.24a	0.15cd	0.20b	0.25a	0.13d	-	0.19	<0.001	0.037
Wheat 2009											
Revenue from grain	1693a	1565abc	1556abc	1422c	1552abc	1603ab	1437bc	-	1547	0.053	173
Revenue from straw	280ab	261ab	274ab	257b	288a	279ab	256b	-	271	0.22	30.6
Gross revenue	1973a	1826ab	1830ab	1679b	1839ab	1883a	1693b		1818	0.04	185
Total variable cost	423c	556b	642a	426c	545b	646a	429c	-	524	<0.001	19.2
Gross margin	1550a	1270b	1188b	1253b	1294b	1237b	1264b	-	1294	0.011	178
B:C ratio	3.66a	2.29c	1.85d	2.94b	2.37c	1.91d	2.95b	-	2.57	<0.001	0.35
Cost kg^{-1} grain	0.05d	0.07b	0.09a	0.06c	0.07b	0.08a	0.06c	-	0.07	<0.001	0.007
Rice 2009											
Revenue from grain	1648bc	1457bc	811d	1815b	1278c	612d	2876a	1758b	1532	<0.001	401.5
Revenue from straw	348ab	290b	184c	378a	291b	206c	372a	402a	309	<0.001	74
Gross revenue	1996bc	1746bc	995d	2193b	1569c	818d	3248a	2161b	1841	<0.001	453
Total variable cost	745g	849d	936b	756f	871c	952a	882c	782e	847	<0.001	11.6
Gross margin	1251bc	898cd	58e	1437b	698d	-134e	2366a	1378b	994	<0.001	451
B:C ratio	1.68b	1.06c	0.06d	1.90b	0.80c	-0.14d	2.68a	1.76b	1.23	<0.001	0.52
Cost kg^{-1} grain	0.19c	0.25bc	0.53b	0.17c	0.30bc	0.86a	0.13c	0.19c	0.33	0.007	0.31
Wheat 2010											
Revenue from grain	1465abc	1505abc	1364bc	1578ab	1450abc	1266c	1676a	1424abc	1466	0.16	283
Revenue from straw	215ab	219a	200abcd	178d	214abc	185cd	210abc	187bcd	201	0.05	29.6
Gross revenue	1680abc	1724abc	1564bc	1756ab	1663abc	1451c	1886a	1611abc	1667	0.17	297.6
Total variable cost	490c	606b	619ab	493c	610ab	637a	493c	493c	555	<0.001	30
Gross margin	1190abc	1118abc	945cd	1263ab	1054bcd	814d	1392a	1117abc	1112	0.013	290
B:C ratio	2.43ab	1.84cd	1.53de	2.56ab	1.73de	1.27e	2.82a	2.26bc	2.06	<0.001	0.50
Cost kg^{-1} grain	0.07cd	0.09bc	0.10ab	0.07d	0.09bc	0.11a	0.06d	0.08cd	0.08	<0.001	0.017

Table 5.6 continued

Item	BP-RH	BP-R50	BP-R100	ZT-RH	ZT-R50	ZT-R100	CT-FI	CT-II	Mean	P-value	LSD (0.05)
System 2008/09											
Gross revenue	4208b	4096bc	3847bc	3805c	3849bc	3857bc	4690a	-	4050	0.001	396
Total variable cost	1202d	1508b	1765a	1213d	1504b	1777a	1360c	-	1476	<0.001	19.3
Gross margin	3005a	2589b	2082c	2592b	2346bc	2080c	3330a	-	2575	<0.001	383
B:C ratio	2.50a	1.72c	1.18d	2.14b	1.56c	1.17d	2.45a	-	1.82	<0.001	0.24
System 2009/10											
Gross revenue	3676bc	3471bc	2559d	3949b	3232c	2268d	5134a	3772bc	3508	<0.001	564
Total variable cost	1235f	1455c	1555b	1250ef	1481c	1589a	1375d	1276e	1402	<0.001	33.2
Gross margin	2441bc	2015cd	1003e	2700b	1751d	679e	3759a	2496bc	2106	<0.001	543
B:C ratio	1.98b	1.38c	0.65d	2.16b	1.18c	0.42d	2.73a	1.96b	1.56	<0.001	0.35
Rice-wheat system											
Gross revenue	3942b	3784bc	3203de	3877bc	3541cd	3063e	4912a	3772bc	3762	<0.001	398
Total variable cost	1219f	1482c	1660b	1231f	1492c	1683a	1368d	1276e	1426	<0.001	22.6
Gross margin	2723b	2302cd	1543e	2646bc	2048bc	1380e	3544a	2496bc	2335	<0.001	382
B:C ratio	2.24b	1.55d	0.91e	2.15bc	1.37d	0.80e	2.59a	1.96c	1.69	<0.001	0.25

BP-RH=bed planting residue harvested, BP-R50=bed planting 50% residue retention, BP-R100=bed planting 100% residue retention, ZT-RH=zero tillage residue harvested, ZT-R50=zero tillage 50% residue retention, ZT-R100=zero tillage 100% residue retention, CT-FI=conventional tillage continuous flood irrigation, CT-II=conventional tillage intermittent irrigation.

5.4 Discussion

Worldwide evidence indicates that farmers need incentives to shift from conventional to innovative cultivation practices. A major incentive is obviously the financial feasibility. For four seasons, the results of this study indicate that changing rice cultivation from flood-irrigated to water-saving irrigation methods reduced overall rice-wheat system productivity, gross margin and B:C ratio over time. However, the CA practices can significantly reduce the amount of irrigation water especially in rice cultivation in the region.

5.4.1 Rice-wheat system productivity

The lower rice-wheat system productivity in the WAD than in CT-FI treatments can mostly be associated with the reduction of rice yield in both years. The reduction was primarily due to the soil-water stress during the grain-setting phase (Chapter 3) and to the higher amount of unaccounted mineral N through WAD irrigation (Chapter 4).

Saharawat et al. (2010) reported similar reductions in a no-till drill-seeded rice-wheat system compared to a conventional system in a semi-arid region of India; the authors attributed this to the reduced rice yield. Water stress in lowland rice can occur when soil-water content drops below saturation (Bouman and Tuong 2001). Also, due to the frequent wet and dry phases, the soil redox potential changes rapidly, which could accelerate the rapid N losses (Vlek and Craswell 1981).

The decline in system productivity in 2009/10 compared to 2008/09 could also be associated with the negative effect of the increasing amount of residue where, in the rice season 2009, a cumulative standing residue of 11.3 t ha^{-1} in R100 and 7.0 t ha^{-1} in R50 was retained (section 4.2.3). With increasing amounts of retained residue, rice yield consistently decreased in both years, while wheat yield was not affected in the first year but reduced under a higher amount of residue in the second year (Table 5.2). The rice yield reduction in the residue-retained treatments was due also to slow crop growth and delayed phenological development rates (Chapter 3). This has previously been associated with the decreased soil temperature under residue retention (Chapter 3; Sandhu et al. 1980, Zhang et al. 2009), higher amount of unaccounted mineral N from wet and dry irrigation combined with residue retention (Chapter 4), N immobilization by residues (Quemada and Cabrera 1995; Jenkinson 1985; Rao and Mikkelsen 1976), higher ammonia volatilization and denitrification losses of N under residue retention (Philips et al. 1980; Rice and Smith 1982, 1984; Patra et al. 2004), and reduced light interception due to the shading effect of the standing residue (Yoshida 1981).

The inconsistent wheat yield among different treatments in 2009 and 2010 could be due to the difference in the amount of retained residue (section 4.2.3). The higher wheat yield in the WAD treatments in 2009 could be due to the availability of higher residual mineral N from the rice crop (Chapter 4). Furthermore, availability of applied N could have been higher due to lower immobilization in the presence of less residues in the first year. In contrast, the lower wheat yield in the residue-retained treatments in 2010 could be due to the lower availability of mineral N (data not available) and N immobilization due to the retention of too much residue (>17 t ha^{-1} in R100 and >11 t ha^{-1} in R50). Rice and wheat residue can immobilize up to 34% of the applied N (Quemada and Cabrera 1995), and the N rate should be increased by 15% under residue-retained zero-till direct-seeded conditions (Ladha et al. 2009a). The more chlorotic leaf and stronger yellowing of the wheat plants in the R100 than in the RH treatments in 2010 (Table 5.3) further indicate that the lower yield was mostly due to N deficiency. Furthermore, the difference in leaf nutrient content in the RH and R100 treatments indicates nutritional imbalance and deficiency with R100. This is possible, as all the fertilizers were broadcast applied in both crops, as an appropriate machine was not available and/or soil moisture conditions were not suitable for drilling fertilizers to the appropriate soil depth. These findings are comparable to the findings of Singh et al. (2008), who compared permanent raised bed rice-wheat systems with and without mulching with 6 t ha^{-1} rice straw and 5 t ha^{-1} wheat straw at the time of seeding wheat and rice, respectively. Mulching caused a significant reduction in the yield of direct-seeded rice on permanent beds in 3 of the 4 years, while there was no effect of mulching on the yield of drill-seeded wheat.

The wider gap in rice-wheat system productivity between the WAD and CT-FI treatments in this study compared to the other studies could be due to (1) differences in weather conditions, i.e., high temperatures and dry weather during the rice season, where the possibility of N loss is high under the alternating aerobic-anaerobic cycle (Vlek and Byrnes 1986; Reddy and Patrick 1976; Patrick and Wyatt 1964), (2) high amount of standing residue retention without chopping and rolling, (3) broadcast application of all fertilizers without proper drilling, which leads to high N loss (Raun and Johnson 1999), and (4) broadcast seeding of wheat in a too thick residue layer. Hence, although mulching is seen as one of the three pillars of conservation agriculture, site-specific recommendations need to be developed regarding the amount of residue to be retained and its management. An insufficient amount would not lead to increased soil-organic carbon and total nitrogen (Chivenge et al. 2007), whilst an over-application of residues may trigger yield decrease instead of higher system stability. Further simulation studies are needed to determine the ideal residue retention. Also, the gap in system productivity can be minimized through the use of proper machinery for fertilizer application, and good residue management and proper seeding in both crops. Furthermore, the rice variety used in this study is adapted and released for flood-irrigated lowland conditions. Upon the availability and the use of suitable aerobic varieties, the yield gap between flood irrigation and wet and dry irrigation can be minimized (Singh et al. 2003).

5.4.2 Water application and balance

Despite the reduction in rice-wheat system productivity, an almost three times lower water application in the residue harvested (RH) treatments with WAD irrigation than in the CT-FI treatments in both years (Figure 5.1) shows the great potential of dry-direct seeded rice on raised beds or zero tillage flat-surface seeded wheat for water saving in the region. The current rice-wheat system productivity of Central Asia (4.5 t ha^{-1} in 2008/09 and 5.2 t ha^{-1} in 2009/10), Uzbekistan (7.5 t ha^{-1} in 2008/09 and 10.1 t ha^{-1} in 2009/10) and the Khorezm region (8.22 t ha^{-1} in 2008/09 and 9.13 t ha^{-1} in 2009/10) (FAOSTAT 2010; OblStat 2010) was significantly lower than the system productivity of the residue-harvested treatments of this experiment in both years (Table 5.2). In the current farmers' practices, the water application in rice-wheat systems in Uzbekistan greatly exceeds 40,000-50,000 m^3 ha^{-1} (Aldaya et al. 2010; Bobojonov 2008). Saving of only 30% of the existing water use (≈60,000 m^3 ha^{-1}) in the conventional method of rice cultivation (CT-FI) may save enough water for an additional 77,000 ha rice-wheat system in the region. Alternately, this amount of water is sufficient to irrigate almost 0.5 million ha of wheat or cotton. Thus, under diminishing water supply conditions, residue-harvested, dry-direct seeded rice-wheat systems with water-saving irrigation could be a potential crop cultivation method in the region.

The amount of water applied during germination and seedling establishment in the WAD treatmements was higher than in the CT-FI. Dry-direct seeding of rice under low volumetric soil moisture content (<15%), high solar intensity (286 w m^{-2}), low relative humidity (38%), and high temperature (27.2 °C) during seeding could be the reasons for the higher demand for water. In contrast, wet-direct seeding of pre-germinated rice seed (24 hours soaked and 24 hours incubated) under CT-FI led to the faster germination and seedling establishment with less irrigation water. The higher water application in the rice-wheat system in the CT-FI treatment than in the WAD treatments in this experiment was mainly due to the higher amount of water applied in the rice season. The continuous flood irrigation with more than 15 cm standing water to control weed is the common farmers’ practice in the region.

The amount of water applied in rice in this study in both WAD and CT-FI treatments was higher than in similar experiments conducted over shallow groundwater depths (<30 cm) in the Philippines by Belder et al. (2005b), who applied 800 mm water in alternate wet and dry and 1200 mm in flood irrigation under transplanted conditions. Similarly, under the same condition in the Philippines, Tabbal et al. (2002) applied 1270 mm irrigation water in dry-direct seeded rice and 1700 mm in flood-irrigated. The higher amount of water applied in this study could be due to the rapid vertical movement of water from soil cracks especially in the WAD treatments. The disappearance of 4-5 cm applied water within 5-6 hours from the WAD treatments further explains the higher water loss through the high infiltration rate of the soil (Figure 5.2) and from the soil cracks. The higher infiltration rate of the soil in the WAD irrigated rice field could be due to the absence of a capillary barrier in the homogenously saturated soil column (Lee et al. 2011) with the shallow groundwater (< 1.2 m) and the no-till management (Abid and Lal 2009). Forkutsa (2006) also reported a topsoil infiltration rate of 1-2 cm h^{-1} in the Khorezm region.

In the presence of cracks, Mishra et al. (1991) and Bhuiyan et al. (1995) also applied similar amounts of water in non-flooded and flooded rice. Furthermore, the presence of a sand layer after 45 cm soil depth (70 % sand, 28% silt and 2% clay), shallow groundwater table (1.6 m in 2008 and 0.9 m in 2009), deep ploughing for laser leveling before the start of the experiment, and no history of rice cultivation in the field in the past 20 years may explain the higher water loss through seepage and percolation. The easily permeable sandy soils in Khorezm are not suitable for paddy rice cultivation, because daily infiltration losses amount to 5.1-5.4 mm (Baraev 1989). Furthermore, as the CT-FI block was close to the drainage canal, the water loss and thus the application rate may have further increased under CT-FI. The amount of irrigation water measured in the farmer’s field (7.4 ha area in rice variety Avangart, 120 days maturity) near the experimental field showed that farmers in this region apply even higher amounts of water than that measured in the CT-FI (Figure 5.1).

Furthermore, there is potential to reduce the amount of irrigation water in WAD treatments through the proper management of cracks through shallow surface tillage (Cabagon and Tuong 2000), through the use of primed seed (Farooq et al. 2006), and through strip till cultivation and transplanting (Sayre and Hobbs 2004).

5.4.3 Soil salinity in rice-wheat system

Soil salinity is the result of the interaction between soil, water, and management practices that contribute to actual salt movement in the soil profile. In all treatments, higher salinity in the top 30 cm soil is associated with the salt movement from high soil moisture to low soil moisture. The decrease in soil salinity in the 2008 rice season compared to the initial level, and the decrease in the 2009 season compared to wheat without early spring leaching indicates that salinity in overall decreases with rice planting under both WAD and CT-FI. Decreased soil salinity due to rice cultivation was also reported by Bhumbla and Abrol (1978). The lowest salinity under CT-FI could be due to the continuous irrigation and maintenance of standing water. Despite the higher soil salinity level in BP, the salinity level in this study remained around or below the threshold level of rice and wheat (Figure 5.3). Similarly, although residue removal increased the salinity, values were also below the threshold level of rice and wheat. Rice is a salt-sensitive crop, and yield reduction starts in soil salinity above 3 dS m^{-1}, going up to 50% at 6 dS m^{-1}, and 90% at 10 dS m^{-1} (Shannon 1997), while in wheat yields declines at 6 dS m^{-1}. The above results indicate that under diminishing water supply conditions, salinity will not be a problem with BP and ZT cultivation methods using water-saving irrigation.

5.4.4 Economic performance and system sustainability

CT-FI showed a higher gross margin than the WAD treatments in the rice-wheat system. As the B:C ratio and the cost kg^{-1} grain in the WAD treatments was almost 50% of that of the CT-FI, even under a 3-4 times higher water price than the current, CT-FI remains more profitable than WAD in arid drylands. The lower gross margins in the rice-wheat system in the WAD treatments were mostly due to lower rice yields. Similar findings in dry-direct seeded rice-wheat systems due to reduction in rice yield were also reported by Dhaliwal et al. (2008) and Ladha et al. (2009a) in India. As wheat was direct-surface seeded into the standing rice in all treatments, the total variable cost of production was same in both CT-FI (single zero-till system) and WAD (double zero-till system).

The non-significant difference in system productivity, B:C ratio and gross margin among the residue-harvested treatments of BP, ZT and CT-II indicates that soil tillage is not necessary for rice and wheat cultivation. Bradfield (1971), Partohardjono and Harahp (1979) and Scheltema (1974) also reported that rice can be grown under no tillage conditions without reduction in yield. Upon adoption of these practices, the indirect benefits from no-tillage on soil quality and the reduction of environmental pollution could be additional advantages.

The actual price of pumping irrigation water (US\$ 0.0038 m^{-3}) in this study is several times lower compared to that in southeast Asia (India, Nepal, Bangladesh, and Pakistan). It these countries, it is US\$ 0.0025-0.02 m^{-3} for flow irrigation from canals and tanks and US\$ 0.15-0.25 m^{-3} for hiring diesel generator sets to pump water from deep tubewells (Shah et al. 2009). Similarly, it is several times lower than the price in Iran (US\$ 0.10-0.20 m^{-3}; Perry 2001), in Palestine (US\$ 0.25-0.37 m^{-3}; Abu-Madi 2009) and in Australia (US\$ 0.012-0.035 m^{-3}; Thompson 2002). In the region, the conventional method of rice cultivation can be profitable up to a 5 times higher price of irrigation water (US\$ 0.019 m^{-3}) than the actual price (US\$ 0.0038 m^{-3}; Figure 5.7). But, a higher price could lead to a substantial reduction in the application of irrigation water in rice. To reduce the demand for irrigation water, a higher price was implemented in Iran (Perry 2001) and Palestine (Abu-Madi 2009). The higher gross margin in the RH treatments than in the CT-FI with a 10 times higher price indicates that when water is free of charge, the conventional method of irrigation is profitable, while when costs for water are higher, RH treatments have higher profits.

The higher groundwater salinity (Figure 5.4) in WAD rice than in CT-FI in 2008 could be due to higher soil salinity (Figure 5.3), as a lower amount of irrigation water was applied (Table 5.4). The difference in groundwater depth (Figure 5.5) between the WAD and CT-FI treatments can also explain this. In contrast, despite lower soil salinity (Figure 5.3), the higher groundwater salinity in CT-FI than in WAD rice in 2009 could be due to the altered flow of salt from the drainage canal to the rice field, where the CT-FI block was close (25 m) to the drainage canal (Figure 3.3). Besides, there was a flood-irrigated farmer's rice field surrounding the CT-FI block in 2009, and the level of the drainwater was raised. The resulting shallow groundwater depth (Figure 5.5) and the increased drainwater level in the drainage canal can explain the secondary soil salinization under CT-FI. Secondary salinization due to over-irrigation in semi-arid regions has also been reported by Forkutsa (2006), Abdullaev (2003), and Rhoades and Loveday (1990).

5.5 Conclusions

Conservation agriculture practices in rice-wheat systems have an enormous water-saving potential, as they require only around 30% of the total amount of water used in CT-FI. However, based on the rice-wheat system productivity and economic analysis, it is clear that farmers will not adopt the CA-based practices with water-saving irrigation in rice cultivation unless the system brings a higher gross margin than the conventional method where water is cheap and easily available. As soil salinity in all WAD treatments remained below the threshold level of both rice and wheat crops without early spring leaching, soil salinity will not be a problem in rice-wheat systems under water-saving irrigation. Despite the reduction in soil salinity, the problem of secondary soil salinization could increase in the region due to the conventional method of rice cultivation. The comparatively higher rice-wheat system productivity and B:C ratio in the second year, i.e., in 2009/10 under ZT-RH, shows that the method can be a suitable alternative to cultivate rice and wheat in the region under diminishing water supply conditions. Further research for fine tuning of CA-based practices regarding time and amount of water application, proper N management, development of proper machinery, optimum residue management, and the use of suitable aerobic rice varieties is needed to improve the rice-wheat system productivity under CA-based practices.

6 SIMULATING THE IMPACT OF CLIMATE CHANGE ON RICE PHENOLOGY AND GRAIN YIELD IN IRRIGATED DRYLANDS OF CENTRAL ASIA

6.1 Introduction

In Central Asia, rice is the second major food crop after wheat and is grown on an area of 0.18 million ha (FAOSTAT 2010) in irrigated lowlands in the Amu Darya and Syr Darya river basins. The region has a mainly continental, arid climate (Kottek et al. 2006) with short hot summers and long cold dry winters. Due to the climatic conditions in the region, rice cultivation is only possible during a period of around 140 days (Christmann et al. 2009). The seeding time of rice, however, is very crucial, as the flowering period may coincide with peak maximum temperatures during early seeding, whilst during late seeding the rice may be affected by low-temperature stress (Devkota et al. 2011, forthcoming).

It is predicted that temperatures will increase by 3-4 °C in the Central Asian countries, which is above the predicted world average of 1.8–4.0 °C (with a likely range of 1.1–6.4 °C) at the end of the 21st century compared to the period 1980–1999 (IPCC 2007). Under increased temperatures (climate change scenarios), crop yields are likely to decrease as much as 30% in the region even when accounting for the direct positive physiological effects of increased CO_2 (IPCC 2007). The predicted negative impact of climatic change on crop yields could even be higher for rice, because during the rice-growing season in Central Asia, the maximum day temperatures are either close to or higher than the critical threshold of 33-35 °C (Nakagawa et al. 2002; Yoshida 1981).

Among the numerous climate change variables, high-temperature stress has a significant impact on rice production (Aggarwal 2003). Biomass accumulation increases with increasing temperatures (18 to 33 °C; Matsushima et al. 1964). High air temperatures reduce grain yield even under CO_2 enrichment (Baker and Allen 1993; Baker et al. 1992; Ziska et al. 1996; Matsui et al. 1997; Horie et al. 2000; Prasad et al. 2006) because of an inhibition of the pollination process that in turn leads to increased spikelet sterility (Satake and Yoshida 1978; Matsui et al. 1997; Baker 2004; Ohe et al. 2007; Jagadish et al. 2007). Furthermore, high night temperatures have also been reported to reduce rice production through the induction of sterility (Peng et al. 2004;

Cheng et. al. 2009; Mohammed and Tarpley 2009). With temperatures below 20 °C and above about 32 °C, spikelet sterility becomes a major yield-limiting factor, even if there is sufficient growth in other plant components (Matthews et al. 1995). Spikelet sterility at high temperatures is attributed to abnormal anther dehiscence (Matsui and Omasa 2002), and impaired pollination (Matsui et al. 2005) and pollen germination (Jagadish et al. 2010). Besides a reduction of pollen fertility, high-temperature stress decreases the net photosynthetic rate of flag leaf and ATPase and root activities, while it leads to an increase in antioxidant enzyme activities (Yun-Ying et al. 2009).

Yield reductions due to low-temperature stress in high-latitude and -altitude areas are reported in Japan (Shimono et al. 2007), Korea, northeast and southern China, Bangladesh, India, Nepal and other countries (Lee 2001; Kaneda and Beachell 1974). Rice plants are susceptible to low-temperatures during the young microspore stage, which occurs 10-12 days before heading (Farrell et al. 2006). Temperatures below 20 °C can result spikelet sterility due to the failure of pollen development at the microspore stage (Sasake and Hayase 1970). Low-temperature can also reduce seedling emergence. A minimum temperature of 12 °C (Sipaseuth et al. 2007) and mean temperature above 20 °C is required for emergence (Basnayake et al. 2006; Basnayake et al. 2003; Ali et al. 2006). Low-temperatures also cause poor crop establishment (Sasaki 1979, 1981; Shimono et al. 2002, 2004, 2007; Lewin and Maccaffery 1985), reduce nutrient uptake (Zia et al. 2008), delay phenological development, and increase spikelet sterility (Farrell et al. 2001; Lee 2001; Gunawardena et al. 2003a,b), resulting in lower yields.

Simulation studies by different models combined with numerous field experiments have shown the potential impact of climatic change and variability on rice production (Baker et al. 1992b; Peng et al. 2004; Kim et al. 2003). The rice growth model ORYZA2000 is capable of simulating the development and potential growth of *indica* and *japonica* rice ecotypes in relation to temperature, solar radiation, CO_2, and characteristics of the varieties used (Matthews et al. 1997). In the past, ORYZA2000 has extensively been used to explore the impact of climate change on lowland rice under various climate-change scenarios, and has served as a useful tool in decision support (Krishnan et al. 2007; Kwak and Lee 2006; Matthews et al. 1997). To explore the impact of climate change on rice, ORYZA2000 has been used in Japan (Horie et al. 1995; Horie et al. 2000), India (Mohandass et al. 1995; Mall and Aggarwal 2002), Malaysia (Singh et al. 1995), South Korea (Sin and Lee 1995), China (Defeng and Sharkai 1995; Bachelet et al. 1995), the Philippines (Centeno et al. 1995), and Bangladesh (Karim et al. 1995). All studies report country-wise variations in rice yield due to climatic change. The simulated yields increased when temperature increases were small, but declined when the decadal temperature increase was more than 0.8 °C (Matthews et al. 1995).

Peng et al. (2004) observed that rice yield declines by 15% $°C^{-1}$. Other studies reported much smaller yield changes ranging from about 2 to 6% $°C^{-1}$ (Matthews et al. 1995; Horie et al. 1995; Baker and Allen 1993). Rice yield was reported to decrease by 0.5 t ha^{-1} $°C^{-1}$, which is about 6% $°C^{-1}$ with an average mean daily temperature of 26 °C (Sheehy et al. 2006). However, to the best of the authors knowledge no such studies have been conducted to understand the impact of increased temperature on rice yield in Central Asia.

The appropriate seeding date is of central importance for high rice yields under climate change scenarios (Blanche and Linscombe 2009; Mandal et al. 2005; Matthews et al. 1997). Rice seeded during the optimum window has, on average, the highest yield potential (Gravois and Helms 1998). Simulation studies on various seeding dates with different maturity-duration rice varieties may contribute to identify the optimum seeding date under current and predicted climate change scenarios (Matthews et al. 1995). This can indirectly overcome the predicted limitations of climate change for rice production in the region. It may contribute to the development of suitable adaptation strategies through agronomic and plant breeding practices. Under climate change scenarios, adjustments in seeding dates may help to avoid the damaging high temperatures around the time of flowering that result in spikelet sterility. Similarly, long-maturity-duration rice varieties can be used to take advantage of the predicted longer growing season (Horie 1991; Okada 1991; Yoshino et al. 1988). Field experiments combined with a simulation model can adequately predict the appropriate seeding date of rice under current and climate change scenarios. The objective of this study was to evaluate the rice growth model ORYZA2000 and to assess the impact of increased temperature on phenology and grain yield of rice at various emergence dates under climate change scenarios.

6.2 Materials and methods

6.2.1 Model description

The ORYZA2000 model is an updated version of the previous models of the ORYZA series. It is an explanatory and dynamic eco-physiological simulation model of the ‘School of De Wit’ (Bouman et al. 1996). It simulates the growth, development and water balance of rice under potential, water-limited and nitrogen-limited environments. It is assumed that in all these production situations, the control of diseases, pests, and weeds is optimal. A detailed explanation of the model and program code is provided by Bouman et al. (2001). Rice has four phenological development stages (DVS); (1) the juvenile phase from emergence (DVS=0) to the start of the photoperiod-sensitive phase (DVS=0.4), (2) the photoperiod-sensitive phase from DVS=0.4 until panicle initiation (DVS=0.65), (3) the panicle development phase from DVS=0.65 until 50% flowering (DVS=1.0), and (4) the grain-filling phase from DVS=1.0 until physiological maturity (DVS=2.0). Each phase has variety-specific development rate constants (Bouman et al. 2001).

The light profile within the canopy is calculated from the amount and vertical distribution of the leaf surface area. When the canopy has not yet closed, leaf area development is calculated based on the mean daily temperature. When the canopy closes, the increase in leaf area is obtained from the increase in leaf weight using the specific leaf area. The daily canopy assimilation rate is calculated by integrating the instantaneous leaf photosynthesis rate over the height of the canopy and over the day. ORYZA2000 calculates dry matter production as a function of light, CO_2, and temperature by considering photosynthetic processes at the leaf level and integrating these over the canopy to obtain crop level values. Respiration is also modeled explicitly as a function of temperature. The daily dry-matter accumulation is obtained after subtraction of maintenance and respiration requirements. The dry matter produced is partitioned among the various plant organs as a function of phenological development, which is tracked as a function of ambient mean air temperature.

Leaf area growth includes the source and sink-limited phases. In the early phase of growth, leaves do not shade each other, and leaf area growth is not limited by the amount of available assimilates. In this phase, the leaf area grows exponentially as a function of temperature sum times a relative leaf growth rate. After the leaf area index

(LAI) is larger than 1, leaf area growth is limited by the amount of carbohydrates available for leaf growth. In this linear phase of growth, the increase in leaf area is calculated from the increase in leaf weight times a specific leaf area that is a function of development stage. The transition from the exponential to linear growth phase is smoothened by taking weighted values of leaf area growth rates derived using an exponential and linear equations.

6.2.2 Grain formation and spikelet fertility

Rice grain yield is determined by carbohydrate production (source size) during grain filling and by the storage capacity of grains (sink size). Sink size is determined by the number and maximum growth rate of spikelets. The number of spikelets at flowering is calculated from the total biomass accumulated from panicle initiation until first flowering (Kropff et al. 1994a). In ORYZA2000, the rate of grain growth from panicle initiation (DVS=0.65) to 50% flowering (DVS=1) is tracked, and the number of spikelets formed (S_i; number of spikelets ha^{-1} d^{-1}) is calculated as the product of biomass accumulation from panicle initiation to 50% flowering (G; kg dry matter ha^{-1} d^{-1}) and spikelet formation factor (Y; number kg^{-1}). The spikelet formation factor (Y) is the slope of relationship between the effect of solar radiation, temperature, nitrogen, competition, and water on spikelet formation.

$$S_i = \sum_{i=p}^{F} (G_i \text{ x } Y) \tag{6.1}$$

where, S is number of spikelets formed, P is date of panicle initiation, F is date of 50% flowering.

Spikelets turn into grains during crop growth. However, some spikelets become sterile because of either too high or too low temperatures and do not fill. In ORYZA2000, spikelet sterility is calculated according to Horie et al. (1992). Sterility caused by cold temperatures is based on the ‘cooling degree-day’ concept (Uchijima 1976). The cooling degree-days (SQ_t, °Cd) is calculated as follows:

$$SQ_t = \sum (22 - T_d) \tag{6.2}$$

where, T_d is the average temperature (corrected for temperature increase caused by drought). The summation of SQ_t is done for the period of highest sensitivity of the rice panicle to low temperatures ($0.75 \leq DVS \leq 1.2$). The relation between the percentage sterility caused by cold (S_c) and the sum of the cooling degree-day is:

$$S_c = 1 - (4.6 + 0.054 \text{ x } SQ_t^{1.56})/100 \tag{6.3}$$

Rice spikelets are also sensitive to high temperature, particularly at anthesis. Damage to the pollen occurs when the temperature at flowering is above approximately 35 °C (Satake and Yoshida 1978; Matsui and Horie 1992). In ORYZA2000 the fraction of fertile spikelets caused by high temperatures (S_h) is calculated as (Horie 1993):

$$S_h = 1/(1 + \exp(0.853(T_{m,a} - 36.6))) \tag{6.4}$$

where, $T_{m,a}$ is average daily maximum temperature over the growing period ($0.96 \leq DVS \leq 1.22$) with elevated and ambient CO_2 concentrations.

6.2.3 Model evaluation

Following Bouman and Van Laar (2006), a combination of graphical presentations and statistical measures were used to evaluate the performance of ORYZA2000. The simulated and measured grain yield, biomass, green leaf dry weight, dead leaf dry weight, and phenological stages were graphically compared. For the grain yield and biomass, we computed the slope (α), intercept (β), and coefficient of determination R^2 of the linear regression between measured (X) and simulated (Y) values. The absolute root mean square errors ($RMSE_a$) and normalized root mean square errors ($RMSE_n$) were calculated as:

$$\text{RMSE normalized} = 100\left(\left(\sum_{i=1,\dots n}(Y_i - O_i)^2\right)\Big/ n\right)^{0.5} \Big/ \overline{O}\ (\%) \tag{6.5}$$

$$\text{RMSE absolute} = \left(\sum_{i=1,\dots n}(Y_i - O_i)^2\right)^{0.5} \Big/ n \tag{6.6}$$

where, Y_i and O_i are simulated and measured values, respectively, and O is the mean of all measured values, and n is the number of measurements.

6.2.4 Field experiments

Three sets of field experiments (one in 2008 and two in 2009) were conducted to evaluate growth and development of widely cultivated Uzbek rice varieties in the Khorezm region of Uzbekistan seeded at different dates. Popular Uzbek rice varieties of short maturity duration (SD; Shoternboy-1, 85 days), medium duration (MD; Allanga-3, 105 days) and long duration (LD; Mustakillik, 125 days) rice varieties were evaluated. All experiments were conducted in a wet-direct-seeded potential production system.

Experiment I

In 2009, the above-mentioned three rice varieties were seeded on six seeding dates at 15-20 day intervals starting on 5 May and ending on 15 July. The experiment was not replicated and the plot size was 5 m^2. Phenological developments for the different seeding dates were recorded according to standard rice evaluation IRRI (2002). Besides phenology, in 1st (5 May) and 2nd (18 May) seeding treatments, biomass and leaf area were measured from 0.16 m^2 area at 15-20 day intervals. Also, final yield and biomass of 200 plants were measured as described by Sayre et al. (2008) from these two seeding dates.

Experiment II

In 2008, the three Uzbek rice varieties were evaluated in a replicated experiment (5 replications) in a 600 m^2 plot size each. Rice was seeded on 19 June and phenology, and final yield and yield attributes were recorded in a 7.5 m^2 area in each plot. Data from experiment I and II were used for model parameterization.

Experiment III

In 2009, the three rice varieties were each seeded on 1 June in an un-replicated 30 m^2 plot. Rice phenology was recorded as described above, and the biomass and leaf area were measured in a 0.25 m^2 area at every 15 day intervals. For each variety, final yield and biomass were measured on three subplots of 2 m^2. The data were used for model evaluation.

6.2.5 Climate change scenario analysis

Historical data on rainfall, minimum and maximum temperature, solar radiation, relative humidity, and vapor pressure deficit (as required by ORYZA2000) were collected for a 29-year period (1971-2000) from the Urgench airport (3 km from the experimental site). The projected changes in surface air temperature under Special Report on Emission Scenarios (SRES) scenario A1F1 (highest future emission trajectory) and B1 (lowest future emission trajectory) for 2050-2079 were collected from the Fourth Assessment Report (AR4) Atmosphere-Ocean General Circulation Models (AOGCMs), Second Working Group, IPCC, 2007. The projected increase in temperature (Table 6.1) was added to the daily minimum and maximum temperature and two climate change scenarios were generated. The monthly minimum and maximum temperatures under these two climate change scenarios compared to historical data are as shown in Figure 6.1.

Table 6.1 Projected changes in surface air temperature for Central Asia under SRES A1FI (highest future emission trajectory) and B1 (lowest future emission trajectory) scenarios for 2050-2079 with respect to the baseline period 1971 to 2000.

Month	A1F1	B1
December, January, February	3.93	2.60
March, April, May	3.71	2.58
June, July, August	4.42	3.12
September, October, November	3.96	2.74

ORYZA2000 was used to simulate the impact of climate change on phenological development (days to flowering and physiological maturity), grain yield, spikelet sterility factor due to low temperature (SF1) and spikelet fertility factors due to high temperature (SF2) in SD, MD and LD rice varieties at eight emergence dates starting from early May to mid July over 29 years under current (historical weather data) and for 2050-2079 under the SRES A1F1 and B1 scenarios. Days to emergence could not be simulated, as the current release version of ORYZA2000 does not have the routine to simulate the emergence date.

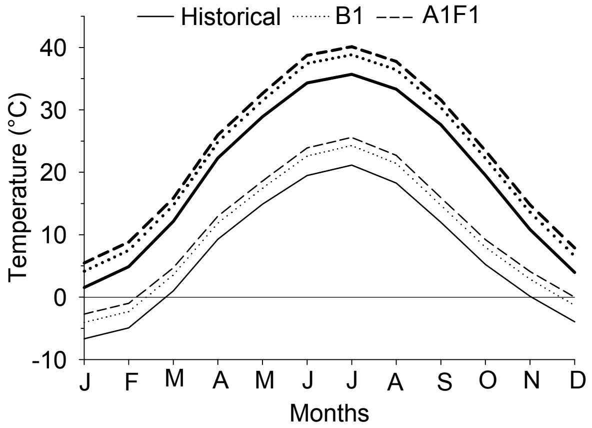


Figure 6.1 Mean monthly minimum (thin line) and maximum (thick lines) temperature (°C) in historical weather data 1971-2000 and SRES B1 and A1F1 climate change scenarios 2050-2079.

6.3 Results

6.3.1 Model parameterization and evaluation

Model parameterization

About 10% of the crop parameters are expected to be variety specific and need empirical derivation. These parameters are development rates, assimilate partitioning factors, specific leaf area, relative leaf growth rate, leaf death rate, fraction of stem reserves and maximum grain weight. These parameters should be derived from well-designed field experiments under potential production conditions, i.e., without any water or nutrient limitations and without disease, pest, or weed infestation. In this study, ORYZA2000 was parameterized for SD (Shoternboy-1, 85 days), MD (Allanga-3, 105 days) and LD (Mustakillik, 125 days) varieties starting with the standard crop parameters for cultivar IR72 and following the procedures set out by Bouman et al. (2001). Two parameterization programs of ORYZA2000, i.e., DRATES for development rates and PRAM for other parameters were used to calculate the variety specific genetic parameters. First, development rates were calculated using observed dates of emergence, panicle initiation, flowering and physiological maturity (Table 6.2). Next, specific leaf area was calculated from the measured values of leaf area and leaf dry weight. The fraction of carbohydrates allocated to the stems that is stored as reserves for each variety was calculated by maximum stem weight (at flowering) minus stem weight at final harvest divided by maximum stem weight. The partitioning of assimilates was derived from the measured data on the biomass of leaf, stem, senesenced leaf and grain. Relative growth rate for leaf development, leaf death rates, and leaf stress parameters of IR72 derived by Bouman et al. (2001) were used.

Table 6.2 Phenological development parameters of the rice varieties.

Variety	DVRJ†	DVRI	DVRP	DVRR
Shoternboy-1	0.002106	0.000758	0.000883	0.002528
Allanga-3	0.001101	0.000758	0.000735	0.002636
Mustakillik	0.000801	0.000758	0.000639	0.002860

[a] DVRJ=development rate in juvenile phase, DVRI=development rate in photoperiod-sensitive phase, DVRP=development rate in panicle development, DVRR= development rate in reproductive phase.

Phenological development

The root mean square error parameters (Figure 6.2 and Table 6.3) show that the observed and simulated phenological stages of all rice varieties over six seeding dates match well. In all three rice varieties, the observed and the simulated panicle initiation, flowering and physiological maturity day did not vary by more than 1-3 days at all seeding dates.

In the SD variety, phenological stages were not affected much when seeding took place before beginning of July. However, in the MD and LD varieties, phenological stages were affected under late seeding conditions. In July seeding, the MD variety did not physiologically mature, while the LD variety did not even enter the flowering stage. In early seeding (before May 20), duration for emergence of all rice varieties was long (10-13 days), while other growth stages were not affected.

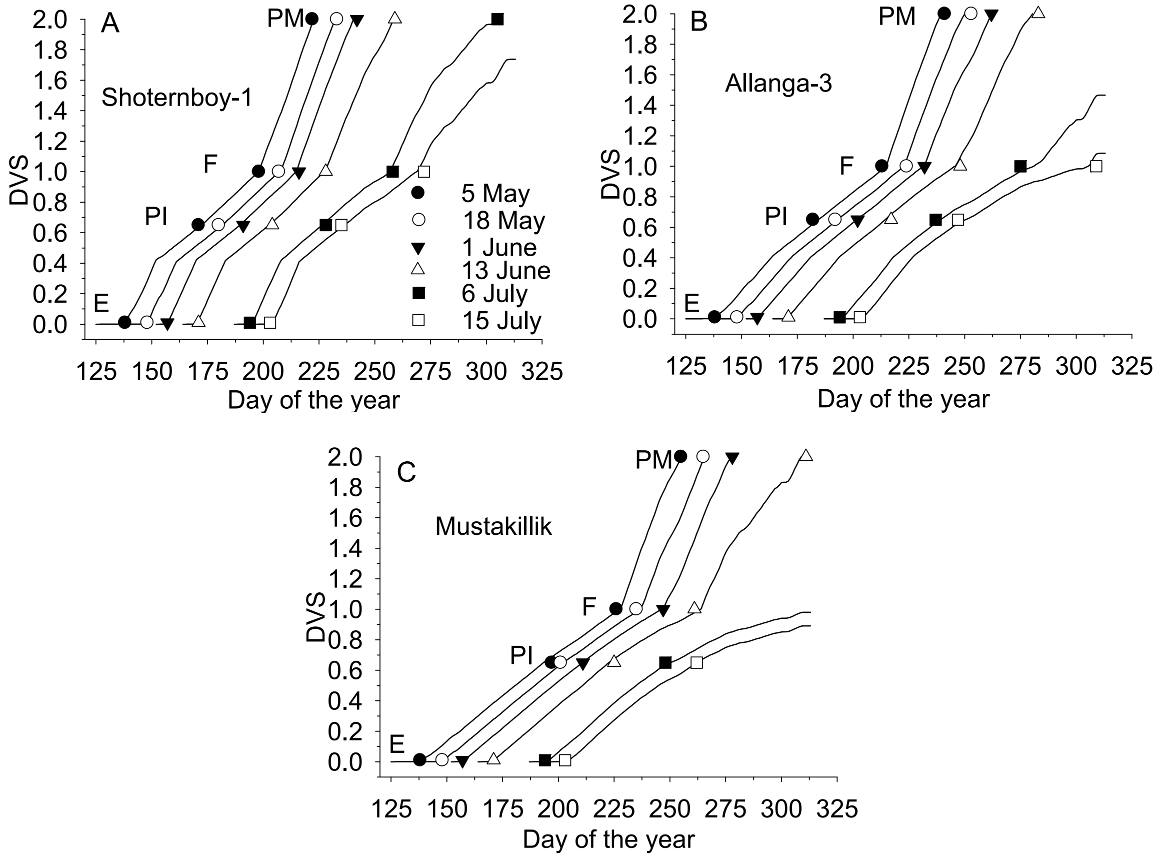


Figure 6.2 Observed and simulated phenological stages of short- (A), medium- (B) and long- (C) duration rice varieties under different seeding dates; DVS=development stages; E=emergence, PI=panicle initiation, F=flowering and PM=physiological maturity (data from experiment I); DVS of 0.65=panicle initiation, 1.0=flowering, 2.0=physiological maturity.

Biomass and LAI

The dynamics in biomass of leaves, stems, senesced leaves, grain, and LAI were simulated quite well throughout the growing season (Figure 6.3). The simulated LAI generally exceeded the measured LAI in all varieties. The measured and simulated grain yield and total aboveground biomass weight (Figure 6.4) were in close agreement. Further, the fairly low $RMSE_n$ (except for LAI) showed the close agreement between simulated and observed variables (Table 6.3).

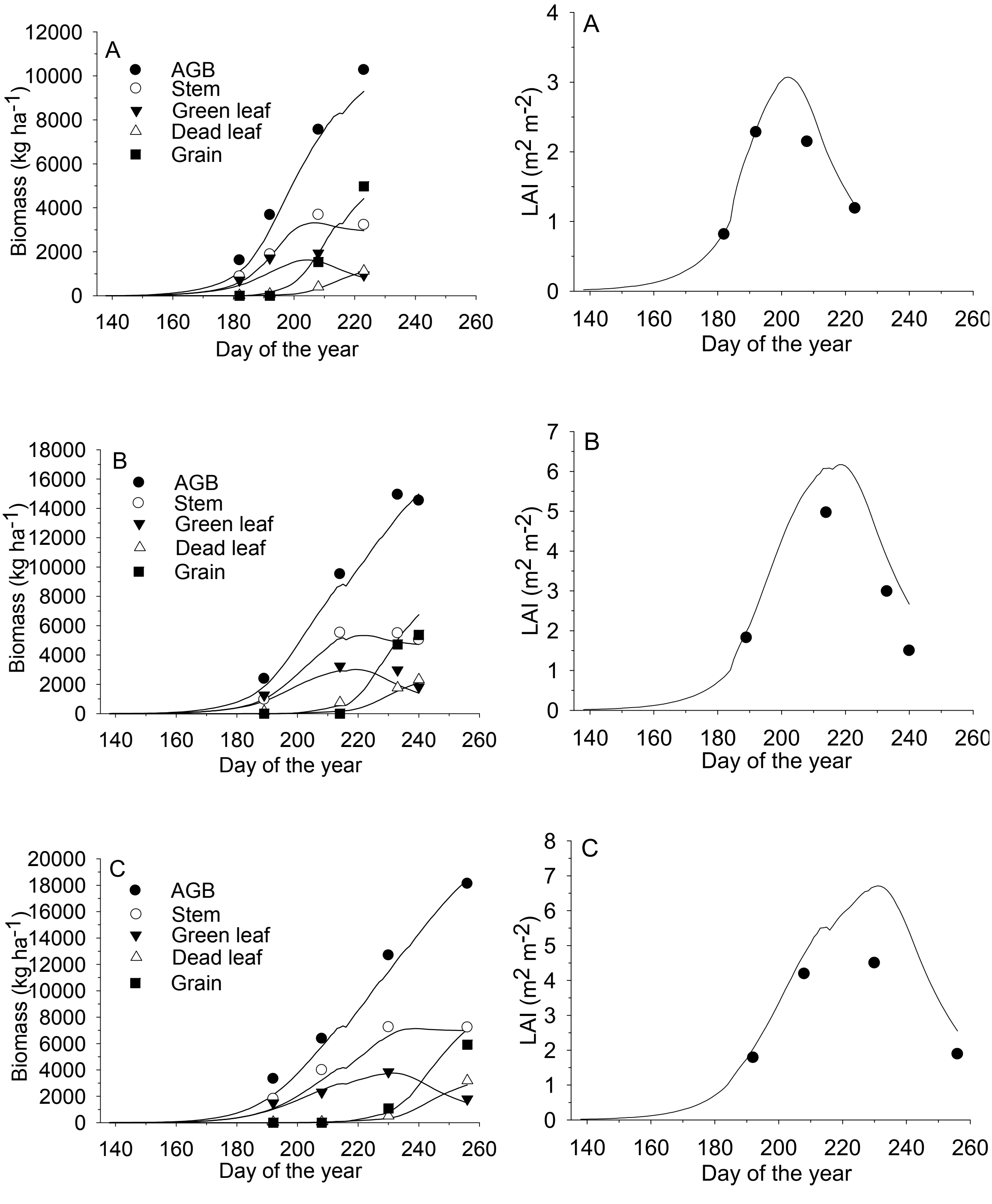


Figure 6.3 Measured and simulated biomass (kg ha^{-1}) of total aboveground biomass (AGB), stem, green and dead leaf, panicles, and leaf area index (LAI) of short-(Shoternboy-1; A), medium- (Allanga-3; B), and long- (Mustakillik; C) duration varieties seeded on 5 May 2009 (data from experiment I).

Table 6.3 Parameterization of ORYZA2000 simulations of grain yield and biomass at harvest, and other crop growth variables over the entire growing season combined over seeding dates and rice varieties from the parameterization data sets 2008-2009 (data from experiment I and II).

Model variable	$RMSE_a$	$RMSE_n$ (%)
Total biomass (kg ha^{-1})	892	6
Grain yield (kg ha^{-1})	714	12
Leaf area index (-)	0.47	21
Panicle initiation (day)	2.08	5
Flowering (day)	2.28	3
Physiological maturity (day)	1.1	1

$RMSE_a$=absolute root mean square error; $RMSE_n$=normalized root mean square error (%).

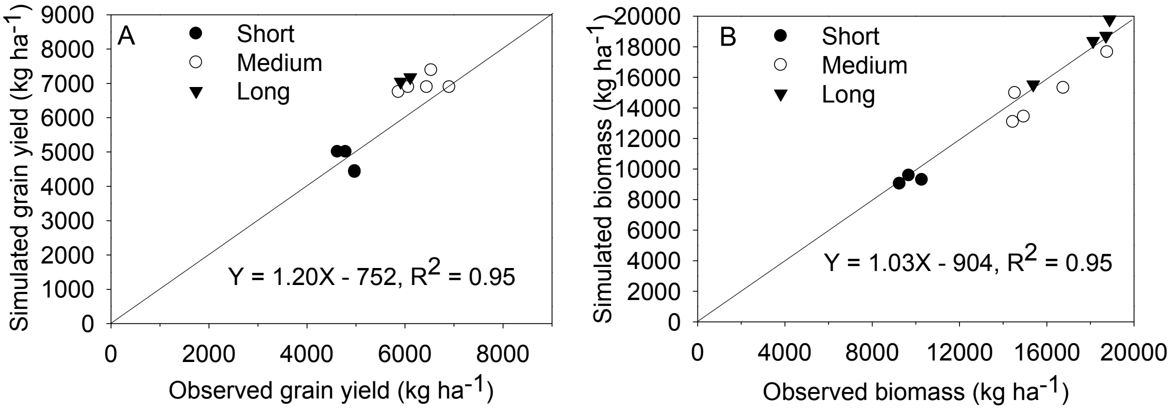


Figure 6.4 Simulated versus measured values of final grain yield (A) and biomass (B) (kg ha^{-1}) of short-, medium- and long-duration rice varieties seeded on 5 May 2009 (data from experiment I) and 19 June in 2008 (data from experiment I and II); solid lines are 1:1 relationship.

6.3.2 Model evaluation

Phenology

Simulated phenological stages differed by 1-3 days in all three rice varieties. The root mean square error parameters (Table 6.4) show that the observed and simulated phenological stages of all rice varieties match well (Figure 6.5).

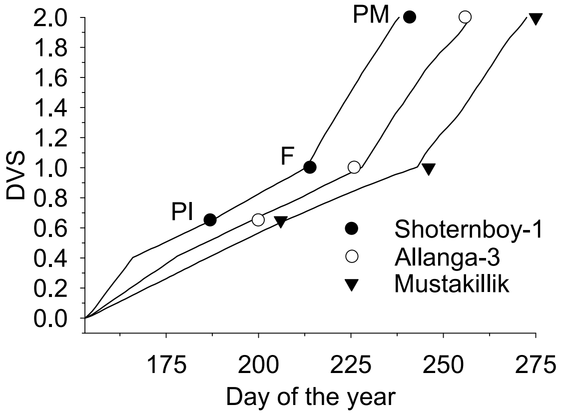


Figure 6.5 Observed and simulated phenological stages of three rice varieties seeded on 1 June in 2009 under potential production system; DVS=development stage; E=emergence, PI=panicle initiation, F=flowering and PM=physiological maturity (data from experiment III); DVS of 0.65=panicle initiation, 1.0=flowering, 2.0=physiological maturity.

Biomass and LAI

Similar to the parameterization data set, the observed dynamics in biomass of leaves, stems, senesced leaves, grain, and LAI matched well with the simulated dynamics throughout the growing season in all rice varieties. As in parameterization data set, the simulated LAI was slightly overestimated during the growing season (Figure 6.6). The low $RMSE_n$ (Table 6.4) shows close agreement between the observed and simulated grain yield and total aboveground biomass weight (Figure 6.7).

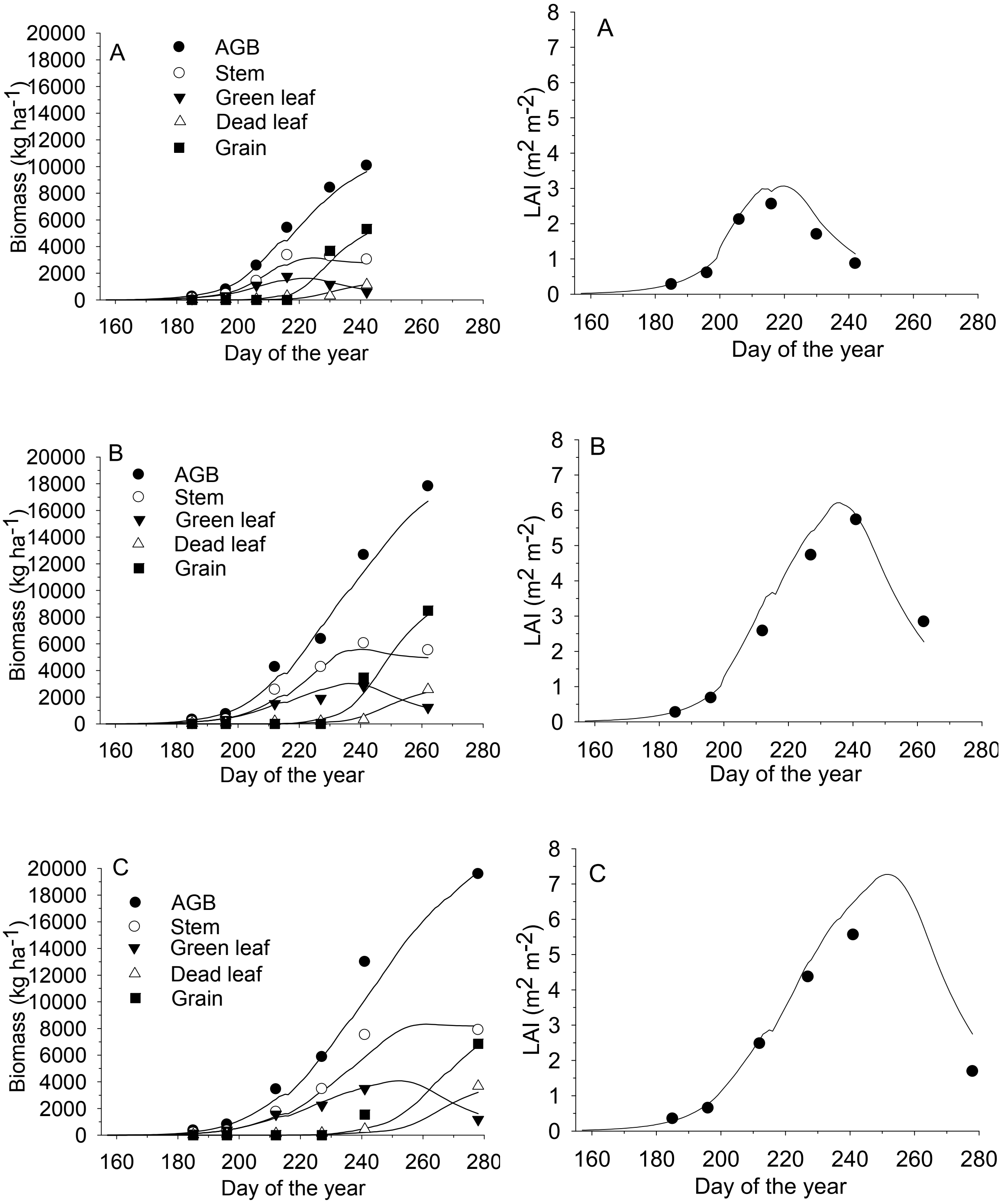


Figure 6.6 Measured and simulated biomass of total aboveground biomass (AGB), stem, green leaf, dead leaf, grain, and LAI of short- (Shoternboy-1; A), medium- (Allanga-3; B) and long- (Mustakillik; C) duration rice varieties grown under potential production system in Khorezm region of Uzbekistan (data from experiment III); AGB=aboveground biomass.

Table 6.4 Model evaluation results for ORYZA2000 simulations of grain yield and biomass at harvest (kg ha^{-1}), and LAI over the entire growing season combined over 3 rice varieties (data from experiment III).

Model variable	RMSE$_a$	RMSE$_n$ (%)
Total biomass (kg ha^{-1})	706	4
Grain yield (kg ha^{-1})	301	4
Leaf area index (-)	0.77	32
Panicle initiation (day)	1.73	1
Flowering (day)	2.56	1
Physiological maturity (day)	1.73	1

RMSE$_a$=absolute root mean square error; RMSE$_n$=normalized root mean square error (%).

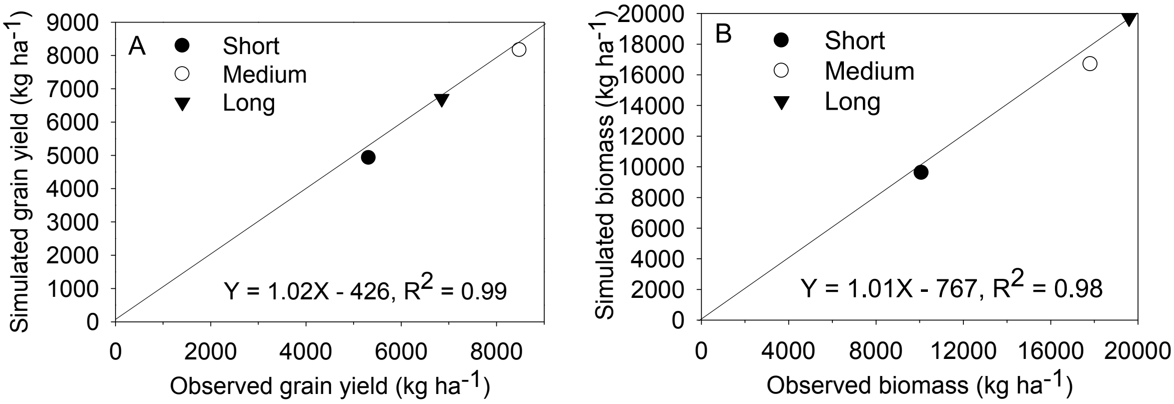


Figure 6.7 Simulated versus measured values of final grain yield (A) and biomass (B) (kg ha^{-1}) of short-, medium- and long-duration rice varieties seeded on 1 June, 2009; solid lines are 1:1 relationship (data from experiment III).

6.3.3 Impact of climate change on rice phenology, grain yield and spikelet sterility

Rice phenology

Days to flowering varied among varieties and emergence dates in both historical weather data and climate change scenarios (Figure 6.8). In historical data, the simulated days to flowering at the farmers' current seeding date in the region (5-15 June emergence) were 59, 77 and 91 days after emergence in the SD, MD and LD varieties, respectively. The predicted values show that for this emergence date (5-15 June emergence) under climate change scenarios of 2050-2079, flowering could be delayed by 4 days under B1 and by 8 days under A1F1 compared to the historical data in all varieties. In the SD variety, flowering was delayed under climate change scenarios compared to the historical data for all emergence dates. For MD and LD varieties, flowering was delayed by 1.5 days °C^{-1} increase in temperature under climate change scenarios than in historical data under early emergence dates, while under late (July) emergence conditions, flowering was later in historical data than in the climate change scenarios.

Flowering was not affected in all emergence dates in SD varieties under both current and climate change scenarios. However, the MD variety emerged on 15 July did not flower in 37% years in the historical data and in 7% years under the B1 scenario (Table 6.5). Similarly, in the LD variety, flowering was affected when emergence was on 5 and 15 July. Physiological maturity was affected at 15 July emergence in SD, after 25 June emergence in MD and after 15 June emergence in LD varieties (Table 6.5). The SD variety emerged at 15 July could not be physiologically matured in 77% years in the historical data, and 33% years under the B1 and 23% years under the A1F1 scenarios. Likewise, the MD variety at 15 July emergence and LD variety at 5 July and at 15 July emergence did not reach maturity in all years in all scenarios.

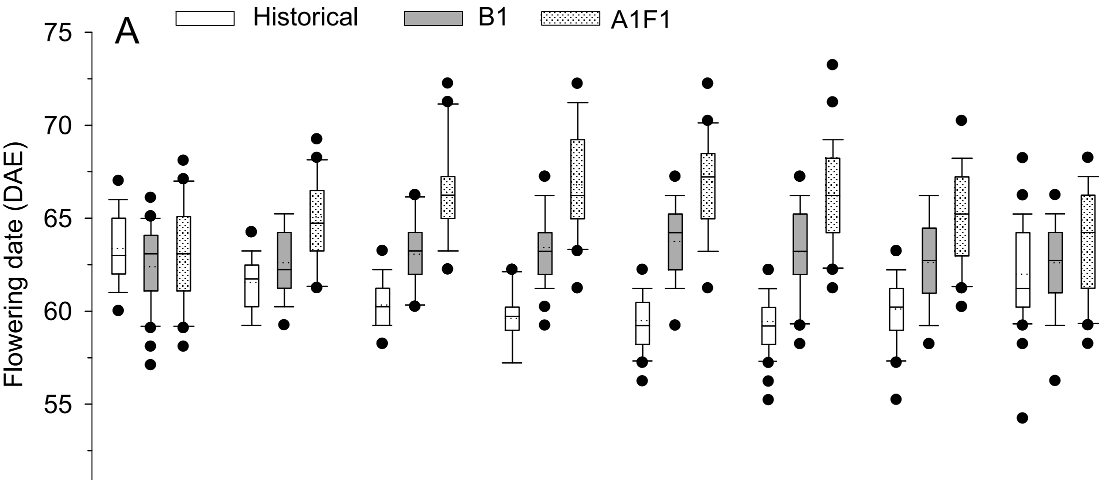


Figure 6.8 Simulated days to flowering of short- (A), medium- (B) and long- (C) duration rice varieties seeded in 10-day intervals in historical weather data and two climate change scenarios (B1 and A1F1) in 2060-2079; dotted line inside the box indicates mean and solid line the median; DAE=days after emergence.

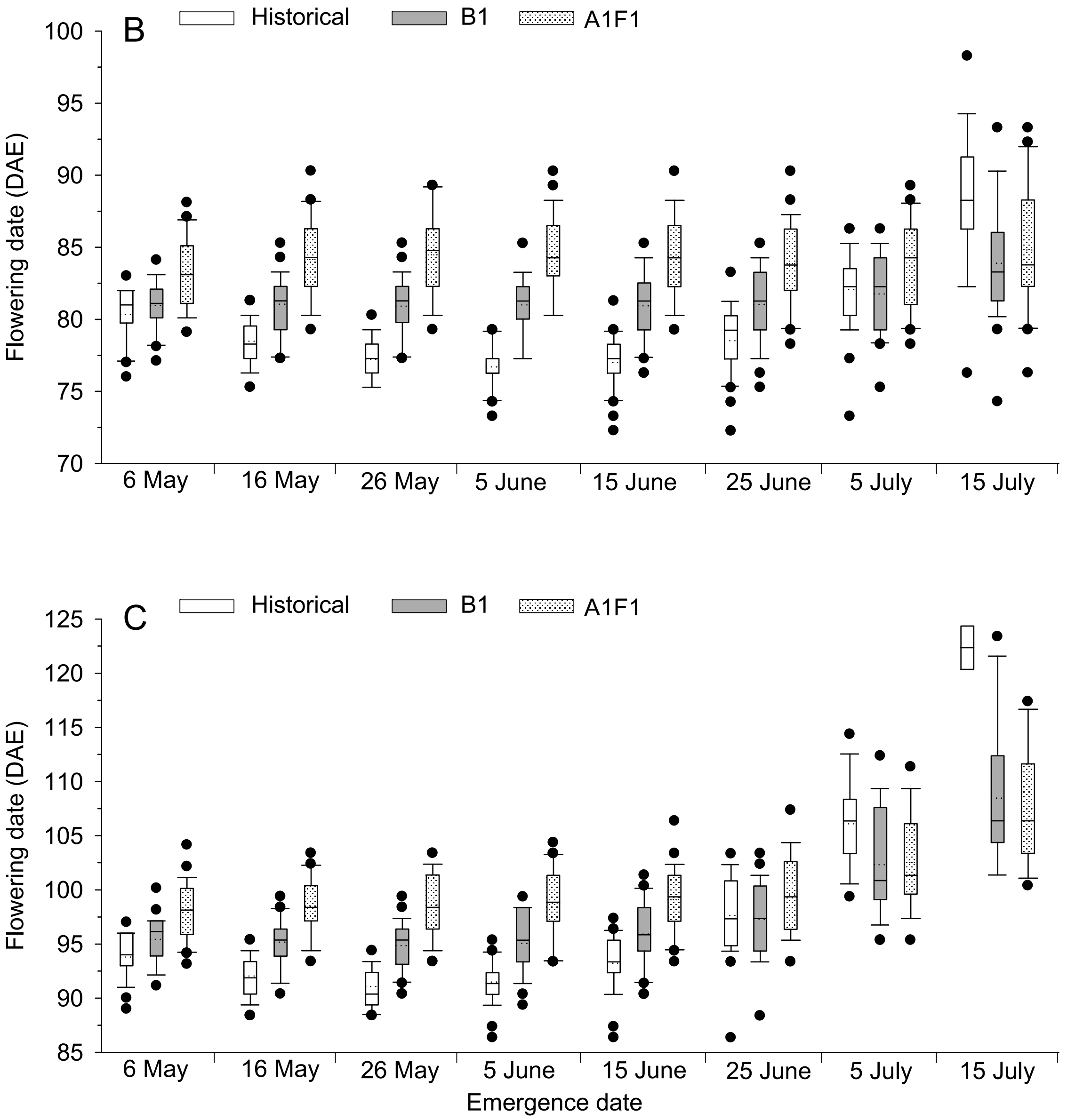
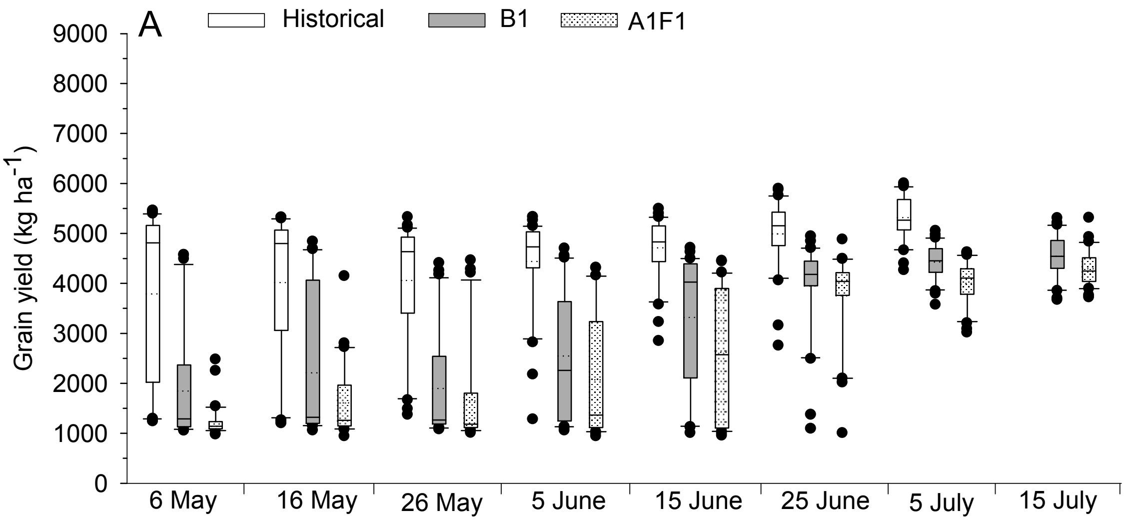


Figure 6.8 continued

Grain yield

In the historical weather data, the simulated grain yield was highest (5.2 t ha^{-1}) at 5 July emergence in the SD, at 15 June (7.8 t ha^{-1}) in the MD and at 5 June (7.3 t ha^{-1}) emergence in the LD variety. For these emergence dates, grain yield of rice was reduced by 17% (1113 kg ha^{-1}) under the B1 and by 23% (1534 kg ha^{-1}) under the A1F1 scenario in all varieties, which is a 393 kg °C^{-1} or 6% °C^{-1} reduction of grain yield in 2050-2079 compared to the baseline years 1971-2000 (Figure 6.9). Under the A1F1 scenario, grain yield was significantly higher in all varieties at 10 days later emergence than at the above mentioned highest yielding emergence dates in historical data, i.e., SD at 15 July, MD at 25 June, and LD at 15 June emergence. However, under the B1 scenario, the yield between the best emergence dates in historical data and 10 days later under climate change, i.e., between 5 and 15 July emergence in the SD, and between 5 and 15 June emergence in LD variety were not significantly different. In historical data, yields decreased by 70-85 kg ha^{-1} day^{-1} when SD rice emerged after 5 July, MD after 15 June and LD after 5 June.

Under early emergence than the highest yielding emergence date in the historical data, grain yield of rice was reduced by 40, 36 and 26% under the B1 and by 51, 47 and 34% under the A1F1 scenario, respectively in SD, MD and LD varieties. However, with later emergence than at the highest yielding emergence date in the historical data, grain yield was higher under the climate change scenarios than in the historical data (grain yield in historical data of SD and LD not shown in the Figure 6.9 as rice in most of the years could not be matured physiologically). In the SD variety, grain yield variability was high in all scenarios up to 15 June emergence, while yields were more consistent afterwards. In the MD and LD varieties, grain yield variability was high under both early and late emergence conditions. Grain yield of the MD variety was more consistent between 26 May and 25 June emergence in the historical data and between 15 June and 25 June in climate change scenarios. Likewise, in the LD variety, it was more consistent in all emergence dates before 5 June in the historical data and between 26 May and 15 June emergence under the climate change scenarios.



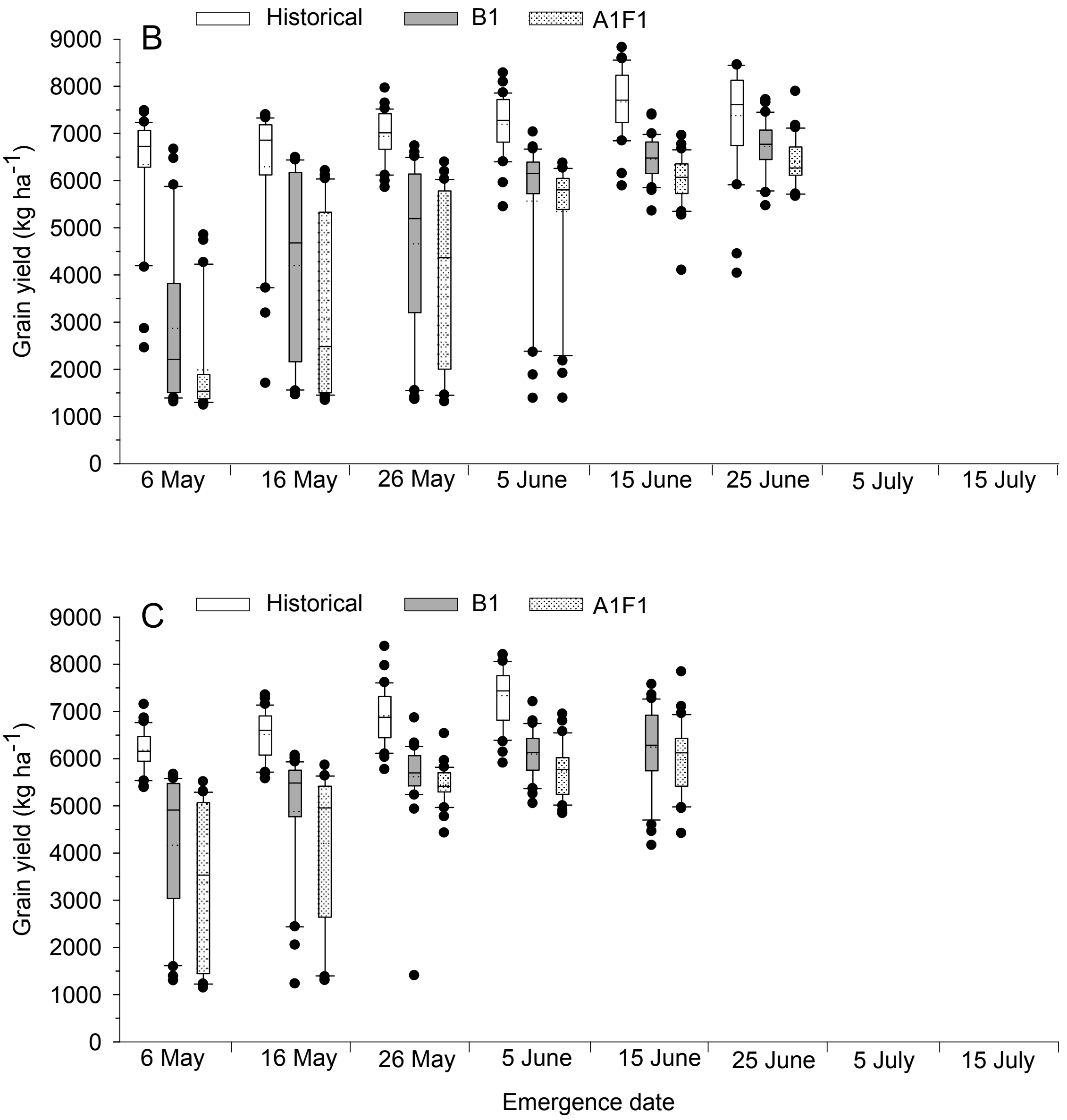


Figure 6.9 Simulated grain yields (kg ha^{-1}) of short (A), medium (B) and long (C) duration rice varieties seeded at 10-day intervals in historical weather data and two climate change scenarios in 2060-2079; dotted line within the box indicates mean and solid line median; data shown only for those years where rice was physiologically matured.

Spikelet sterility

In the historical weather data, under best emergence dates, i.e., 15 to 25 June emergence for a MD rice variety (Allanga-3), the average spikelet sterility was 5% due to high and 10% due to low temperatures (Figure 6.10). During this emergence period, spikelet sterility due to high temperature was higher under climate change scenarios (14% in B1 and 19% in A1F1) than in the historical data, while spikelet sterility due to low temperature was lower under climate change scenarios (6% in B1 and 5% in A1F1) than in the historical data. Spikelet fertility factor due to high temperature at early emergence (compared to above mentioned best emergence dates) was significantly low under the climate change scenarios, where it was lowest under A1F1 followed by B1 and historical data. In contrast, spikelet sterility due to low temperature at late emergence was higher in the historical data followed by the B1 and A1F1 scenarios. The same trend was also observed in the SD and LD varieties (data not shown).

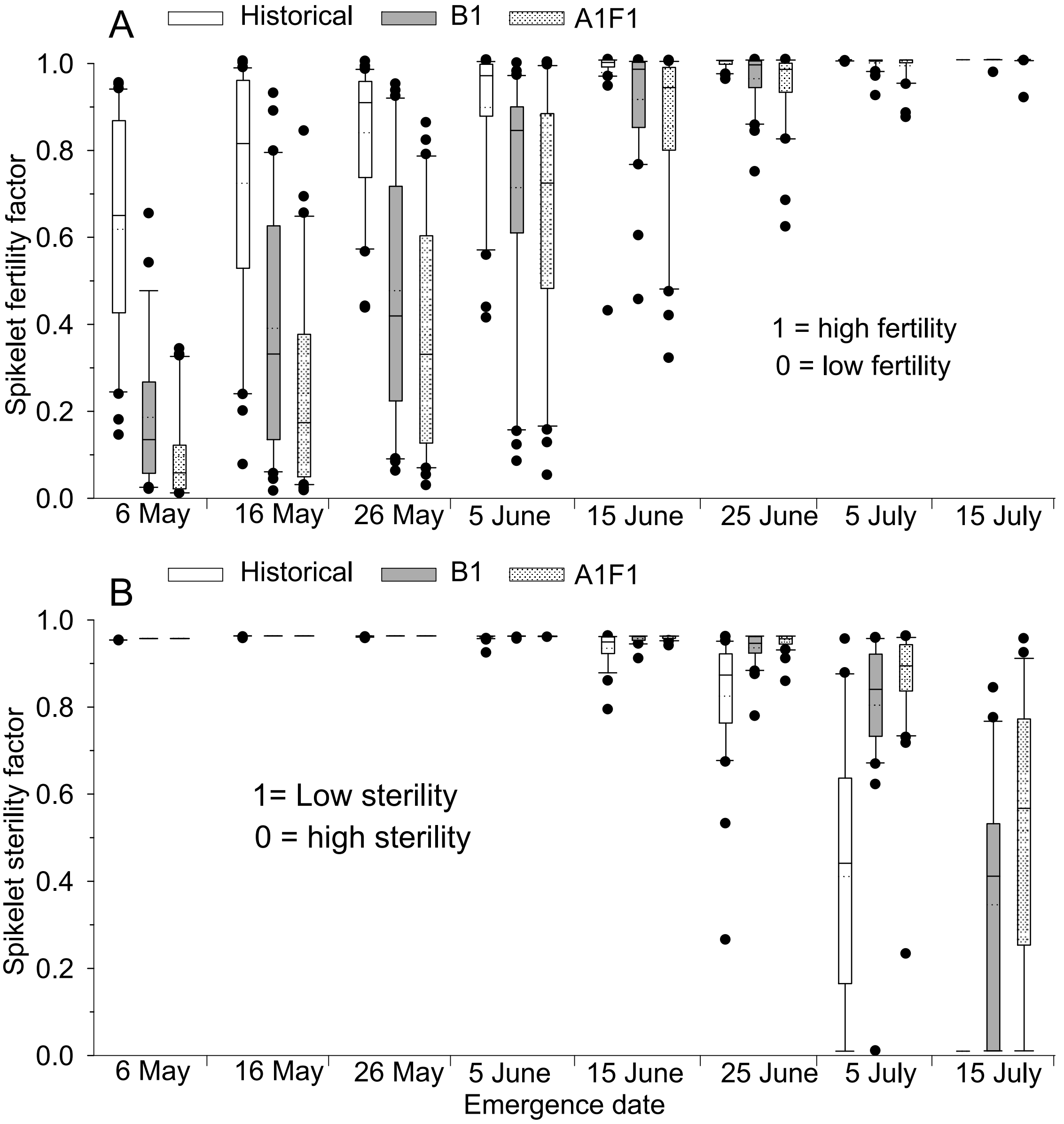


Figure 6.10 Simulated spikelet fertility factor due to high temperature (A) and spikelet sterility factor due to low temperature (B) in historical data and under two climate change scenarios for different emergence dates.

The grain filling process and spikelet fertility due to high temperature on one of the early emergence dates (May 16) in three rice varieties is shown in Figure 6.11. In all rice varieties, the spikelet fertility factor is less than 1 in all scenarios, which is lower than in the historical data. Under the climate change scenarios, the grain filling process continued only for a few days after flowering, and stopped due to high temperature stress after which it remained constant till maturity in all varieties. In contrast, in the historical data, the process was long and gradual.

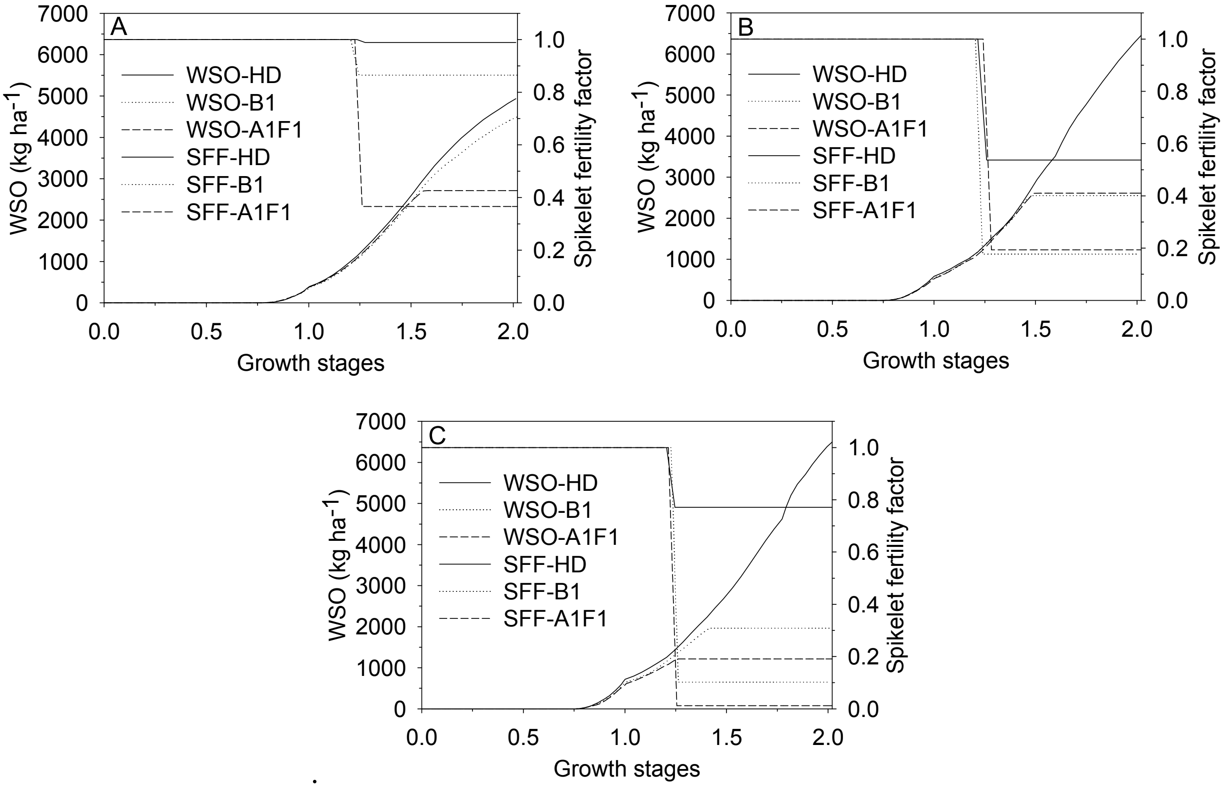


Figure 6.11 Simulated grain yield (kg ha^{-1}) and spikelet fertility factor due to high temperature in short (A), medium (B) and long (C) duration rice varieties emerged on 16 May in historical data in 1999 and climate change scenarios in 2079; WSO=weight of storage organ, WSO-HD=weight of storage organ in historical data, WSO-B1=weight of storage organ in B1 scenario, WSO-A1F1=weight of storage organ in A1F1 scenario, SFF-HD=spikelet fertility factor in historical data, SFF-B1=spikelet fertility factor B1 scenario and SFF-A1F1=spikelet fertility factor in A1F1 scenario; growth stage 1=flowering, 2=physiological maturity.

6.4 Discussion

The impact of climate change on rice has been extensively studied and reported in many rice-producing countries, mostly in Southeast Asia. But to the best of the authors knowledge, no such study has been conducted in arid drylands of Central Asia. Under climate change scenarios, seeding date of rice could vary compared to historical data. The best seeding date is of central importance for higher rice yields (Blanche and Linscombe 2009; Mandal et al. 2005; Matthews et al. 1997). Simulation studies on various seeding dates with different maturity duration rice varieties may help to identify the optimum seeding date for different maturity duration rice varieties under both historical weather data and predicted climate change scenarios (Matthews et al. 1995). Thus, the objective of this study was to evaluate the rice growth model ORYZA2000 and to assess the impact of increased temperature on phenology and grain yield of rice at various emergence dates under climate change conditions.

6.4.1 Evaluation of rice growth model

The modeled biomass, leaf area index, and phenological development matched well with the observed values (Figure 6.2 to 6.7). The slightly lower measured LAI than the simulated values could be due to a lower leaf production (5-8 leaves). In general, rice varieties have 6-14 living leaves during flowering (De Datta 1981). Results of the statistical evaluation of parameterization and evaluation of the model are comparable in terms of accuracy with previous studies by Belder et al. (2007), Bouman and Van Laar (2006), Jing et al. (2007), Li-jiao et al. (2006) and Wikarmpapraharn and Kositsakulchai (2010), where ORYZA2000 was evaluated in potential production and water and nitrogen limited conditions mostly in the humid tropic region of Asia. Furthermore, the evaluation results of this study are comparable with those of Amiri and Rezaei (2010), who evaluated the model in a semi-arid region of Iran under potential and water- and nitrogen-limited conditions. This suggests that the ORYZA2000 model is able to simulate phenological development and grain yield of rice accurately for arid climate conditions in Central Asia.

6.4.2 Impact of climate change on rice phenology

The very long days to emergence (10-13 days; Figure 6.2) before May 20 seeding could be related to the temperature that was lower than required for emergence. In the 39-years average (1970-2009), the minimum and average temperature before 20 May was 14 and 20 °C, respectively, which is slightly lower than the critical threshold temperatures required for emergence (Yoshida 1981). Rice requires an average temperature of more than 20 °C for emergence (Basnayake et al. 2006). At temperatures lower than 8 °C and higher than 45 °C, no emergence occurs. However, under the climate change scenarios, the temperature during early May (20 May) was higher than the threshold temperature required for emergence (20 °C), but as the current version of ORYZA2000 starts simulation only after emergence (Bouman et al. 2001), required emergence days under climate change conditions could not be simulated.

The higher temperature than the threshold could be associated with the delayed flowering (Figure 6.8) under the climate change scenarios. The base, optimum and maximum temperatures for rice are 8, 30 and 42 °C, respectively (Gao et al. 1992). The development rate of rice increases linearly above the base temperature to the optimum temperature. Beyond the optimum temperature, the development rate decreases linearly until a maximum temperature is reached (Kiniry et al. 1991). Below the base temperature or above the maximum temperature, the development rate is zero. Furthermore, flowering is longer at a mean temperature of 33 °C in comparison to 29 °C (Matthews et al. 1995).

The delayed physiological maturity of rice (Table 6.5) under late seeding conditions could be related to low temperature. For physiological maturity, rice requires minimum temperatures of 12-18 °C and an optimum temperature of 30 °C (Yoshida 1981). Due to the extreme aridity of the climate, even under the climate change scenarios, the minimum and average temperatures required for maturity are lower than the threshold temperature for proper maturity (Figure 6.1).

6.4.3 Impact of climate change on rice yield

Like earlier findings of Karim et al. (1995) in Bangladesh, Horie et al. (2000) in Japan, Bachelet et al. (1995) in China, Mall and Aggarwal (2002) in India, and Matthews et al. (1995) in many Asian countries, even at the appropriate emergence dates, the increased temperature would cause a decline in rice grain yields (Figure 6.9) by 20% (6% °C^{-1} or 393 kg °C^{-1}) in the year 2079 than in 2000 in arid climate conditions of Central Asia. This finding is in agreement with a previously stated yield decrease by 0.5 t ha^{-1} °C^{-1}, which is about 2-6% °C^{-1} (Sheehy et al. 2006; Matthews et al. 1995; Horie et al. 1995; Baker and Allen 1993); but lower than observed by Peng et al. (2004) and Baker and Allen (1993) who reported a decrease by 10% for each 1 °C increase in the growing-season minimum temperature in the dry season, whereas the effect of maximum temperature on crop yield was non-significant.

The main reason for the yield reduction under the climate change scenarios is the high daily maximum temperature around the time of flowering, which resulted in a significant reduction of spikelet fertility (Figure 6.10) and grain filling time (Figure 6.11). Increased daily average and maximum temperature decreases the length of the grain-filling (Bachelet et al. 1993) and seed-setting rate (Guan-fu 2008). Further, in the historical data, the spikelet fertility factor lower than 1 in all varieties occurred on one of the early emergence dates (Figure 6.11) and with a maximum temperature of more than 35 °C during flowering time (July; Figure 6.1). This indicates the region already has a temperature equal to or higher than the upper threshold. Temperatures higher than 35 °C for more than 1 hour during flowering lead to a high spikelet sterility (Jagadish et al. 2007; Yoshida 1981); 34.5 °C daily mean temperatures during the panicle formation period can produce more than 98% sterile spikelets (Mohandass et al. 1995; Matthews et al. 1997). Optimum temperature for flowering is 21–29 ºC (Matsui et al. 2001; Guan-fu 2008). At grain filling, spikelet fertility is strongly influenced by the maximum daily temperature.

Under early emergence conditions, spikelet fertility (especially in the climate change scenarios) is reduced (Figure 6.10) in all rice varieties due to the coincidence of flowering and grain-filling period with high temperature. Flowering in rice occurs over an extended time period of 7-10 days (Yoshida 1981); and the high temperatures during flowering could cause significant spikelet sterility (Defeng and Shaokai 1995). Furthermore, in ORYZA2000, respiration is modeled explicitly as a function of temperature (Bouman et al. 2001; Matthews et al. 1995). Thus, yield reduction under early emergence conditions could also be related with higher respiration rates. Under late emergence conditions, the decreased yield could be due to the slow development rate (Figure 6.2, Figure 6.6), and to delayed and incomplete grain filling and poor physiological maturity and increased cold-temperature-induced spikelet sterility due to the onset of the cold winter (Farrell et al. 2001; Lee 2001; Gunawardena et al. 2003a,b; Sasake and Hayase 1970).

In the historical data, the lower grain yield variability and highest yield at July 5 emergence in the SD, at June 15 in the MD, and at June 5 in the LD varieties compared to the other emergence dates suggests that these are the best emergence dates for a consistently higher yield in the region. However, under the A1F1 climate change scenario, consistently higher grain yield (Figure 6.9) and phenological development (Figure 6.8) at July 15 emergence in the SD, June 25 in the MD and June 15 in the LD rice varieties suggests that the effect of increased temperature can be minimized through seeding 10 days later than in the historical data. Shifting the planting date of rice can increase yield by avoiding from temperature stress (Dingkuhn 1995). While, under the B1 scenario, the non-significant yield difference between the highest yielding emergence dates in the historical data and the 10-day later emergence date especially in the SD and LD varieties indicates that it may not be necessary to shift seeding from the best seeding dates in the historical data for SD and LD varieties.

The comparatively higher grain yield of MD and LD varieties than SD under the climate change scenarios (especially under early emergence conditions) suggests that the use of MD and LD varieties could be an alternative adaptation strategy under climate change scenarios. The use of long duration varieties has also been suggested by Matthews et al. (1997) for southeast Asian countries. But under arid climatic conditions, growing LD rice may not allow cultivation of two crops (rice and wheat) in a year. Thus, MD that allows two crops a year could be the best alternative in the region.

Climate change may have both beneficial and harmful effects on rice in Central Asia. Increased temperatures in the region would increase the number of frost-free days. In the historical weather data, the frost-free period is approximately from April-September, while, under climate change scenarios, it may last one month longer, i.e., from mid March to mid October. However, a longer frost-free period increases the number of days when the average temperature exceeds 35 °C (upper threshold temperature of rice), which leads to heat stress. Currently, rice experiences heat stress at flowering for a few days in July. Under climate change scenarios, this heat stress at flowering could last three months, i.e., June, July and August. Thus, the negative effect of heat stress due to climate change on rice phenology and grain yield could surpass the beneficial effect of increased growing duration due to rising temperatures. Furthermore, longer season (under increased temperature) at very early emergence (April), flowering of most of the rice varieties could coincide with the high-temperature period in June. At very late emergence (July), rice could not mature physiologically due to the sharp decline in temperatures after 15 October even under climate change scenarios (Figure 6.1). Thus, rice varieties tolerant to high- and low-temperatures and having better adaptation in the region need to be explored.

6.5 Conclusions

ORYZA2000 is capable of simulating rice growth and development under different seeding dates in arid drylands. Under climate change scenarios, as the time period for rice cultivation could further be reduced, the selection and use of appropriate rice varieties and seeding dates are crucial. The appropriate seeding dates under the current climate conditions is July 5 for SD, 15 June for MD, and 5 June for LD varieties. Under the A1F1 climate change scenario, all varieties seeding 10 days later than in the current (historical data) can give comparatively higher rice yields, while under the B1 scenario, the current seeding date could be appropriate. Despite the yield reduction, as the existing rice varieties are still producing 80% of the current yield (upon seeding at the appropriate dates); it is possible to cultivate rice even under climate change conditions. As the SD varieties could be affected most under climate change scenarios, breeding programs should focus on finding the appropriate heat-tolerant MD and LD rice varieties.

7 OVERALL DISCUSSION, CONCLUSIONS AND OUTLOOK

7.1 Introductory remarks

Intensified cropping during the Soviet Union era in Uzbekistan (1924-1991) involved intensive soil tillage, and excessive irrigation and chemical inputs (Gupta et al. 2009). Especially the rapid extension of the irrigated area increased the demand for water resources. The introduced mainstream agricultural practices, however, deteriorated soil quality, declined soil fertility, increased water logging and soil salinity, increased production cost, and rendered soils susceptible to wind and water erosion. Resource conservation cultivation techniques can mitigate the widespread and still on-going land degradation (Toderich et al. 2008; Martius et al. 2009) and lessen the demand for irrigation water. Future irrigation schemes in the arid drylands of Uzbekistan should be based on plant-water demand and should replace the common flooding practices with much lower water applications. This in the end would lead to a lower groundwater table and thus combat secondary soil salinization (Vlek et al. 2001).

Conservation agriculture (CA), mainly practiced under rainfed conditions, improves soil quality, reduces production cost, and increases crop production (Govaerts et al. 2007). Such benefits are also to be expected in irrigated crop production systems in Central Asia. As wheat and rice are the first and second major food crops in this region, sustainability of cultivation practices for these crops plays a pivotal role in food security. Conservation agriculture is recommended to minimize the adverse effects of the current conventional crop production systems, and can be the most sustainable crop cultivation option for the future (Hobbs et al. 2007). However, rice and wheat production and their rotation under CA practices under arid conditions have only recently been introduced in Uzbekistan, and the impact and performance still are poorly understood. In rice-wheat systems in tropical regions of Southeast Asia, CA practices increased water productivity (Rejesus et al. 2010; Kukal et al. 2010), improved soil quality and water- and nutrient-use efficiency (Timsina and Conner 2001), and increased farmers' incomes (Bhushan et al. 2007; Gupta and Sayre 2007; Gupta and Seth 2007). But it is a major challenge to promote such practices in the rice-wheat areas in arid drylands.

In this chapter, the initial evaluation of water-saving and CA practices and their potential in rice-winter wheat rotation are discussed for the irrigated arid lowlands of Central Asia. The aim was to explore resource conservation options to make rice-wheat systems sustainable in the region, as residue management for this kind of system, and proper N and water management strategies for the climatic conditions in Central Asia had not yet been researched at the time of this study. Although the rice yield in the treatments were reduced through the use of anaerobic rice varieties under the aerobic conditions, which turned out to be unsuitable, the results of this study show that there is great potential to improve the yield of rice in frequent wet and dry irrigated (WAD) treatments upon fine-tuning of certain CA practices. Hence, the findings could be extrapolated to areas with similar agro-ecological conditions as those in the study region Khorezm.

7.2 Potential of water-saving irrigation and conservation agriculture practices for rice cultivation

7.2.1 Water-saving irrigation

Under a diminishing water supply, the introduction of rationed water-saving irrigation increases the sustainability of irrigated agriculture. Several studies, conducted mostly in tropical and sub-tropical regions, have shown water-saving potential in rice cultivation that varied between 10-55% (Borrell et al. 1997; Bouman and Tuong 2001; Sharma et al. 2002). But several studies repeatedly also showed a yield reduction under water-saving irrigation. Both findings are supported in this study by a 68-73% water saving potential but a 30-56% yield reduction (section 3.3.6), but this high yield reduction in WAD irrigated rice can be avoided through the proper management of irrigation water and proper drilling of N fertilizer. For example, flood irrigation up to panicle initiation or flowering stage and intermittent irrigation thereafter, or flood irrigation up to panicle initiation and flowering stages and at the time of N-fertilizer application (section 3.3.6) can increase N uptake, soil mineral N content and minimize the N loss via leaching and denitrification. These practices can alleviate both water stress and the water-stress-induced N stress during crop growth and development.

The present practice of flood irrigation for rice cultivation demands more than 60,000 m^3 ha^{-1} water during the crop cycle (section 3.3.8; Table 3.6), which is 2-3 times higher than reported for rice cultivation in tropical regions (Belder et al. 2005; Tabbal et al. 2002). The potential of reducing irrigation water exists, but levels cannot be reduced to those in tropical regions because: (1) rice in Uzbekistan is cultivated as a summer season crop, meaning that some of its early growth stages coincide with extreme hot and dry weather, which demands high irrigation water application due to high evapotranspiration rates (section 5.3.2; Allen et al. 1998), and (2) rice is predominantly cultivated on alluvial meadow soils (section 2.3) characterized by high infiltration rates (Figure 5.2), and high seepage and percolation losses (section 5.3.2). Due to the combined impact of these factors on the water balance (evapotranspiration rate, seepage and percolation), water demand during rice cultivation under such arid conditions is higher than under tropical conditions.

The current paddy rice varieties perform well when exposed to standing water (Figure 3.7). However, as soil on which rice is presently cultivated has high hydraulic conductivity (section 3.2.1), the maintenance of the standing water collar demands high amounts of irrigation water that also need to be permanently applied. This indicates that, as the current rice cultivation practices need continuous flood irrigation, the soil in the region is not the most suitable unless sufficient water is abundantly available. Also, continuous flood-irrigated rice cultivation has a high potential of soil water logging and secondary salinization (section 5.3.4) as well as of methane emissions (Forkutsa 2011, forthcoming; Scheer 2008). Thus, the present wide-spread practice of flooding in rice cultivation, which is highly profitable to farmers (section 5.3.4) because water is freely available (Figure 5.7), is hardly sustainable given the predicted decrease in water supply and increase in soil degradation.

Despite the adverse consequences of permanent irrigation during rice cultivation, rice is a major part of the diet in many Central Asian countries. Discontinuing domestic rice cultivation would demand large rice imports at great expense. Hence, an alternative option for rice irrigation and cultivation is continuous flood irrigation up to panicle initiation and intermittent irrigation thereafter (section 3.3.6; Figure 3.8), which has the potential of saving 30-40% water. Given the conservative estimate that about 10,000 ha in Khorezm is annually cropped by rice, this would amount to about 180 to 240 million m^3 irrigation water savings each year.

7.2.2 Conservation agriculture practices

Residue retention

Another option for water saving during rice cultivation is the adoption of CA practices, which involve the retention of crops residues (Govaerts et al. 2007). However, a retention of high amounts of standing residues reduced rice grain yield (section 3.3.6), which was likely due to the shading effect leading to reduced soil temperatures (section 3.3.11). This in turn delayed germination, led to a delay in early crop establishment, and slowed down early growth and development rates. Thus, the yield reductions observed in 2008 compared to 2009 under full crop residue retention (R100) could be due to the retention of very high amounts of standing wheat residues: In 2008, 3 t ha^{-1} chopped residues were applied as mulch, while in 2009 more than 14 t ha^{-1} standing residues were retained.

On the other hand, residue retention reduced soil salinity by more than 18% (section 5.3.3), and has potential to increase the soil organic matter content, which is especially important for the region. According to Rawson and Gomez-Macpherson (2000), about 4 t ha^{-1} crop residues is a suitable amount to enhance crop growth and management. After three years of field research in Uzbekistan, Bezborodov et al. (2010) reported that soil salinity levels in cotton fields were reduced by 20% following a mulching with 1.5 t ha^{-1} wheat residues compared to non-mulch treatments. This gives an idea of how much crop residues need to be left in the field.

No-till direct seeding

Direct seeding on no-tilled fields reduced production expenses (section 5.3.5) and the consequences of soil degradation caused by intensive soil tillage as previously postulated (e.g., Sayre and Hobbs 2004; Wang et al. 2006; Tursonov 2008). The present findings indicate no-difference in grain yield (section 3.3.6) and a benefit:cost (B:C) ratio (section 5.3.5) between conventionally tilled and no-tilled direct-seeded wet and dry irrigated rice (section 3.3.6). This in turn may be an argument for reducing soil tillage practices in rice cultivation. Further, the absence of yield differences between CT-II (conventional tillage intermittent irrigation) and ZT-II (zero tillage intermittent irrigation) and CT-FI (conventional tillage continuous flood irrigation) and ZT-FI (zero tillage continuous flood irrigation) treatments (Figure 3.8) is additional evidence supporting the hypothesis that tillage can be avoided during rice cultivation. Despite soil salinity being below threshold levels in both zero tillage (ZT) and bed planting (BP) treatments (section 5.3.3), the higher grain yield of rice in zero tillage residue harvested (ZT-RH) compared to bed planting residue harvested (BP-RH) in 2009 indicates that in the region rice could perform better under ZT than under BP. Even though soil salinity was below threshold levels, the high soil salinity and shallow and saline groundwater increased salinity levels on the top of the bed (in BP) compared to ZT (section 5.3.3); this demanded extra water for leaching. Water saving and water productivity (section 3.3.8), however, could be higher in BP than in ZT.

7.3 Potential of conservation agriculture practices for wheat cultivation

In this study, wheat grain yields (>6.5 t ha^{-1}; section 5.3.1) of no-till surface-seeded wheat were higher as compared to the irrigated, conventionally tilled wheat yields in Uzbekistan (4.74 t ha^{-1}) and the Khorezm region (4.85 t ha^{-1}; OblStat, 2010). This indicates that wheat cultivation after rice could be introduced without the present tillage operations and without compromising on yields. As surface-seeded wheat does not require field preparation, it allows timely seeding and thus proper crop establishment and growth before the occurrence of low winter temperatures. This could be one of the explanations for the higher yields observed in these treatments. Furthermore, the higher water productivity and lower water application (section 3.3.8), higher production (section 5.3.1), higher gross margin and B:C ratio (section 5.3.5) and reduction of soil salinity to below threshold levels (section 5.3.3) in BP compared to ZT indicate that BP could be the best option for wheat in the region.

Full residue retention (R100) did not boost wheat yields. The retention of about 40-50% residue (3.0-4.0 t ha^{-1}) could provide the adequate environment for reaching sustainable grain yields and improve soil quality in the long run. Retention of rice residue reduced soil salinity during wheat cultivation (section 5.3.3) and increased soil organic matter content.

7.4 Potential of water-saving irrigation and conservation agriculture practices in rice-wheat systems

Through the use of water-saving irrigation systems, water application can be reduced and water productivity increased (section 3.3.8). Grain yield in the rice-wheat system can be improved, as wheat yield can be increased by more than 1.5 t ha^{-1} through the adoption of CA practices (section 5.3.1), and rice yield can be sustained through the use of ZT-FI-II (zero tillage continuous flood irrigation up to panicle initiation and intermittent irrigation thereafter) and ZT-FI (section 3.3.6, Figure 3.8).

Residue retention has the potential to improve the existing low soil organic matter. After two cycles of rice-wheat rotation, the retention of more than 11 t ha^{-1} residue in R50 and more than 17 t ha^{-1} residue in R100 (section 4.2.3; Table 4.2) led to an increase of at least 2,500 kg ha^{-1} C to the soil with R50 and 5,000 kg ha^{-1} C with R100 compared to the common farmers' methods of crop residue management. Also, crop residue retention has the potential to reduce soil salinity in rice-wheat systems (section 5.3.3). Thus, CA practices in rice-wheat systems have short-term (e.g., reduced water demand, increased soil organic matter, decreased soil salinity, improved food security) and long-term (e.g., improvement of soil quality, prevention of salinization and desertification, and environmental conservation and protection) potentials, which can sustain the rice-wheat cropping system in arid climate conditions.

7.5 Adaptation strategies for rice production under climate change conditions in Central Asia

In Central Asia, maximum day temperatures are already close to or sometimes even higher than the critical threshold of 33-35 °C (Nakagawa et al. 2002; Yoshida 1981). At higher temperatures, rice yield often will be reduced by 17% under the B1 and by 23% under the A1F1 scenarios and the yield reduction is estimated to be 393 kg $°C^{-1}$ or 6% $°C^{-1}$. Despite such yield reductions, as the existing rice varieties are still producing 80% of the current yield (seeded at the appropriate dates), it is possible to cultivate rice in the region even under the climate change scenarios. But as the short-duration variety could be affected most under climate change conditions, breeding programs should focus on finding appropriate heat-tolerant, medium- and long-duration rice varieties. Adaptation strategies, e.g., adjustment of planting dates and the use of heat- and cold-tolerant rice varieties could prevent the spikelet sterility caused by the hot and cold temperatures in the region.

The ORYZA2000 parameterized in this study can be used for simulating growth and yield of rice under different climate change scenarios. Further, it can be used to explore the water-saving potential with different soil types, seeding dates, crop establishment methods, irrigation methods, N fertilizer doses, and rice varieties.

7.6 Overall conclusions

The results of this study show that water-saving irrigation practices could save water in rice cultivation but that they could lead to yield reductions. Conservation agriculture practices (reduced tillage and residue retention) show promise for wheat but need to be fine-tuned for implementation in rice cultivation. The following conclusions can be made:

- Water-saving irrigation has the potential to save more than 70% of the total amount of water applied in conventional flood irrigation and has higher water productivity, but it leads to yield reduction when using varieties adapted for flood-irrigated conditions;
- Conservation agriculture practices are beneficial for rice cultivation in the region, but these practices need to be fine-tuned further. They can, however, already be recommended to the farmers for wheat cultivation;
- Under water-saving and CA practices in rice, water stress, water-stress induced N stress, retention of very high amounts of standing residue, and improper application of N fertilizer are the major causes of yield reduction;
- Soil tillage is neither necessary for rice or wheat crops.
- Bed planting is superior to zero-tillage flat planting and has a higher water-saving potential and system productivity and profitability for both rice and wheat crops;
- Residue retention is effective for reducing soil salinity in rice-wheat systems, but full residue retention is not necessary. The optimum residue retention strategy could be retention of rice residue and removal of wheat residue;
- Loss of mineral N is high in rice cultivation, and especially in WAD treatments, while there is none in wheat cultivation.

Despite the fact that the current conventional rice cultivation practice is highly profitable, it is likely to be unsustainable in the future and could especially increase the predicted water stress in the region.

7.7 Recommendations for water-saving and CA practices in rice-wheat systems

Water-saving and CA practices have the dual objective of sustainability and profitability. Based on the results of a 2-year study on water-saving and CA practices in a rice-wheat system in the Khorezm region, Uzbekistan, system productivity could be improved through the fine tuning of CA practices. Conservation agriculture is rather new, and only a very little research has been conducted for the irrigated conditions in the saline, arid drylands of Central Asia. Nevertheless, based on the results of this study, the following recommendations can be made for the fine tuning of CA-based practices in rice-wheat systems:

- Reduction of inter-row spacing to 15 cm in zero-tillage flats, seeding three rows of rice in 67-cm width bed, and reduction of the amount of seed in the row: These measures could decrease the competition among the plants for nutrient and water within the row, and the plants can utilize the larger under-utilized inter-row space. This could decrease weed infestation in these spaces.
- Use of technologies that enhance early crop establishment, e.g., use of primed seed and high and fast tillering rice varieties: Poor seedling establishment is a major deterrent in direct-seeded rice. Seed priming to obtain better crop stands is a promising approach in direct-seeded rice (Farooq et al. 2006). Seed priming combined with the use of high and fast tillering varieties can lead to a more rapid cover of the space between the rows, which can improve seedling establishment and suppress the weeds.
- Reduction of bed height to less than 15 cm: With a higher bed height, the probability of increasing salinity on the top of the bed is high in salt-affected drylands. Salt leaching under such conditions demands irrigation water application up to at least a few centimeters above the top of the bed, which requires a large amount of water.
- Seeding rice on the slope and in the furrow in bed planting: Due to the accumulated salt on the top of the bed, growth of rice seeded on the slope and in the furrow was

better than that on the top of the bed. Slope or furrow seeding could avoid the salt stress in bed planting and lead to substantial water saving.

- Proper weed management: Despite the application of selective post-emergence herbicides, weed management is still a major challenge in dry-direct-seeded rice. Combined application of pre-emergence herbicides (Pendimethaline; N-(1-ethylpropyl)-3, 4-dimethyl-2, 6-dinitrobenzenamine) immediately after the first irrigation after rice seeding and the post-emergence herbicide Gulliver (Azimsulfuron 50 WG) within 15-20 days after emergence can control most of the weeds germinating in the rice field.

7.8 Future research to increase the understanding of CA-based rice-wheat systems

7.8.1 Development and promotion of appropriate varieties

Water-saving irrigation demands varieties bred to provide higher yield with a much lower water input than required for traditional rice cultivation (Singh et al. 2010; Jat et al. 2009; Saharawat et al. 2010). To date, such aerobic rice varieties have been developed for China and Brazil only, but the yield of even these varieties decline drastically after 3-4 years of mono-cropping (Humphreys et al. 2005). Development and adoption of such varieties could reduce water application to the level of water-wise cropping conditions. Similarly, the introduction of short-duration winter wheat varieties could provide a sufficient time slot for the proper maturity and harvesting of wheat and for the timely seeding of rice in the region. Short-duration wheat varieties can mature and be harvested earlier, and thus rice can be seeded on time. This can increase the overall cropping system intensity, system productivity, and thus the overall food security.

7.8.2 Rice transplanting

Compared to direct seeded rice, transplanted rice can save 5,000-10,000 m^3 ha^{-1} water without yield reduction (Devkota et al. 2011, forthcoming). At the time of rice seeding, high temperatures and dry weather leads to high evaporation losses. This demands frequent irrigation to protect the young seedlings. However, water can be saved by growing seedlings in a small nursery for 25-30 days followed by transplanting.

Further, due to long and cold winters, growing rice and wheat as a double crop under such climatic conditions may be restricted by time. Transplanting would provide a one-month time advantage. As field preparation is not required with BP or ZT, strip-till transplanting with short-duration rice varieties (Shoternboy-1 or Nukus-2) would allow timely seeding of wheat. Yet, the manual transplanting of rice between the standing wheat stubbles is labor demanding, and agriculture equipment is necessary to overcome this problem. However, although transplanting increases the production cost and labor demand compared to direct-seeded rice, the benefits gained by higher yields may surpass the cost associated with transplanting. Thus, mechanical transplanting could potentially reduce both the cost and the labor demand (Humphreys et al. 2005).

7.8.3 Pricing policy for irrigation water

Despite the reduced availability of irrigation water, it is cheap in Kyrgyzstan, Kazakhstan and Tajikistan, and no direct water payments fees are charged in Uzbekistan and Turkmenistan (Abdullaev et al. 2005; Bobojonov 2008). The cost of irrigation water, i.e., US$ 0.0038 m^{-3} (section 5.3.5) is far below the fees charged in Southeast Asia (Shah et al. 2009), Iran (Perry 2001), Palestine (Abu-Madi 2009) and Australia (Thompson 2002). Hence, the conventional methods of irrigation in the region are only profitable because water is available at low or no direct charges (Figure 5.7). The introduction of a price of water up to US$ 0.018 m^{-3} may substantially reduce the wasteful application in conventional rice cultivation without loss in farmers' income (section 5.3.5). A pricing policy could also discourage over-irrigation in other crops such as cotton.

7.8.4 Use of proper machinery

Conservation agriculture is not possible without adequate and appropriate machinery. No-till machines allow precision seed placement through consistent soil penetration and depth and also supply fertilizer in bands, which is crucial for minimizing nutrient losses in zero-till systems (Hobbs et al. 2008). But although such machines are the pre-requisite for CA-based technologies, they are not yet available in the region. Thus, it will be important to provide incentives to the farmers such as financial subsidies or credit support.

7.8.5 Balance between livestock farming and residue retention

Mixed crop-livestock systems are the dominant forms of agriculture among smallholder farmers across the region. In order to achieve the potential benefits of CA, it is essential to ensure that adequate levels of crop residues are retained to cover the soil surface. However, the residue retention may compete with the current farmers' practice of feeding rice and wheat residues to their animals. The tradeoffs between the end users of crop residues on the welfare of the entire farming systems, especially for livestock productivity need to be determined.

8 REFERENCES

Abdolniyozov B (2000) Scientific farm system in the Khorezm Region. Urgench, Khorazm publishing house (in Uzbek)

Abdullaev C (2003) Republic of Uzbekistan. Land degradation assessment in dry lands (LADA). State Design and Research Institute (Uzgip), Tashkent. Tashkent

Abdullaev I, Manthrithilake H and Kazbekov J (2006) Water security in Central Asia: Troubled future or pragmatic partnership? Paper 11, International Conference "The Last Drop?" Water, Security and Sustainable Development in Central Eurasia, 1-2 December 2006. Institute of Social Studies (ISS), The Hague, Netherlands

Abid M and Lal R (2009) Tillage and drainage impact on soil quality: II. Tensile strength of aggregates, moisture retention and water infiltration. Soil and Tillage Research 103:364–372

Abu-Madi MO (2009) Farm-level perspectives regarding irrigation water prices in the Tulkarm district, Palestine. Agricultural Water Management 96:1344–1350

Aggarwal PK (2003) Impact of climate change on Indian agriculture. J Plant Biol 30:189–198

Aggrawal PK and Mall RK (2002) Climate change and rice yields in diverse Agro-environments of india. II. Effect of uncertainties in scenarios and crop models on impact assessment. Climatic Change 52:331–343

Akramkhanov A, Lamers JPA, and Martius C (2010) Conversion factors to estimate soil salinity based on electrical conductivity for soils in Khorezm region, Uzbekistan. In: Qadir M, Wichelns D, Oster J, Jacobsen SE, Basra SMA and Choukr-Allah R (eds.): Sustainable management of saline waters and salt-affected soils for agriculture. Proceedings of the Second Bridging Workshop, 15-18 November 2009, Aleppo, Syria

Aldaya, MM, Munoz G and Hoekstra AY (2010) Water footprint of cotton, wheat and rice in Central Asia. March 2010. Value of water research report series 41. UNESCO-IHE Institute for Water Education, Delft, the Netherlands

Ali MG, Naylor REL and Matthews S (2006) Distinguishing the effects of genotype and seed physiological age on low temperature tolerance of rice (Oryza sativa L.). Experimental Agriculture 42:337–349

Al-Kaisi M and Licht MA (2004) Effect of strip tillage on corn nitrogen uptake and residual soil nitrate accumulation compared with no-tillage and chisel plow. Agron J 96:1164–1171

Allen RG, Pereira LC, Raes D and Smith M (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage paper 56. FAO, Rome, p 1–300

Amiri E and Rezaei M (2010) Evaluation of water–nitrogen schemes for rice in Iran, using ORYZA2000 model. Communications in Soil Science and Plant Analysis 41:2459–2477

Aulakh MS, Khera TS, Doran JW and Bronson KF (2001) Denitrification, N_2O and CO_2 fluxes in rice–wheat cropping system as affected by crop residues, fertilizer N and legume green manure. Biol Fertil Soils 34:375–389

Aulakh MS, Rennie DA and Paul EA (1984) Gaseous nitrogen losses from soils under zero-tillage as compared with conventional tilled management systems. J Environ Qual 13:130-136

Bachelet D, Kern J and Tolg M (1995) Balancing the rice carbon budget in China using spatially-distributed data. Ecol Model 79 (1/3):167–177

Bachelet D, Van Sickle J and Gay CA (1993) The impacts of climatic change on rice yield: evaluation of the efficacy of different modelling approaches. In: de Vries FWT Penning, Teng PS, Metselaar K (eds.) Systems Approaches for Agricultural Development Kluwer Academic Publishers, Dordrecht, The Netherlands, p 145-174

Baker JT (2004) Yield responses of southern US rice cultivars to CO_2 and temperature. Agricultural and Forest Meteorology 122:129–137

Baker JT and Allen Jr LH (1993) Contrasting crop species responses to CO_2 and temperature: rice, soybean, and citrus. In: Rozema J, Lambers H, Van de Geijn SC (eds.) CO_2 and Biosphere. Elsevier, Amsterdam, p 239–260

Baker JT, Allen LH and Boote KJ (1992) Temperature effects on rice at elevated CO_2 concentration. Journal of Experimental Botany 43:959–964

Baker JT, Allen LH, Boote KJ (1992b) Response of rice to carbon dioxide and temperature. Agricultural and Forest Meteorology 60:153–166

Balasubramanian R and Krishnarajan J (2003) Water management in direct-seeded lowland rice. International Rice Research Notes 28 (1):71–72

Banba H and Ohkubo T (1981) Relationship between root distribution of upland crops and their yield. III. Influence of soil moisture levels on root distribution and root dry matter of upland-cultured paddy rice, crossbred paddy and upland rice, and upland rice. Japanese Journal of Crop Science 50:1–7

Baraev F (1989) Vodosberegajuschaja technologia oroschenija rica. Taschkent "Mechnat", p 582

Barker R, Wade D, Tuong TP, Bhuiyan SI and Guerra LC (1999) The outlook for water resources in the year 2020: challenges for research on water management in rice production. In: Assessment and Orientation towards the 21st Century. Proceedings of the 19th session of the International Rice Commission, 7–9 September 1998, Cairo, Egypt. Food, Agriculture Organization, p 96–109

Basnayake J, Fukai S and Ouk M (2006) Contribution of potential yield, drought tolerance and escape to adaptation of 15 rice varieties in rainfed lowlands in Cambodia. Proceedings of the Australian Agronomy Conference. Australian Society of Agronomy. Brisbane, Australia

Basnayake J, Sihathep V, Sipaseuth, Sonekham P, Senthonghae M, Sibounheuang V, Phamixay V, Sengkeo Chanphengxay M and Fukai S (2003) Effects of time of planting on agronomic and yield performance of several rice cultivars under various temperature conditions in Lao PDR. In: Proceedings of the 11th Agronomy Conference. Melbourne. www.regional.org.au/au/asa/2003/, last accessed 6.02.2010

Bateman EJ and Baggs EM (2005) Contributions of nitrification and denitrification to N2O emissions from soils at different water-filled pore space. Biol Fertil Soils 41:379–388

Bazaya BR, Sen A and Srivastava VK (2009) Planting methods and nitrogen effects on crop yield and soil quality under direct seeded rice in the Indo-Gangetic plains of eastern India. Soil and Tillage Research 105:27–32

Becker M, Asch F, Maskey SL, Pande KR, Shah SC and Shrestha SM (2007) Effects of transition season management on soil N dynamics and system N balances in rice-wheat rotations of Nepal. Field Crops Research 103:98–108

Bekchanov M, Karimov A and Lamers JPA (2010) Impact of water availability on land and water productivity: A temporal and spatial analysis of the case study region Khorezm, Uzbekistan. Water 2:668–684

Bekturova G and Romanova O (2007) Traditional land management knowledge in Central Asia: Resource pack. Almaty 2007, S-Print, p 86

Belder P, Bouman BAM, and Spiertz JHJ (2007) Exploring option for water savings in lowland rice using a modeling approach. Agricultural Systems 92:91–114

Belder P, Bouman BAM, Cabangon R, Guoan L, Quilang EJP, Li Y, Spiertz JHJ, and Tuong TP (2004) Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. Agricultural Water Management 65:193–210

Belder P, Bouman BAM, Spiertz JHJ, Peng S, Castaneda AR and Visperas RM (2005b) Crop performance, nitrogen and water use in flooded and aerobic rice. Plant and Soil 273:167–182

Beyrouty CA, Grigg BC, Norman RJ and Wells BR (1994) Nutrient uptake by rice in response to water management. J Plant Nutr 17(1):39−55

Bezborodov GA, Shadmanov DK, Mirhashimov RT, Yuldashev T, Qureshi AS, Noble AD and Qadir M (2010) Mulching and water quality effects on soil salinity and sodicity dynamics and cotton productivity in Central Asia. Agriculture, Ecosystems and Environment 138:95–102

Bhuiyan SI, Sattar MA and Khan MAK (1995) Improving water use efficiency in rice irrigation through wet-seeding. Irrig Sci 16:1–8

Bhumbla DR and Abrol IP (1978) Saline and sodic soils. Paper presented at the symposium "Soils and Rice" at the IRRI Los Banos, Laguna, Phillipines, 20–23 September, 1977, p 719–738

Bhushan L, Ladha JK, Gupta RK, Singh S, Tirole-Padre A, Saharawat YS, Gathala M, Pathak H (2007) Saving of water and labor in rice–wheat system with no-tillage and direct seeding technologies. Agron J 99:1288–1296

Blanche SB and Linscombe SD (2009) Stability of rice grain and whole kernel milling yield is affected by cultivar and date of planting. Agron J 101:522–528

Bobojonov IB (2008) Modeling crop and water allocation under uncertainty in irrigated agriculture. A case study on the Khorezm region, Uzbekistan. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Boonjung H and Fukai S (1996) Effects of soil water deficit at different growth stages on rice growth and yield under upland conditions. 2. Phenology, biomass production and yield. Field Crops Research 48:47–55

Borrell AK, Garside AL and Fukai S (1997) Improving efficiency of water for irrigated rice in semi-arid tropical environment. Field Crops Research 52:231–248

Bouman BAM (2001) Coping with the water crisis: Water management strategies in rice production. Paper presented at the International Symposium on Sustainable Soil and Water Resources Management. 30–31 May 2001. Diliman, Quezon City, the Philippines

Bouman BAM and Tuong TP (2001) Field water management to save water and increase its productivity in irrigated lowland rice. Agricultural Water Management 49:11–30

Bouman BAM and Van Laar HH (2006) Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions. Agricultural Systems 87:249–273

Bouman BAM, Feng L, Tuong TP, Lu L, Wang H and Feng Y (2007) Exploring options to grow rice using less water in nitrogen China using a modelling approach, II. Quantifying yield, water balance components, and water productivity. Agricultural Water Management 88:23–33

Bouman BAM, Kropff MJ, Tuong TP, Wopereis MCS, Berge HFM and Van Laar HH (2001) ORYZA2000: modeling lowland rice. Los Banos, Philippines, and Wageningen, The Netherlands: IRRI and Wageningen University and Research Centre

Bouman BAM, Peng S, Castaneda AR and Visperas RM (2005) Yield and water use of irrigated tropical aerobic rice systems. Agricultural Water Management 74:87−105

Bouman BAM, van Keulen H, van Laar HH and Rabbinge R (1996) The 'School of de Wit' crop growth simulation models: pedigree and historical overview. Agricultural Systems 52:171–198

Bouman BAM, Yang X, Wang H, Wang Z, Zhao J and Chen B (2006) Performance of aerobic rice varieties under irrigated conditions in North China. Field Crops Research 97:53–65

Bouwman AF (1996) Direct emission of nitrous oxide from agricultural soils. Nutrient Cycling in Agro-ecosystem 46:53–70

Bradfield R (1971) Mechanized maximum cropping systems for the small farms of the rice belt of tropical Asia. Agric Mechanization Asia 1:55-57

Bremner JM and Mulvaney CS (1982) Nitrogen-total. In: Page AL (ed.), Methods of soil analysis: Part 2. Chemical and microbiological properties. Agron. Monograph Number 9, ASA and SSSA, Madison, WI. p 595–624

Brouwer C, Prins K, Kay M and Heibloem M (1988) Irrigation water management: irrigation methods. Training Manual No. 5. Food and Agriculture Organization of the United Nations. Rome, Italy. http://www.fao.org/docrep/ s8684e / s8684e00.htm#Contents, last accessed 14.10.2010

Bucknall J, Klytchnikova I, Lampietti J, Lundell M, Scatasta M and Thurman M (2003) Irrigation in Central Asia: social, economic and environmental considerations. World Bank Report. Washington, DC, USA

Buresh RJ and De Datta SK (1991) Nitrogen dynamics and management in rice-legume cropping systems. Adv Agron 85:316–321

Buresh RJ, Woodhead T, Shephard KD, Flordelis EV and Cabangon RC (1989) Nitrate accumulation and loss in mungbean/lowland rice cropping system. Soil Sci Am J 53:477–482

Cabangon RJ and Tuong TP (2000) Management of cracked soils for water saving during land preparation for rice cultivation. Soil and Tillage Research 56:105–116

Cabangon RJ, Tuong TP and Abdullah NB (2002) Comparing water input and water use efficiency of transplanted and direct-seeded rice production systems. Agricultural Water Management 57:11–13

Cai X, McKinney DC and Rosegrant MW (2003) Sustainability analysis for irrigation water management in the Aral Sea Region. Agricultural Systems 76:1043-1066

Cassman KG, Peng S, Olk DC, Ladha JK, Reichardt W, Dobermann A and Singh U (1998) Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. Field Crops Research 56:7–39

Centeno HGS, Balbarez AD, Fabellar NG, Kropff MJ and Matthews RB (1995) Rice production in the Philippines under current and future climates. In: Matthews RB, Kropff MJ, Bachelet D, van Laar HH (eds.) Modeling the Impact of Climate Change on Rice Production in Asia. CAB International, UK, p 237–250

Cheng W, Sakai H, Yagi K and Hasegawa T (2009) Interactions of elevated [CO_2] and night temperature on rice growth and yield. Agricultural and Forest Meteorology 149:51–58

Chernishov AK and Shirokova YI (1999) Express method of soil and water salinity evaluation in Uzbekistan (in Russian). Selskoe hoziaistvo Uzbekistana (Agriculture of Uzbekistan)

Chivenge PP, Murwira HK, Giller KE, Mapfumo P and Six J (2007) Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. Soil and Tillage Research 94:328–337

Chou CH, Chiang YC, Cheng HH and Farrow FD (1982) Transformations of ^{15}N-enriched fertilizer nitrogen during rice straw decomposition in submerged soil. Bot Bull Acad Sinica 23(2), 119-133

Christmann S, Martius C, Bedoshvili D, Bobojonov I, Carli C, Devkota K, Ibragimov Z, Khalikulov Z, Kienzler K, Manthrithilake H, Mavlyanova R, Mirzabaev A, Nishanov N, Sharma RC, Tashpulatova B, Toderich K and Turdieva M (2009) Food security and climate change in Central Asia and the Caucasus, Tashkent, Uzbekistan 2009. CGIAR-PFU, ICARDA Tashkent, P.O.Box 4564, Tashkent, 100 000, Uzbekistan

CIA Factbook (2010) Central Intelligence Agency. Central Asia, Uzbekistan. https://www.cia.gov/library/publications/the-worldfactbook/geos/uz, last accessed 28.12.2010

Clayton H, Mc Taggart IP, Parker J, Swan L and Smith KA (1997) Nitrous oxide emissions from fertilized grassland: A 2 year study of the effects of N fertilizer form and environmental conditions. Biol Fertil Soils 25:252–260

Collinson ST, Ellis RH, Summerfield RJ and Roberts EH (1995) Relative importance of air and floodwater temperatures on the development of rice (*Oryza sativa*). Experimental Agriculture 31:151–160.

Connor DJ, Timsina J and Humphreys E (2003) Prospects for permanent beds in the rice-wheat system. In: Ladha JK, Hill JE, Duxbury JM, Gupta RK, Buresh RJ (eds.) Improving the productivity and sustainability of rice-wheat systems: issues and impacts. ASA Special Publication 65. ASA Inc., CSSA Inc., SSSA Inc., Madison, Wisconsin, USA, p 197–210

Conrad C (2007) Estimation of water productivity in irrigated river basins using remote sensing and geo-information techniques: a case study in Khorezm river basin, Uzbekistan. Dissertation, Julius-Maximilians-Universität Würzburg. p 282

Conrad C, Fritsch S, Zeidler J, Rücker G and Dech S (2010) Per-field irrigated crop classification in arid central asia using SPOT and ASTER data. Remote Sensing 2:1035–1056

Cruz RT, O'Toole JC, Dingkuhn M, Yambao EG, Thangaraj M and De Datta SK, (1986) Shoot and root responses to water deficits in rainfed lowland rice. Australian Journal of Plant Physiology 13:567–575

Davidson EA, Hart SC, Shanks CA and Firestone M K (1991) Measuring gross nitrogen mineralization, immobilization, and nitrification by ^{15}N isotopic pool dilution in intact soil cores. Journal of Soil Science 42:335–349

De Datta SK (1981) Principles and practices of rice production. A Wiley-Interscience publication, John Wiley and Sons, Newyork, USA

De Datta SK and Buresh RJ (1989) Integrated nitrogen management in irrigated rice. Adv Soil Sci 10:143-169

Defeng Z and Shaokai M (1995) Rice production in China under current and future climates. In: Matthews RB, Kropff MJ, Bachelet D and van Laar HH (eds.) Modeling the Impact of Climate Change on Rice Production in Asia. CAB International, UK, p 217–235

Deng L, Chen M, Liu Z, Shen Q, Wang H and Wang J (2003) Effects of different ground covers on soil physical properties and crop growth on saline-alkaline soil. Chinese Journal of Soil Science 34 (2):93–97

Derpsch R and Friedrich T (2009) Global overview of conservation agriculture no-till adoption. In 4th World Congress on Conservation Agriculture New Delhi, India, 4-7 February. http://www.fao.org/ag/ca/doc/Global-overview-CA-adoption-Derpschcomp2.pdf, last accessed 12.10.2010

Devkota KP, Ruzibaev E, Egamberdiv O, Devkota MK and Gupta RK (2011) Exploring innovations to sustain rice production in Central Asia: A case study from Khorezm region of Uzbekistan. ZEF/UNESCO, Khorezm Project Book (Forthcoming)

Devkota MK (2011) Nitrogen management in irrigated cotton-based systems under conservation agriculture on salt-affected lands of Uzbekistan. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn (Forthcoming)

Dhaliwal HS, Singh RP, Singh T, Singh Y, Humphreys E and Kukal SS (2008) A financial analysis of permanent raised beds for rice–wheat and alternative cropping systems in Punjab, India. In: Humphreys E and Roth CH (eds.) Permanent beds and Rice-residue Management for Rice–Wheat System of the Indo-Gangetic Plain. ACIAR Proceedings 127:79–91

Dingkuhn M, Sow A, Samb A, Diack S and Asch F (1995) Climatic determinants of irrigated rice performance in the Sahel-I. Photothermal and micro-climatic responses of flowering. Agricultural Systems 48:385–410

Djanibekov N (2008) A micro-economic analysis of farm restructuring in the Khorezm Region, Uzbekistan. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Djumaniyazov A (2004) Literature review of field experiments on use of mineral fertilizers for cotton, conducted at the Khorezm branch of the Uzbek Cotton Research Institute (1927–2003). ZEF internal report. Center for Development Research (ZEF), Urgench, Uzbekistan, p 43

Djumaniyazov A (2006) Literature review of soils in Khorezm. Internal report. ZEF, Urgench, Uzbekistan, p 34

Dong B, Molden D, Loeve R, Li YH, Chen CD and Wang JZ (2004) Farm level practices and water productivity in Zhanghe Irrigation System. Paddy and Water Environment 2: 217–226

Egamberdiev O (2007) Dynamics of irrigated alluvial meadow soil properties under the influence of resource saving and soil protective technologies in the Khorezm region. Dissertation, National University of Uzbekistan

Ekanayake IJ, De Datta SK and Steponkus PL (1989) Spikelet sterility and flowering response of rice to water stress at anthesis. Annals of Botany 63:257–264

European Commission (EC) (1995) Water resources management and agricultural production in the Central Asian Republics, WARMAP Project Report, vol. 1–6

Fagi AM and Kartaatmadja S (2002) Gogorancah rice in Indonesia: a traditional method in the modern era. In: Pandey S, Mortimer M, Wade L, Tuong TP, Lopez K, Hardy B (eds). Direct seeding: research issues and opportunities. Proceedings of the International Workshop on Direct Seeding in Asian Rice Systems: Strategic Research Issues and Opportunities, 25-28 January 2000, Bangkok, Thailand. Los Banos (Philippines): IRRI, Philippines, p 43-53

Falkenmark M and Rockstrom J (2004) Balancing water for humans and nature. The New Approach in Ecohydrology. Earthscan, London, UK, p 247

FAO (1997) Uzbekistan; http://www.fao.org/ag/agl/aglw/aquastat/ countries/ uzbekistan/index.stm, last accessed 23.02.2008

FAOSTAT (2010) Food and Agriculture Organization of the United Nations. http://faostat.fao.org/site/567/default.aspx#ancor, last accessed 10.02.2011

Farooq M, Barsa SMA and Wahid A (2006) Priming of field-sown rice seed enhances germination, seedling establishment, allometry and yield. Plant Growth Regul 49:285–294

Farooq M, Kobayashi N, Wahid A, Ito O and Basra SMA (2009) Strategies for producing more rice with less water. Adv Agron 101:351–388

Farrell TC, Fox KM, Williams RL and Fukai S (2006) Genotypic variation for cold tolerance during reproductive development in rice: Screening with cold air and cold water. Field Crops Research 98:178–194

Farrell TC, Fox KM, Williams RL, Fukai S, Reinke RF and Lewin LG (2001) Temperature constraints to rice production in Australia and Lao PDR: a shared problem. In: Fukai S and Basnayake J (eds.) ACIAR Proceedings 101; Increased Lowland Rice Production in the Mekong Region. Australian Centre for International Agricultural Research, GPO Box 1571, Canberra, ACT 2601, p 129–137

Firestone MK and Davidson EA (1989) Microbiological basis of NO and N_2O production and consumption in soil. In: Andreae MO and Schimel DS (eds.) Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere, Wiley and Sons Ltd., Chichester, p 7–21

Forkutsa I (2006) Modelling water and salt dynamics under irrigated cotton with shallow groundwater in the Khorezm region of Uzbekistan. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Forkutsa I, Sommer R, Shirokova J, Lamers JPA, Kienzler K, Tischbein B, Martius C and Vlek PLG (2009) Modeling irrigated cotton with shallow groundwater in the Aral Sea Basin of Uzbekistan: I. Water dynamics. Irrigation Sci 27 (4):331–46

Forkutsa O (2011) Modeling of soil C and N dynamics of rice-wheat cropping systems under conservation agriculture in Khorezm. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn (Forthcoming)

Fowler DB, Limin AE and Ritchie JT (1999) Low-temperature Tolerance in Cereals: Model and Genetic Interpretation. Crop Sci 39:626–633

Gao D, Jin Z, Huang Y and Zhang D (1992) Rice clock model a computer model to simulate rice development. Agricultural and Forest Meteorology 60:1–16

Gathala MK, Ladha JK, Saharawat YS, Pathak H, Gupta RK and Yadav MP (2006) Performance of no-till rice–wheat system in the Indo-Gangetic Plains. In: Proceedings of 2nd International Rice Congress, New Delhi, India, 9–13 October, p 474

George T, Ladha JK, Buresh RJ and Garrity DP (1992) Managing native and legume fixed nitrogen in lowland rice-based cropping systems. Plant and Soil 141:69–91

George T, Ladha JK, Garrity DP and Buresh RJ (1993) Nitrate dynamics during aerobic soil phase in lowland rice-based cropping systems. Soil Sci Soc Am J 57:1526–1532

Giessen C van der (1942) Gogorancah method of rice cultivation. Contribution No. 11. Chuo Noozi Sikenzyoo, Bogor, p 1–6.

Govaerts B, Sayre KD, Lichter K, Dendooven L and Deckers J (2007) Influence of permanent raised bed planting and residue management on physical and chemical soil quality in rainfed maize/wheat systems. Plant and Soil 291 (1–2):39–54

Govaerts B, Sayre KD and Deckers J (2005) Stable high yields with zero tillage and permanent bed planting? Field Crops Research 94:33–42

Gravois KA and Helms RS (1998) Seeding date effects on rough rice yield and head rice and selection for stability. Euphytica 102:151–159

Griggs BR, Norman RJ, Wilson CE and Slaton NA (2007) Ammonia volatilization and nitrogen uptake for conventional and conservation tilled dry-seeded, delayed-flood rice. Soil Sci Soc Am J 71:745–751

Guan-fu F, Long-xing T, Jian S, Xi W, Li-yong C and Shi-hua C (2008) Responses of yield characteristics to high temperature during flowering stage in hybrid rice Guodao. Rice Science 15(3): 215–222

Guerif J, Richard G, Durr C, Machet J M, Recous S and Roger-Estrade J (2001) A review of tillage effects on crop residue management, seed bed conditions and seedling establishment. Soil and Tillage Research 61:13–32

Gunawardena TA, Fukai S and Blamey P (2003a) Low temperature induced spikelet sterility in rice. I. Nitrogen fertilisation and sensitive reproductive period. Australian Journal of Agricultural Research 54:937–946

Gunawardena TA, Fukai S and Blamey P (2003b) Low temperature induced spikelet sterility in rice. II. Effects of panicle and root temperature. Australian Journal of Agricultural Research 54: 947–956

Gupta R and Seth A (2007) A review of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo-Gangetic plains (IGP). Crop Protection 26:436–447

Gupta R, Kienzler K, Martius C, Mirzabaev A, Oweis T, de Pauw E, Qadir M, Shideed K, Sommer R, Thomas R, Sayre K, Carli C, Saparov A, Bekenov M, Sanginov S, Nepesov M and Ikramov R (2009) Research Prospectus: A Vision for sustainable land management research in Central Asia. ICARDA Central Asia and Caucasus Program. Sustainable Agriculture in Central Asia and the Caucasus Series No.1. CGIAR-PFU, Tashkent, Uzbekistan, p 84

Gupta RK and Sayre K (2007) Conservation agriculture in South Asia. Journal of Agricultural Sciences, Cambridge 145:207–214

Gupta RK, Naresh RK, Hobbs PR, Jiaguo Z and Ladha JK (2003) Sustainability of post-green revolution agriculture: the rice-wheat cropping systems of the Indo-Gangetic Plains and China. In: Ladha JK, Hill JE, Duxbury JM, Gupta RK and Buresh RJ (eds.) 'Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts'. ASA Special Publication 65 (ASAInc, CSSAInc, SSSAInc, Madison, USA), p 25

Hamid A (1972) Efficiency of N uptake by wheat, as affected by time and rate of application, using ^{15}N-labelled ammonium sulphate and sodium nitrate. Plant and Soil 37:389–394

Harmon WL, Michels GJ and Wiese AF (1989) A conservation tillage system for profitable cotton production in the central Texas high plains. Agron J 81:615–618

Hassan I, Hussain Z and Akbar G (2005) Effect of permanent raised beds on water productivity for irrigated maize–wheat cropping system. In: Roth CH, Fischer RA and Meisner CA (eds.) Evaluation and performance of permanent raised bed cropping systems in Asia, Australia and Mexico. ACIAR Proceeding. No. 121

Hayat K, Awan IU and Hassan G (2003) Impact of seeding dates and varieties on weed infestation yield and yield components of rice under direct wet seeded culture. Pakistan Journal of Weed Science Research 9(1-2):59-65

Heenan DP and Thompson JA (1984) Growth, grain yield and water use of rice grown under restricted water supply in New South Wales. Aust J Exp Agric Anim Husb 24:104–109

Hobbs P and Gupta RK (2003) Rice-wheat cropping systems in the Indo-Gangetic Plains: issues of water productivity. I. Relation to new resource-conserving technologies. In: Kijne JW, Barker R, Molden D (eds.) Water productivity in agriculture: limits and opportunities for improvement. CABI Publishing, Wallingford, UK, p 239–253

Hobbs PR and Gupta RK (2002) Rice–wheat cropping systems in the Indo-Gangetic plains: Issues of water productivity in resource conserving technologies. Water Productivity Workshop, 12–14 Nov. 2001. International Water Management Institute, Colombo, Sri Lanka

Hobbs PR and Gupta RK (2004) Problems and challenges of no-till farming for the rice–wheat systems of the Indo-Gangetic Plains in South Asia In: Lal R, Hobbs P, Uphoff N, Hansen DO (eds.) Sustainable Agriculture and the Rice–wheat System. Ohio State University, Marcel Dekker, Columbus, OH, New York, USA, p 101–119

Hobbs PR and Moris ML (1996) Meeting South Asia's future food requirements from rice–wheat cropping systems: priority issues facing researchers in the post green revolution era. NRG Paper 96–01. CIMMYT, Mexico, p 46

Hobbs PR, Sayre K and Gupta R (2008) The role of conservation agriculture in sustainable agriculture. Philosophical Transactions of the Royal Society of Biological Sciences 363:543–555

Horie T (1991) Model analysis of the effect of climatic variation on rice yield in Japan. In: Geng S and Cady CW (eds.) Climatic Variation and Change: Implications for Agriculture in the Pacific Rim. University of California, Davis, CA, USA

Horie T (1993) Predicting the effects of climatic variation and effect of CO_2 on rice yield in Japan. Jpn Agric Meteorol 48:567–574

Horie T, Baker JT, Nakagawa H and Matsui T (2000) Crop ecosystem responses to climatic change: rice. In: Reddy KR and Hodges HF (eds.) Climate Change, Plant Productivity and Global Implications. CABI Publishing, New York, NY, p 81–106

Horie T, Nakagawa H, Centeno HGS and Kropff MJ (1995) The rice crop simulation model SIMRIW and its testing. In: Matthews RB, Kropff MJ, Bachelet D, van Laar HH (eds.) Modeling the impact of climate change on rice production in Asia. CAB International, UK, p 51–66

Horie T, Yajima M and Nakagawa H (1992) Yield forecasting. Agricultural Systems 40:211-236

Horst MG, Shamutalov SS, Pereira LS and Goncalves JM (2004) Field assessment of the potential for water saving furrow irrigation in Fergana, Aral Sea Basin. Agricultural Water Management 77:210–231

Hu F, Yang M, Liang Y, Liu M and Chen X (1999) A study on fertility characteristics of paddy soils under plastic film mulching condition. In: Soil Committee of Jiangsu Province (eds.) Soil Science Towards 21st Century (Jiangsu Vol.). Hehai University Press, Nanjing (Abstract in English)

Huang Q, Yin Z and Tian C (2001) Effect of two different straw mulching methods on soil solute salt concentration. Arid Land Geography 24:52–56

Humphreys E, Meisner C, Gupta R, Timsina J, Beecher HG, Lu TY, Singh Y, Gill MA, Masih I, Zheng JG and Thomposon JA (2005) Water savings in rice-wheat systems. Plant Prod Sci 8:242–258

Ibragimov N, Evett S, Esanbekov Y, Kamilov B, Mirzaev L and Lamers JPA (2007) Water use efficiency of irrigated cotton in Uzbekistan under drip and furrow irrigation. Agricultural Water Management 90:112–120

Ibrakhimov M (2005) Spatial and temporal dynamics of groundwater table and salinity in Khorezm (Aral Sea Basin), Uzbekistan. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Ibrakhimov M, Park SJ and Vlek PLG (2004) Development of groundwater salinity in a region of the lower Amu-Darya River, Khorezm, Uzbekistan. Agriculture in Central Asia: Research for Development. Proceedings of a Symposium held at the American Society of Agronomy Annual Meeting at Indianapolis, Indiana, USA, 10-14 Nov. International Centre for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria, p 56-75

IPCC (2007) Impacts, adaptation and vulnerability. In: ML Parry, Canziani OF, Palutikof JP, van der Linden PJ, and Hanson CE (eds.) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, p 469–506

IRRI (2002) Standard evaluation system for rice (SES). Manila, Philippines, IRRI, p 56.

Ismali AM (2006) Activities of IRRI in Central Asia and the Caucasus (CAC) region in 2006. Annual Report submitted to IRRI, Metro Manila Philippines

Jagadish SVK, Craufurd PQ and Wheeler TR (2007) High temperature stress and spikelet fertility in rice (*Oryza sativa* L.). Journal of Experimental Botany 58:1627–1635

Jagadish SVK, Muthurajan R, Oane R, Wheeler TR, Heuer S, Bennett J and Craufurd PQ (2010) Physiological and proteomic approaches to address heat tolerance during anthesis in rice (*Oryza sativa* L.). Journal of Experimental Botany 61:143–156

Jalota SK and Arora VK (2002) Model based assessment of water balance components under different cropping systems in north-west India. Agricultural Water Management 57: 75–87

Jat ML, Gathala MK, Ladha JK, Saharawat YS, Jat AS, Kumar V, Sharma SK, Kumar V and Gupta RK (2009) Evaluation of precision land leveling and double zero-till systems in the rice–wheat rotation: Water use, productivity, profitability and soil physical properties. Soil and Tillage Research 105:112–121

Jing Q, Bouman BAM, Hengsdijk, van Keulen H and Cao W (2007) Exploring options to combine high yields with high nitrogen use efficiencies in irrigated rice in China. European Journal of Agronomy 26:166–177

Kaneda C and Beachell HM (1974) Response of indica-japonica rice to low temperature. SABROJ 6:17–32

Karim Z, Ahmed M, Hussain SG and Rashid KB (1995) Impact of climate change on the production of modern rice in Bangladesh. Bangladesh Agricultural Research Council, Dhaka, Bangladesh

Karunatilake U, van Es HM and Schindelbeck RR (2000) Soil and maize response to plow and no-tillage after alfalfa-to-maize conversion on a clay loam soil in New York. Soil and Tillage Research 55:31–42

Kato Y, Okami M and Katsura K (2009) Yield potential and water use efficiency of aerobic rice (*Oryza sativa* L.) in Japan. Field Crops Research 113:328–334

Katyal JC, Singh B, Vlek PLG and Crasswell ET (1985) Fate and efficiency of nitrogen fertilizers applied to wetland rice. II. Punjab, India. Fertilizer Research 6:279–290

Keeney DR and Follett RF (1991) Overview and introduction. In: Follett RF (ed.) Managing nitrogen for groundwater quality and farm profitability. SSSA, Madison, WI, p 1–7

Khamzina A (2006) The assessment of tree species and irrigation techniques for afforestation of degraded agricultural landscapes in Khorezm, Uzbekistan, Aral Sea Basin. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Kienzler K (2010) Improving the nitrogen use efficiency and crop quality in the Khorezm region, Uzbekistan. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Kim HY, Lieffering M, Kobayashi K, Okada M, Mitchell MW and Gumpertz M (2003) Effects of free-air CO_2 enrichment and nitrogen supply on the yield of temperate paddy rice crops. Field Crops Research 83:261–270

Kiniry JR, Rosenthal WD, Jackson BS and Hoogenboom G (1991) Predicting leaf development of crop plants. In: Hodges T (ed.) Predicting crop phenology. Boca Raton, Fla. (USA): CRC Press, p 29–42

Kiseliova IK and Lifshits EA (1971a) The Khorezm region (in Russian). In: Legostaev VM and Mednisa MP (eds.) Regimes of irrigation and hydro-module zoning in Uzbekistan. "Uzbekistan", Tashkent, p 303

Kitamura Y, Yano T, Honna T, Yamamoto S and Inosako K (2006) Causes of farmland salinization and remedial measures in the Aral Sea basin–Research on water management to prevent secondary salinization in rice-based cropping system in arid land. Agricultural Water Management 85:1–14

Kottek M, Grieser J, Beck C, Rudolf B and Rubel F (2006) World map of Köppen-Geiger climate classification updated. http://koeppen-geiger.vu-wien.ac.at/, last accessed 22.10.2009

Kraatz DB and Mahajan IK (1975) Small hydraulic structures FAO Irrigation and Drainage Paper 26/2, Rome, p 198

Kreye C, Bouman BAM, Reversat G, Fernandez L, Vera Cruz C, Elazegui F, Faronilo JE and Llorca L (2009) Biotic and abiotic causes of yield failure in tropical aerobic rice. Field Crops Research 112:97–106

Krishnan P, Swain DK, Chandra B, Nayak SK and Dash RN (2007) Impact of elevated CO_2 and temperature on rice yield and methods of adaptation as evaluated by crop simulation studies. Agriculture, Ecosystems and Environment 122: 233–242

Kropff MJ, van Laar HH and Matthews RB (1994a) ORYZA1: an ecophysiological model for irrigated rice production. SARP Research Proceedings. Wageningen (Netherlands): IRRI/AB-DLO, p 110

Kropff MJ, Williams RL, Horie T, Angus JF, Singh U, Centeno HG and Cassman KG (1994) Predicting yield potential of rice in different environments. In: Humphreys et al. (eds.) Temperate Rice Achievements and Potential. Proceedings of Temperate Rice Conference, Yanco, NSW, Australia, p 657–663

Kukal SS, Singh Y, Yadav S, Humphreys E, Kaur A and Thaman S (2008) Why grain yield of transplanted rice on permanent raised beds declines with time? Soil & Tillage Research 99:261–267

Kukal SS, Yadav S, Humphreys E, Kaur A, Singh Y, Thaman S, Singh B and Timsina J (2010) Factors affecting irrigation water savings in raised beds in rice and wheat. Field Crops Research 118:43–50

Kundu DK and Ladha JK (1995) Efficient management of soil and biologically fixed N2 in intensively-cultivated rice fields. Soil Biol Biochem 27:431–439

Kwak KS and Lee CK (2006) How will the increase air temperature by global warming influence on the yield capacity and quality of rice in Korea. In: Proceedings of the Japanese Society of Crop Science Symposium (Spring) on ‘‘Current Research Topics on Crop Eco-physiology in Asia with Emphasis on the Impact of Global Warming on Rice Eco-physiology’’

Kyaw KM, Toyota K, Okazaki M, Motobayashi T and Tanaka H (2005) Nitrogen balance in a paddy field planted with whole crop rice (*Oryza sativa* cv. Kusahonami) during two rice-growing seasons. Biol Fertil Soils 42:72–82

Ladha JK, Kumar V, Alam M, Sharma S, Gathala M, Chandna P, Saharawat YS and Balasubramanian V (2009a) Integrating crop and resource management technologies for enhanced productivity, profitability, and sustainability of the rice–wheat system in South Asia. In: Ladha JK (ed.), Integrated Crop and Resource Management in the Rice–Wheat System of South Asia. IRRI, Los Banos, Philippines, p 69–108

Ladha JK, Pathak H, Padre AT, Dave D and Gupta RK (2003) Productivity trends in intensive rice–wheat cropping systems in Asia, in: Ladha JK (ed.), Improving the Productivity and Sustainability of Rice–Wheat Systems: Issues and Impacts. ASA Special Publication No. 65, ASA, CSSA, and SSSA, Madison, WI, USA, p 45–76

Lavahun MF, Joergensen RG and Meyer B (1996) Activity and biomass of soil microorganisms at different depths. Biol Fertil Soils 23:38–42

Lee LM, Kassim A and Gofar N (2011) Performances of two instrumented laboratory models for the study of rainfall infiltration into unsaturated soils. Engineering Geology 117:78–89

Lee MH (2001) Low temperature tolerance in rice: the Korean experience. In: Fukai S and Basnayake J (eds.) ACIAR Proceedings 101; Increased Lowland Rice Production in the Mekong Region. Australian Centre for International Agricultural Research, GPO Box 1571, Canberra, ACT 2601:138–146

Letey J (1984) Impact of salinity on the development of soil science. In: Shainberg I and Shalhevet J (eds.) Soil salinity under irrigation. Processes and management. Ecological Studies 51. Springer-Verlag, New York, p 1–9

Lewin L and Maccaffery D (1985) Rice seedling growth is influenced by water depth and temperature. Farmer’s Newsletter Large Area No. 127

Li Y (2001) Research and practice of water-saving irrigation for rice in China. In: Barker R, Li Y and Tuong TP (eds.) Water-Saving Irrigation for Rice. Proceedings of the International Workshop, 23–25 March 2001, Wuhan, China. International Water Management Institute, Colombo, Sri Lanka, p 135–144

Li-jiao Y, Zhong Y, Zhi-ming Zi and Hua-bin L (2006) Simulation of potential production and optimum population quantitative indices for the second hybrid rice. Agricultural Sciences in China 5(7):498–505

Lilley JM and Fukai S (1994) Effect of timing and severity of water deficit on four diverse rice cultivars. II. Physiological responses to soil water deficit. Field Crops Research 37 215–223

Lin S, Dittert K, Tao H, Kreye C, Xu Y, Shen Q, Fan X and Sattelmacher B (2003b) The ground-cover rice production system (GCRPS): A successful new approach to save water and increase nitrogen fertilizer efficiency. In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong TP and Ladha JK (eds.) ''Water-Wise Rice Production''. Proceedings of a Thematic Workshop on Water-Wise Rice Production, 8–11 April 2002 at IRRI Headquarters in Los Banos, Philippines. IRRI, Los Banos, Philippines

Linn DM and Doran JW (1984) Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and no-tilled soils. Soil Sci Soc Am J 48:1267–1272

Liu XJ, Wang JC, Lu SH, Zhang FS, Zeng XZ, Ai YW, Peng SB and Christie P (2003) Effects of non-flooded mulching cultivation on crop yield, nutrient uptake and nutrient balance in rice–wheat cropping systems. Field Crops Research 83:297–311

Lu G, Cabangon R, Tuong TP, Belder P, Bouman BAM and Castillo E (2002) The effects of irrigation management on yield and water productivity of inbred, hybrid, and aerobic rice varieties In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong TP, Ladha JK (eds.) Water-wise rice production. Proceedings of the International Workshop on Water-wise Rice Production, 8-11 April 2002, Los Banos, Philippines. Los Banos (Philippines): IRRI, p 356

Lu J, Hirasawa T and Lu J (2001) Study on intermittent irrigation for paddy rice. I. Water use efficiency. Pedosphere 11:49–56

Maclean JL, WADe DC, Hardy B and Hettel G (2002) Rice Almanac, third edition. IRRI, Los Banos, Philippines, p 253

MacRae IC, Ancajas RR and Salandanan S (1968) The fate of nitrate in some tropical soils following submergence. Soil Science 105:327-334

Mall RK and Aggarwal PK (2002) Climate change and rice yields in diverse agro-environments of India. I. Evaluation of impact assessment models. Climate Change 52:315–330

Mandal N, Nag K and Ghosh M (2005) Planting date effects on phenological development, yield, and quality of hybrid rice. Tropical Agriculture 82 (1–2): 34–39

Martius C, Froebrich J and Nuppenau EA (2009) Water resource management for improving environmental security and rural livelihoods in the irrigated Amu Darya lowlands. In: Brauch HG, Spring UO, Grin J, Mesjasz C, Kameri-Mbote P, Behera NC, Chourou B, Krummenacher H (eds.) Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts. Hexagon Series on Human and Environmental Security and Peace. (Berlin – Heidelberg – New York: Springer-Verlag), 4:749–762

Matsui T and Horie T (1992) Effect of elevated CO_2 and high temperature on growth and yield of rice. 2. Sensitive period and pollen germination rate in high temperature sterility of rice spikelets at flowering. Japanese Journal of Crop Science 61:148–149

Matsui T and Omasa K (2002) Rice (*Oryza sativa* L.) cultivars tolerant to high temperature at flowering: Anther characteristics. Annals of Botany 89:683–687

Matsui T, Kobayashi K, Kagata H and Horie T (2005) Correlation between variability of pollination and length of basal dehiscence of the theca in rice and a hot-and-humid condition. Plant Prod Sci 8:09–114

Matsui T, Namuco OS, Ziska LH and Horie T (1997) Effect of high temperature and CO_2 concentration on spikelet sterility in indica rice. Field Crops Research 51:213–219

Matsui T, Omasa K and Horie T (2001) The difference in sterility due to high temperature during the flowering period among japonica rice varieties. Plant Prod Sci 4(2): 90–93

Matsushima S, Tanaka T and Hoshino T (1964) Analysis of yield determining process and its application to yield-prediction and culture improvement of lowland rice. LXX. Combined effect of air temperature and water temperature at different stages of growth on the grain yield and its components of lowland rice. Proceeding of Crop Science Society of Japan 33:53–58

Matthews RB, Horie T, Kropff MJ, Bachelet D, Centeno HG, Shin JC, Mohandass S, Singh S, Defeng Z and Lee MH (1995) A regional evaluation of the effect of future climate change on rice production in Asia. In: Matthews RB, Kropff MJ, Bachelet D, van Laar HH (eds.) Modeling the Impact of Climate Change on Rice Production in Asia. CAB International, UK, p 95–139

Matthews RB, Kropff MJ, Horie T and Bacheletd D (1997) Simulating the impact of climate change on rice production in Asia and evaluating options for adaptation. Agricultural Systems 54 (3):399–425

Meteo-infospace (2004) Russia's Weather Server-Weather Archive. http://meteo.infospace.ru

Mikkelsen DS (1987) Nitrogen budgets in flooded soils used for rice productions. Plant and Soil 100:71–97

Mishra HS, Rathore TR and Pant RC (1990) Effect of intermittent irrigation on groundwater table contribution, irrigation requirement and yield of rice in mollisols of Tarai region. Agricultural Water Management 18:231–241

Mishra S, Rathore TR and Pant RC (1991) Effect of varying water regimes on soil physical properties and yield of rice in mollisols of Tarai region. Agricultural Water Management 20:71–80

Mkhabela MS, Madani A, Gordon R, Burton D, Cudmore D, Elmi A and Hart W (2008) Gaseous and leaching nitrogen losses from no-tillage and conventional tillage systems following surface application of cattle manure. Soil and Tillage Research 98:187–199

Mohammed AR and Tarpley L (2009) Instrumentation enabling study of plant physiological response to elevated night temperature. Plant Methods 5(7): doi:10. 1186/1746-4811-5-7

Mohandass S, Kareem AA, Ranganathan TB and Jeyaraman S (1995) Rice production in India under current and future climates. In: Matthews RB, Kropff MJ, Bachelet D, van Laar HH (eds.) Modeling the Impact of Climate Change on Rice Production in Asia. CAB International, UK, p 161–179

Monfreda C, Ramankutty N and Foley JA (2008) Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000, Global Biogeochemical Cycles, Vol. 22, GB1022, doi:10.1029/2007GB002947

Müller M (2006) A general equilibrium approach to modeling water and land use reforms in Uzbekistan. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Myagkov S (2006) Climate change impact on the river runoff in Central Asia: risks of water management. Asia Capacity Building Workshop "Earth Observation in the Service of Water Management”. 26-28 September, 2006, Bangkok, Thailand

Nakagawa H, Horie T and Matsui T (2002) Effects of climate change on rice production and adaptive technologies. In: Mew TW, Brar DS, Peng S, Dawe D and B Hardy eds.) ‘‘Rice Science: Innovations and Impact for Livelihood’’ IRRI, Philippines p 635–657

Nesbitt M, Simpson St J and Svanberg I (2010) History of rice in Western and Central Asia. http://www.ancientgrains.org/rice2010nesbitt.pdf.pdf, last accessed 5.03.2011

O’Hara SL (2000) Lessons from the past: water management in Central Asia. Water Policy 2 (4-5):365–384

O’Toole JC and Baldia EP (1982) Water deficits and mineral uptake in rice. Crop Sci. 22: 1144–1150

OblStat (2010) Cotton-raw and wheat production in Uzbekistan during 1991-2001 (in all farm types, including different soil types). Regional Department of Statistics, Urgench, Khorezm region

Ochs WJ and Smedema LK (1996) Planning for drainage development in the Aral Sea basin. In: Bos MG (ed.) The inter-relationship between irrigation, drainage and the environment in the Aral Sea Basin. Proceedings of the NATO advanced research workshop on drainage and development in arid zones. Kluwer Academic Publisher, the Netherlands, p 28–29

Ockerby SE and Fukai S (2001) The management of rice grown on raised beds with continuous furrow irrigation. Field Crops Research 69:215-226

Ohe I, Saitoh K and Kuroda T (2007) Effect of high temperature on growth, yield and dry-matter production of rice grown in the paddy field. Plant Prod Sci 10(4):412–422

Okada M (1991) Variations of climate and rice production in Northern Japan. In: Geng S and Cady CW (eds.) Climate Variations and Change: Implications for Agriculture in the Pacific Rim, University of California, Davis, CA, USA

Panda MM, Mosier AR, Mohanty SK, Chakravorti SP, Chalam AB and Reddy MD (1995) Nitrogen utilization by lowland rice as affected by fertilization with urea and green manure. Fertilizer Research 40:215–223

Pang HC, Li YY, Yang JS and Liang YS (2009) Effect of brackish water irrigation and straw mulching on soil salinity and crop yields under monsoonal climatic conditions. Agricultural Water Management 97 (12-15):1971–1977

Partohardjono S and Z Harahap (1979) Varietal choice and crop management strategies for dry-sown rice in shallow rainfed or partially irrigated fields. Paper presented at the International Rice Research Conference, 16-20 April 1979, IRRI, Los Banos, Philippines

Pathak H, Li C, Wassmann R and Ladha JK (2006) Simulation of nitrogen balance in rice–wheat systems of the Indo-Gangetic plains. Soil Sci Soc Am J 70:1612–1622

Patra AK, Chhonkar PK and Khan MA (2004) Nitrogen loss and wheat (*Triticum aestivum* L.) yields in response to zero-tillage and sowing time in a semiarid tropical environment. Journal of Agronomy and Crop Science (190):324–331

Patrick WH and Wyatt R (1964) Soil nitrogen loss as a result of alternate submergence and drying. Soil Sci Soc Am J 28:647–653

Peng S, Bouman BAM, Visperas RM, Castaneda A, Lixiao N and Hong-Kyu P (2006) Comparison between aerobic and flooded rice: agronomic performance in a long-term (8-season) experiment. Field Crops Research 96:252–259

Peng S, Huang J, Sheehy JE, Laza RC, Visperas RM, Zhong X, Centeno GS, Khush GS and Cassman KG (2004) Rice yields decline with higher night temperature from global warming. Proceeding of National Academy of Science USA. 101:9971–9975

Perry CJ (2001) Charging for irrigation water: The issues and options, with a case study from Iran. Research Report 52. Colombo, Sri Lanka: International Water Management Institute

Pirmoradian N, Sepaskhah AR and Maftoun M (2004) Deficit irrigation and nitrogen effects on nitrogen-use efficiency and grain protein of rice. Agronomie 24:143-153

Ponnamperuma FN (1985) Chemical kinetics of wetland rice soils relative to soil fertility. In: Wetland soils: Characterization, classification, and utilization. IRRI, Philippines, p 71-80

Prasad PVV, Boote KJ, Allen Jr LH, Sheehy JE and Thomas JMG (2006) Species, ecotype and cultivar differences in spikelet fertility and harvest index of rice in response to high temperature stress. Field Crops Research 95:398–411

Protasov PV (1977) Methods of agro-chemical analyses of soil and plants. All Union Research Institute of Cotton Science, Tashkent

Puckridge DW and O'Toole JC (1981) Dry matter and grain production of rice, using a line source sprinkler in drought studies. Field Crops Research 3:303–319

Qiao H, Liu X, Li W, Huang W, Li C and Li Z (2006) Effect of deep straw mulching on soil water and salt movement and wheat growth. Chinese Journal of Soil Science 37 (5):885–889

Quemada M and Cabrera ML (1995) Carbon and nitrogen mineralized from leaves and stems of four cover crops. Soil Sci Soc Am J 59:471–477

Rao DN and Mikkelsen DS (1976) Effect of rice straw incorporation on rice plant growth and nutrition. Agron J 68 752–755

Rasmussen KJ (1999) Impact of ploughless soil tillage on yield and soil quality: a Scandinavian review. Soil and Tillage Research 53:3–14

Raun RW and Johnson GV (1999) Improving nitrogen use efficiency for cereal production. Agron J 91:357–363

Rawson HM, Gomez-Macpherson H (2000). Irrigated Wheat. FAO, Rome, p 96

Reddy KR and Patrick WH (1976) Effect of frequent changes in aerobic and anaerobic conditions on redox potential and nitrogen loss in a flooded soil. Soil Biol Biochem 8:491–495

Rejesus RM, Palis FG, Rodriguez DGP, Lampayan RM and Bouman BAM (2011) Impact of the alternate wetting and drying (AWD) water-saving irrigation technique: Evidence from rice producers in the Philippines. Food Policy 36(2) 280-288

Rekhi RS, Meelu OP and Gupta RK (1982) Lysimeter studies on recovery of ^{15}N-labeled urea in wetland rice. Plant and Soil 66:57–67

Rhoades JD and Loveday J (1990) Salinity in irrigated agriculture. In: Stewart BA and Nielson DR (eds.) Irrigation of agriculture crops. Agronomy Monograph 30. ASA, CSSA, and SSSA, Madison, WI, p 1089–1142

Rhoades JD, Chanduvi F and Lesch S (1999) Soil salinity assessment: Methods and interpretation of electrical conductivity measurements. FAO Irrigation and Drainage Paper 57. FAO, Rome

Rice CW and Smith MS (1982) Denitrification in no-till and plowed soils. Soil Sci Soc Am J 46:1168-1173

Rochette P, Angers DA, Chantigny MH, MacDonald JD, Bissonnette N and Bertrand N. (2009). Ammonia volatilization following surface application of urea to tilled and no-till soils: A laboratory comparison. Soil and Tillage Research 103:310–315

Sadanandan N and Mahapatra IC (1973) Studies in multiple cropping–balance sheet of nitrogen in various cropping patterns. Indian J Agron 18:323–327

Saharawat YS, Singh B, Malik RK, Ladha JK, Gathala M, Jat ML and Kumar V (2010) Evaluation of alternative tillage and crop establishment methods in a rice–wheat rotation in North Western IGP. Field Crops Research 116:260–267

Sainju UM and BP Singh (2001) Tillage, cover crop, and kill-planting date effects on corn yield and soil nitrogen. Agron J 93:878–886

Sainju UM, Singh BP, Whitehead WF and Wang S (2006) Carbon supply and storage in tilled and non-tilled soils as influenced by cover crops and nitrogen fertilization. J Environ Qual 35:1507–1517

Sandhu BS, Khera KL, Prihar SS and Singh B (1980) Irrigation needs and yield of rice on a sandy loam soil as affected by continuous and intermittent submergence. Indian J Agric Sci 50:492–496

SAS Institute (2008) SAS 9.2 Copyright 2002-2008. SAS Institute Inc., Cary, NC, USA

Sasake T and Hayase H (1970) Male sterility caused by cooling treatment at the young microspore stage in rice plants. 5. Estimations of pollen development stage and the most sensitive stage to coolness. Proceeding of Crop Science Society of Japan 39:473–486

Sasaki T (1979) Relationship between germination rate of rice seeds at low temperature and the subsequent early growth of seedlings, 5: Germination and emergence of radicle at low-temperature. Japanese Journal of Crop Science 48:39–45

Sasaki T (1981) The relationship between germination rate of rice seeds at low temperature and the subsequent early growth of seedlings. 6. Effect on the germinability at low-temperature and initial growth of seedling by high temperature treatment of rice-seeds. Japanese Journal of Crop Science 50:19–24

Satake T and Yoshida S (1978) High temperature-induced sterility in indica rice at flowering. Japanese Journal of Crop Science 47:6–17

Sayre KD (2008) Method of estimating wheat yield components in combine harvested and hand harvested plots

Sayre KD and Hobbs PR (2004) The raised-bed system of cultivation for irrigated production conditions. In: Lal R, Hobbs PR, Uphoff N, Hansen DO (eds.) Sustainable Agriculture and the Rice-Wheat System. Chapter 20, Ohio State University. Columbus, Ohio, USA, p 337–355

Sayre KD and Moreno Ramos OH (1997) Applications of raised bed-planting system to wheat. Wheat Program Special Report. CIMMYT, Mexico

Scheer C (2008) Biosphere-atmosphere-exchange of C and N trace gases and microbial N turnover processes in irrigated agricultural systems of the Aral Sea Basin, Uzbekistan. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Scheer C, Wassmann R, Butterbach-Bahl K, Lamers JPA and Martius C (2008a) The relationship between N_2O, NO, and N_2 fluxes from fertilized and irrigated dryland soils of the Aral Sea basin, Uzbekistan. Plant and Soil 314 (1-2):273–283

Scheltema W (1974) Puddling against dry plowing for lowland rice culture in Surinam: effect on soil and plant, and interactions with irrigation and nitrogen dressing. Agric Res Rep 828. Cent Agric Publ Doc, Wageningen

Scholefield D, Hawkins JMB and Jackson SM (1997) Use of a flowing helium atmosphere incubation technique to measure the effects of denitrification controls applied to intact cores of a clay soil. Soil Biol Biochem 29:1337–1344

Scopel E, Triomphe B, Ribeiro MFS, Seguy L, Denardin JE and Kochhann RA (2004) Direct seeding mulch-based cropping systems (DMC) in Latin America. New directions for a diverse planet. In: Proceedings of the Fourth International Crop Science Congress. 26 September–1 October 2004. Brisbane, Australia, p 16

Senewiratne ST and Mikkelsen DS (1961) Physiological factors limiting growth and yield of Oryza sativa under un-flooded conditions. Plant and Soil 14 (2):127–145

Shah T, Hassan MUL, Khattak MZ, Banerjee PS, Singh OP and Rehman SUR (2009) Is irrigation water free? A reality check in the Indo-Gangetic basin. World Development 37 (2):422–434

Shannon MC (1997) Adaptation of plants to salinity. Adv Agron 60:75-120

Sharma PK, Bhushan L, Ladha JK, Naresh RK, Gupta RK, Balasubramanian BV and Bouman BAM (2002) Crop-water relations in rice-wheat cropping under different tillage systems and water-management practices in a marginally sodic, medium-textured soil. In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong TP, Ladha JK (eds.) Water-wise rice production. Proceedings of the International Workshop on Water-wise Rice Production, 8-11 April 2002, Los Banos, Philippines, p 356

Sharma PK, Ladha JK and Bhushan L (2003) Soil physical effects of puddling in rice–wheat cropping system. In: Ladha et al. (eds.) Improving the productivity and sustainability of rice–wheat systems: Issues and impacts. ASA Special Publication 65. ASA, CSSA, and SSSA, Madison, WI, p 97–114

Sheehy JE, Mitchell PL and Ferrer AB (2006) Decline in rice grain yields with temperature: Models and correlations can give different estimates. Field Crops Research 98:151–156

Shen SH, Yang SB, Zhao YX, Xu YL, Zhao XY, Wang ZY, Liu J and Zhang WW (2011) Simulating the rice yield change in the middle and lower reaches of the Yangtze River under SRES B2 scenario. Acta Ecologica Sinica 31:40–48

Shimono H, Hasegawa T and Iwama K (2002) Response of growth and grain yield in paddy rice to cool water at different growth stages. Field Crops Research 73:67–79

Shimono H, Hasegawa T, Fujimura S and Iwama K (2004) Responses of leaf photosynthesis and plant water status in rice to low water temperature at different growth stages. Field Crops Research 89:71–83

Shimono H, Okada M, Kanda E and Arakawa I (2007). Low temperature-induced sterility in rice: Evidence for the effects of temperature before panicle initiation. Field Crops Research 101:221–231

Sin CJ and Lee MH (1995) Rice production in South Korea under current and future climates. In: Matthews RB, Kropff MJ, Bachelet D, van Laar HH (eds.) Modeling the Impact of Climate Change on Rice Production in Asia. CAB International, UK, p 199–214

Singh AK, Choudhury BU and Bouman BAM (2002) Effects of rice establishment methods on crop performance, water use, and mineral nitrogen. In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban B, Toung TP and Ladha JK (eds.) 'Water-wise Rice Production'. Proceedings of the International Workshop on Water-wise Rice Production, 8–11 April 2002, Los Banos, Philippines, p 237–246

Singh AK, Choudhury BU and Bouman BAM (2003) Effects of rice establishment methods on crop performance, water use, and mineral nitrogen. In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong TP and Ladha JK (eds.) ''Water-Wise Rice Production. Proceedings of a Thematic Workshop on Water-Wise Rice Production, 8–11 April 2002 at IRRI, Los Banos, Philippines

Singh S, Rajan A, Ibrahim YB and Wan Sulaiman WH (1995) Rice production in Malaysia under current and future climates. In: Matthews RB, Kropff MJ, Bachelet D, van Laar HH (eds.) Modeling the Impact of Climate Change on Rice Production in Asia. CAB International, UK, p 183–195

Singh Y and Ladha JK (2004) Principles and practices of no-tillage systems in rice–wheat systems of Indo-Gangetic plains. In: Lal et al. (eds.) Sustainable agriculture and the rice–wheat systems. Marcel Dekker, New York, p 167–207

Singh Y, Singh VP, Singh G, Yadav DS, Sinha RKP, Johnson DE and Mortimer AM (2011) The implications of land preparation, crop establishment method and weed management on rice yield variation in the rice–wheat system in the Indo-Gangetic plains. Field Crops Research 121 (1):64–74

Singh Yadvinder, Sidhu HS, Singh M, Humphreys E and Kukal SS (2008) Straw mulch, irrigation water and fertilizer N management effects on yield, water use and N use efficiency of wheat sown after rice. In: Humphreys E and Roth CH (eds.) Proceedings of Permanent Beds and Rice Residue Management for Rice–Wheat Systems in the Indo-Gangetic Plains. ACIAR Workshop Proceedings No. 127, ACIAR, Canberra, Australia, p 196

Sipaseuth JB, Fukai S, Farrell TC, Senthonghae M, Sengkeo, Phamixay S, Linquist B and Chanphengsay M (2007) Opportunities to increasing dry season rice productivity in low temperature affected areas. Field Crops Research 102: 87–97

Sommer R, Djanibekov N, Salaev O and Rücker G (2008a) Integrated bio-economic optimization of water and resource allocation on farm-aggregated level in Khorezm, Uzbekistan. Model description and scenario analysis. ZEF Discussion paper

Tabbal DF, Bouman BAM, Bhuiyan SI, Sibayan EB and Sattar MA (2002) On-farm strategies for reducing water input in irrigated rice; case studies in the Philippines. Agricultural Water Management 56:93–112

Teosdale JR, Beste CE and Potts WE (1991) Response of weeds to tillage and cover crop residues. Weed Sci 39:195–199

Thompson JA (2002) Water management of rice in southern New South Wales, Australia.. In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong TP and Ladha JK (eds.) Water-wise rice production. Proceedings of the International Workshop on Water-wise Rice Production, 8-11 April 2002, Los Banos, Philippines, p 63-71

Thuy NH, Shan Y, Singh B, Wang K, Cai Z, Singh Y and Buresh RJ (2008) Nitrogen supply in rice-based cropping systems as affected by crop residue management. Soil Sci Soc Am J 72: 514-523

Timsina J and Connor DJ (2001) Productivity and management of rice-wheat cropping systems: issues and challenges. Field Crops Research 69:93–132

Timsina J and Humphreys E (2006) Performance of CERES-Rice and CERES-Wheat models in rice–wheat systems: A review. Agricultural Systems 90:5–31

Timsina J, Singh U, Badaruddin M, Meisner C and Amin MR (2001) Cultivar, nitrogen, and water effects on productivity, and nitrogen-use efficiency and balance for rice-wheat sequences of Bangladesh. Field Crops Research 72:143–161

Toderich KN, Ismail S, Juylova EA, Rabbimov AR, Bekchanov BB, Shyuskaya EV, Gismatullina LG, Kozan O and Radjabov T (2008) New approaches for Bio-saline Agriculture development, management and conservation of sandy desert ecosystems. In: Abdelly C, Ozturk M, Ashraf A and Grignon C (eds.) Bio-saline Agriculture and Salinity Tolerance in Plant, Basel

Tuong TP and Bouman BAM (2003) Rice production in water-scarce environments. In: Proceedings of the Water Productivity Workshop. 12–14 November 2001, Colombo, Sri Lanka. International Water Management Institute, Colombo, Sri Lanka

Tuong TP, Bouman BAM and Mortimer M (2005) More rice, less water–integrated approaches for increasing water productivity in irrigated rice-based systems in Asia. Plant Prod Sci 8:231–241

Tursunov LT and Abdullaev S (1987) Characteristic of soil-physical properties in lower Amu Darya (In Russian). FAN, Tashkent

Tursunov M (2009) Potential of conservation agriculture for irrigated cotton and winter wheat production in Khorezm, Aral Sea Basin. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Uchijima T (1976) Some aspects of relation between low air temperature and sterile spikelets in rice plants. J Agric Meteorol 31:199-202

UNEP (2005) Aral Sea, GIWA Regional assessment 24. University of Kalmar, Kalmar, Sweden. Severskiy I, Chervanyov I, Ponomarenko Y, Novikova NM, Miagkov SV, Rautalahti E and Daler D (eds.) www.unep.org/dewa/giwa/areas/reports/giwa_regional_assessment_24.pdf, last accessed 07.04.2011

UNESCO (2000) Water related vision for the Aral Sea basin for the year 2025, Fontenoy, France, p 237

UNFPA (2009) State of the world population 2009 annual report facing a changing world: women, population and climate. http://www.unfpa.org/swp/2009/en/pdf/EN_SOWP09.pdf, last accessed 07.04.2011

Uri ND (1999) Factors affecting the use of conservation tillage in the United States. Water, Air and Soil Pollution 116:621–638

Veldwisch GJA (2008) Cotton, rice and water: The transformation of agrarian relations, irrigation technology and water distribution in Khorezm, Uzbekistan. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Ventura W and Watanabe I (1978) Dry season conditions and soil nitrogen availability to wet season wetland rice. Soil Sci Plant Nutr 24:535–545

Vinogradov S and Langford VPE (2001) Managing trans-boundary water resources in the Aral Sea Basin: In search of a solution. International Journal of Global Environmental Issues 1(3–4):345–362

Vlek PLG and Byrnes BH (1986) The efficacy and loss of fertilizer N in lowland rice. Fertilizer Research 9:131–147

Vlek PLG and Craswell ET (1981) Ammonia volatilization from flooded soils. Fertilizer Research 2:227–245

Vlek PLG and Uzo Mokwunye A (1989) Soil fertility problems in the semiarid tropics of Africa. In: Christianson CB (ed.), Soil Technology and Fertilizer Management in Semi-Arid Tropical India. IFDC Special Publication - 11 Muscle Shoals, Al. 35662, USA

Vlek PLG, Fillery IRP and Burford JR (1981) Accession, transformation, and loss of nitrogen in soils of the arid region. Plant and soil 58 (1–3):133–175

Walter H and Leith H (1967) Klimadiagramm-Weltatlas. 3rd edition. Jena, VEB Gustav-Fischer-Verlag

Wang X (2006) Conservation tillage and nutrient management in dryland farming in China. Dissertation, Wageningen University

Wehrheim P and Martius C (2008) Farmers, cotton, water and models - introduction and overview. In: Wehrheim, P., Schoeller-Schletter, A., Martius, C. (eds.) Continuity and change: land and water use reforms in rural Uzbekistan. Studies on the Agricultural and Food Sector in Central and Eastern Europe. Halle (Saale), Germany: Leibniz-Institut für Agrarentwicklung in Mittel- und Osteuropa, Studies on the Agricultural and Food Sector in Central and Eastern Europe, Vol. 43, p 1-16

Wikarmpapraharn C and Kositsakulchai E (2010) Evaluation of ORYZA2000 and CERES-rice models under potential growth condition in the central plain of Thailand. Thai Journal of Agricultural Science 43(1):17–29

Won JG, Choi JS, Lee SP, Son SH and Chung SO (2005) Water saving by shallow intermittent irrigation and growth of rice. Plant Prod Sci 8:487–492

Wopereis MCS, Kropff MJ, Maligaya AR and Tuong TP (1996) Drought-stress responses of two lowland rice cultivars to soil water status. Field Crops Research 46: 21–39

Yang J, Liu K, Wang Z and Zhu Q (2007) Water-saving and high-yielding irrigation for lowland rice by controlling limiting values of soil water potential. Journal of Integrative Plant Biology 49:1445–1454

Yang XG, Bouman BAM, Wang HQ, Wang ZM, Zhao JF and Chen B (2005) Performance of temperate aerobic rice under different water regimes in North China. Agricultural Water Management 74:107−122

Yoshida S (1981) Fundamentals of rice crop science. IRRI, Los Banos, Philippines, p 269

Yoshino MM, Horie T, Seino H, Tsujii H, Uchijima T and Uchijima Z (1988) The effects of climate variations on agriculture in Japan. In: Parry ML, Carter TR and Konijn NT (eds.) The impact of Climate Variations on Agriculture. Vol. 1: Assessments in Cool Temperate and Cold Regions. Kluwer Academic Publishers, Dordrecht, The Netherlands, p 725–865

Yun-Ying CAO, Hua DUAN, Li-Nian YANG, Zhi-Qing WANG, Li-Jun LIU and YANG Jian-Chang (2009) Effect of high temperature during heading and early filling on grain yield and physiological characteristics in Indica Rice. Acta Agronomica Sinica 35(3): 512–521

ZEF (2001) Project proposal. Economic and ecological restructuring of land- and water use in the region Khorezm (Uzbekistan): A pilot project in development research. Bonn, Germany, Center for Development Research (ZEF)

Zhang H, Zhang S, Zhang J, Yang J and Wang Z (2008) Postanthesis moderate wetting drying improves both quality and quantity of rice yield. Agron J 100:726–734

Zhang MZ, Li YH, Cui YL, Wu LC and Fang RJ (1994) Studies on the growth and physiological mechanism of rice under the conditions of deficit irrigation. Irrigation and Drainage 13(4): 6–10

Zhang Y, Tang Q, Zou Y, Li D, Qin J, Yang S, Chen L, Xia B and Peng S (2009) Yield potential and radiation use efficiency of "super" hybrid rice grown under subtropical conditions. Field Crops Research 114:91–98

Zia AM, Salim M, Aslam M, Dill MA and Rahamatulla (2008) Effect of low temperature of irrigation water on rice growth and nutrient uptake. Journal of Agronomy and Crop Science 173:22–31

Ziska LH, Manalo PA and Ordonez PA (1996) Intraspecific variation in the response of rice (*Oryza sativa* L.) to increased CO_2 and temperature: growth and yield response of 17 cultivars. Journal of Experimental Botany 47:1353–1359

ACKNOWLEDGEMENTS

I would like to express my greatest gratitude to all those who have contributed directly and indirectly to this study.

My sincere gratitude goes to my first supervisor Prof. Paul Vlek for his trust in me to conduct this study and his constant advice and support throughout the entire study, and his detailed review of my thesis. I would also like to thank Prof. Frank A. Ewert (Institute of Crop Science and Resource Conservation INRES, University of Bonn) for his critical and constructive comments and suggestions.

Further, my sincere thanks go to Dr. Ahmad Manschadi and Dr. John. Lamers for their valuable guidance and advice, their continued support and encouragement during the field research and data presentation and write-up, and for their detailed review of my thesis.

I wish to thank the ZEF doctoral program administration, especially Dr. Günter Manske, for the administrative and technical support during my stay in Germany. Special thanks go to Mrs. Rosemarie Zabel for her invaluable support, which made my stay in Germany very pleasant. I wish to thank the ZEFc and Khorezm project team in Bonn for providing the good working environment and technical support. I would also like to thank Guido Lüchters for his guidance in the statistical analysis. The ZEF staff and Ph D students in all departments are thanked for their valuable discussions and warm friendship and support.

Special thanks go to Dr. Oybek Egamberdiev, Prof. Nazar Ibragimov, Erkin Ruzibaev and the conservation agriculture team for the setup of the experiment and for their guidance and help during field work. My warmest thanks go to Dr. Ken D. Sayre and Dr. Raj Gupta for their invaluable suggestions and encouragement during the field experiments. I would like to thank Oksana Forkutsa for her help in some of the data recording. I would like to express my special thanks to the team of student assistants from the Urgench State University, and a farmer's family who helped me with the field management, sampling and measurements and laboratory work. I would also like to thank the drivers in the Khorezm project, especially Maksud Yusupov, for their patience.

My warmest thanks go to Dr. Ebrahim Amiri (Iran), Dr. BAM Bouman (IRRI), Tao Li (IRRI), and Dr Xike Zhang (Queensland Climate Change Centre, Australia), who helped me especially by providing the rice growth model ORYZA2000 and helping me in the different stages of simulation. My warmest thanks go also to Dr. Andrew McDonald and Dr. Patrick Wall, who selected me for the post-doctoral cropping systems scientist position in CIMMYT even before I had formally finished my Ph D study, this greatly encouraged me. I also thank Dr. Kirsten Kienzler, who helped me a lot during the initial stage of my field study. I am also deeply thankful to all the Khorezm project staffs, who provided great help and often wonderful company. Special thanks to Liliana Sin and Natasha Shermetova for their good management of my stay in Uzbekistan and help with the visa process. I also would like to thank Ms. Guzal Matniyazova for translating the abstract in Russian. Many thanks go to Tjotij Galya for the good food in Urgench.

I am also very grateful to PD Dr. Christopher Martius, Dr. Bernhard Tischbein, Dr. Akmal Akramkhanov, Dr. Asia Khamzina, Dr. Hayot Ibrakhimov, and Dr. Jumanazar Ruzimov for their support and suggestions. I would like to thank the

Cotton Research Station staff for providing the research site, office space and technical suggestions.

This work would not have been possible without the stipendium and the PhD research funds from the German Ministry for Education and Research (BMBF)/ZEF-UNESCO Khorezm Project. I am most grateful for the financial support.

Last but not least, my greatest gratitude goes to my parents, parents-in-law, brothers and sisters and all family members for their continued support, and to my wife Mina Devkota-Wasti for her invaluable support and encouragement during the entire study period. Special thanks go to our beloved daughter Arminda Devkota and son Aabiskar Devkota for their patience and understanding.