INRES

Improving the nitrogen use efficiency and crop quality in the Khorezm region, Uzbekistan

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For my family.

Ich werde nicht sterben.
Heute an diesem Tag voller Vulkane,
ich trete hervor, der Menge entgegen, dem Leben zu.

Pablo Neruda
(„Voy a Vivir", Canto General, 1949)

ABSTRACT

In the irrigated agriculture of Central Asia, low nitrogen (N) fertilizer use efficiency in cotton (*Gossypium hirsutum* L.) and winter wheat (*Triticum aestivum* L.) decreases yields and farm income. Current N-fertilizer use is based on recommendations from Soviet times when fertilizer supply was subsidized to maximize production at all costs. Modern N management needs to enable farmers to obtain stable crop yields of good quality and preserve the environment. The present study, based on field experiments conducted 2004-2006 in the Khorezm region, Uzbekistan, intended to (i) establish cotton and wheat yield and quality responses to N fertilization; (ii) evaluate N-fertilizer use efficiency of officially recommended N use and farmers' practice; (iii) simulate soil N dynamics and yields under varying N rates, irrigation water quantities and groundwater levels with CropSyst; and (iv) determine the financial feasibility of different N practices. The study included labeled N fertilizer (^{15}N) experiments in 2005 to quantify the fate of the applied N fertilizer.

Although N was the most limiting nutrient, the N response curve of cotton and wheat yield to increasing N rates was rather flat with a yield maximum at 120 and 180 kg N ha^{-1}, respectively. This can be attributed to unaccounted N supplements from ground- and irrigation water of around 5-61 kg ha^{-1}. The official N recommendations of 200 and 180 kg N ha^{-1}, for cotton and wheat respectively, corresponded well with both the measured and simulated N uptake at yield maximum. However, at this rate, the opening of cotton bolls was delayed beyond the period during which the ginneries offer the highest prices for cotton.

Total N-use efficiency was very high for both crops (81-84 %). The large share of soil-^{15}N (48 and 47 %, respectively) indicates that immobilization processes and/or pool substitution strongly influenced recovery rates. Farmers' N fertilization practice gave highest cotton yields, but around 22 % lower total ^{15}N recovery rates (64 %). For wheat, an additional late N application at the heading stage yielded highest total ^{15}N recovery rates (52 and 53 % in plant biomass and the soil, respectively). N fertilization with diammonium phosphate before seeding showed the highest N-use efficiency for wheat and cotton as compared to urea fertilizer.

Cotton fiber quality was of lowest grade (i.e. 31 mm length, 25 g tex^{-1} strength, and 4.08 micronaire) and remained unaffected by N treatments, timing of applications or N-fertilizer types. Fertilized with the recommended N amount, protein and gluten content of wheat kernels (12.3 and 23.0 %, respectively) met the criteria of only satisfactory to good wheat filler and low to medium flour thickener. Increasing N rates enhanced kernel protein (15 % at 300 kg N ha^{-1}), but not gluten content (25.0 %). Protein content and yield were negatively related, showing the need for breeding or introducing wheat varieties with narrower quality and yield potential suitable for irrigated conditions in Uzbekistan.

The cotton-generic routine developed for the CropSyst model predicted the experimental yields with a high accuracy (RSME 1.08 Mg kg^{-1}). Simulations show that gaseous N losses can be reduced by lowering the groundwater level. Increasing cotton yields without increasing N losses seems possible when matching water demand and supply more closely.

For cotton, returns to N investments were highest (1,069,332 UZS ha^{-1} net benefit) for the farmers' N practice and for N rates below 120 kg ha^{-1}, which encouraged fast maturation of cotton bolls at pick 1 and 2. The economic optimum thus diverged from the plant-N demand and recommendations of 200 kg ha^{-1}. The economically most promising wheat treatments were those fertilized with the recommended N rate of 180 kg ha^{-1} and those receiving additional N just before anthesis (340,669 UZS ha^{-1} net benefit). However, the present reimbursement system at the mills lacks attractive quality-based incentives to encourage high quality production.

Overall, the N management and N-use efficiency in irrigated cotton and wheat production can be improved by changing the payment system of the ginneries and mills to encourage sustainable N practices and increase crop quality. Wheat quality can be further enhanced through late N application, or by (breeding for) better varieties. CropSyst could demonstrate the impact of different agricultural practices on cotton yields and soil parameters and thus can help identifying changes in the current management system.

KURZFASSUNG

VERBESSERUNG DER STICKSTOFFEFFIZIENZ UND QUALITÄT VON BAUMWOLLE UND WEIZEN IN DER REGION KHOREZM, USBEKISTAN

In den bewässerten Regionen Zentralasiens verringert die geringe Effizienz der Stickstoffdüngung (N) im Baumwoll- (*Gossypium hirsutum* L.) und Weizenanbau (*Triticum aestivum* L.) die Erträge und das Einkommen der Landwirte. Der derzeitige Einsatz von N-Düngern basiert auf Empfehlungen noch aus der Sowjetzeit. Damals wurde Dünger subventioniert, um mit allen Mitteln die landwirtschaftliche Produktion zu maximieren. Modernes N-Management muss den Landwirten ermöglichen, stabile Erträge von guter Qualität zu erzielen und dabei die Umwelt zu schonen. Die vorliegende Arbeit basiert auf Feldexperimenten, die 2004-2006 in der Region Khorezm in Usbekistan durchgeführt wurden. Darin werden (i) Baumwoll- und Weizenertrags- und -qualitätsfunktionen für die N-Düngung etabliert; (ii) die Düngeeffizienz offiziell empfohlener mit der von Landwirten praktizierter N-Düngung verglichen und evaluiert; (iii) mit Hilfe von CropSyst die Stickstoffdynamik in Böden und die Erträge unter variierenden N-Düngeraten, Bewässerungsmengen und Grundwasserständen simuliert ; und (iv) die finanzielle Machbarkeit dieser verschiedenen N-Praktiken bestimmt. Die Studie beinhaltete Experimente mit markiertem N-Dünger (^{15}N) im Jahr 2005, um das Verbleiben des applizierten N-Düngers zu quantifizieren.

Obwohl N der limitierendste Nährstoff war, verlief die N-Ertragskurve für Baumwolle und Weizen mit zunehmenden N-Raten relativ flach, mit einem Ertragsmaximum von jeweils 120 und 180 kg N ha^{-1}. Dies kann nicht erfasstem N-Eintrag von rund 5-61 kg ha^{-1} durch Grund- und Bewässerungswasser zugeschrieben werden. Die offiziellen N-Empfehlungen von 200 und 180 kg N ha^{-1} für Baumwolle und Weizen stimmen gut mit der gemessenen und simulierten N-Aufnahme für den maximalen Ertrag überein. Jedoch wird bei dieser N-Rate das Öffnen der Baumwollkapseln über den Zeitraum der Ernte hinaus verzögert, in welchem die Baumwollfabriken den höchsten Preis für Rohbaumwolle bezahlen.

Die gesamte N-Nutzungseffizienz war für beide Kulturen sehr hoch (81-84 %). Der große Anteil an Boden-^{15}N (jeweils 48 und 47 %) weist darauf hin, dass Immobilisierungsprozesse und die Substitution des N-Pools im Boden die Wiederfindungsraten stark beeinflussen. Düngung gemäß der lokal gängigen Praxis führte zu höchsten Erträgen, jedoch zu etwa 22 % niedrigeren totalen ^{15}N-Wiederfindungsraten (64 %). Für Weizen führte eine zusätzliche späte N-Applikation zum Zeitpunkt des Ährenschiebens zu höchsten Gesamt-^{15}N-Wiederfindungsraten (52 und 53 % in Pflanzen und Boden). N-Düngung mit Diammoniumphosphat vor der Saat zeigte die höchste N-Nutzungseffizienz für Weizen und Baumwolle im Vergleich zu Ureadünger.

Die Baumwollfaserqualität war von niedrigster Kategorie (usbekische Klassifikation, d.h. 31 mm Länge, 25 g tex^{-1} Faserstärke, und 4,08 Micronaire) und blieb unbeeinflusst von N-Anwendung, Zeitpunkt der Applikation oder N-Düngeform. Trotz Düngung in empfohlener Höhe erwiesen sich die Protein- und Klebergehalte (jeweils 12,3 and 23,0 %) lediglich als von befriedigender und guter Qualität und als schlechte bis mittlere Mehlverbesserer. Zunehmende N-Raten erhöhten das Protein in den Körnern (15 % bei 300 kg N ha^{-1}), jedoch nicht den Klebergehalt (25,0 % bei 300 kg N ha^{-1}). Der Proteingehalt und der Ertrag waren negativ korreliert. Dies zeigt die Notwendigkeit der Züchtung oder Einführung von Weizensorten mit einem engeren, auf die Bewässerungslandwirtschaft Usbekistans zugeschnittenen Qualitäts- und Ertragspotenzialverhältnis.

Die generische Baumwollroutine, die für das CropSyst-Modell entwickelt wurde, prognostizierte die experimentellen Erträge mit hoher Genauigkeit. Die Simulationen zeigten, dass gasförmige N-Verluste durch die Absenkung des Grundwasserspiegels reduziert werden

können. Eine Erhöhung der Baumwollerträge ohne zunehmende N-Verluste ist möglich, wenn Wasserbedarf und -verfügbarkeit besser aufeinander abgestimmt werden.

Für Baumwolle waren die Renditen der N-Investitionen am höchsten zu den von den Bauern praktizierten Düngezeitpunkten (1.069.332 UZS ha^{-1} Gewinn), und auch bei niedrigen N-Gaben, welche die schnelle Reifung der Baumwolle zur ersten und zweiten Pflücke stimulieren. Das ökonomische Optimum unterschied sich daher sowohl vom N-Bedarf der Pflanzen als auch von den offiziellen (höheren) Düngeempfehlungen. Die ökonomisch vielversprechendsten Weizenexperimente waren diejenigen, welche mit der empfohlenen N-Menge gedüngt wurden und jene, die eine zusätzliche N-Düngung kurz vor der Blüte erhielten (340.669 UZS ha^{-1} Gewinn). Jedoch fehlt dem Zahlungssystem der Weizenmühlen derzeit der qualitätsbezogene finanzielle Anreiz, um die Bauern zu motivieren, Weizen höherer Qualität zu erzeugen.

Das N-Management und die N-Nutzungseffizienz in der Baumwoll- und Weizenproduktion können durch Veränderungen im Zahlungssystem der Baumwollfabriken und Weizenmühlen verbessert werden. Die dort geschaffenen Anreize können zur nachhaltigen N-Düngepraxis anregen und gleichzeitig die Produktqualität erhöhen. Die Weizenqualität kann durch späte N-Düngeapplikationen oder durch bessere Sorten(züchtung) gesteigert werden. Das Model CropSyst konnte den Einfluss verschiedener landwirtschaftlicher Praktiken auf den Baumwollertrag und auf die Bodenparameter aufzeigen. Es kann somit helfen, Veränderungen im derzeitigen Mangementsystem anzuregen.

АБСТРАКТ

ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ИСПОЛЬЗОВАНИЯ АЗОТА И КАЧЕСТВА ПРОДУКЦИИ В ХОРЕЗМСКОЙ ОБЛАСТИ УЗБЕКИСТАНА

В условиях орошаемых почв Центральной Азии низкий уровень эффективности азотных удобрений на посевах хлопчатника (*Gossypium hirsutum* L.) и озимой пшеницы (*Triticum aestivum* L.) приводит к снижению урожайности и доходов фермерских хозяйств. Применение азота (N-удобрений) в настоящее время основано на рекомендациях разработанных в бытность Союза, где основной целью являлось получение максимальных урожаев культур. Современные методы применения N-удобрений призваны оказать помощь фермерам в получении стабильных урожаев, обеспечивая при этом высокое качество продукции и сохранение окружающей среды.

Настоящее исследование, основанное на полевых опытах, проведенных в период 2004-2006 гг. в Хорезмской области Узбекистана, имеет следующие цели: (i) определение влияния N-удобрений на урожай и качество хлопка-сырца и озимой пшеницы; (ii) оценка эффективности использования N-удобрений на основе официальных рекомендаций и фермерской практики; (iii) с помощью модели CropSyst симуляция динамики азота почвы и урожайности в зависимости от норм азота и полива, а также уровня грунтовых вод; (iv) экономическая оценка разных практик применения N-удобрений. В исследованиях (2005 г.) использовался изотоп азота ^{15}N для количественной оценки эффективности использования растениями азота вносимых удобрений.

Результаты исследований показали то, что хотя азот и является основным лимитирующим элементом питания растений, отзывчивость урожаев хлопка-сырца и зерна озимой пшеницы на возрастающие нормы N-удобрений была слабой, с максимумом при 120 и 180 кг N га$^{-1}$, соответственно. Это можно объяснить влиянием неучтенных количеств азота, содержащихся в поливной и близлежащей к дневной поверхности почвы грунтовой воде в объеме 5-61 кг га$^{-1}$. Нормы азота 200 и 180 кг га$^{-1}$ по рекомендации узбекских НИИ хорошо согласовываются с нашими данными по выносу азота растениями при максимуме урожаев, определенных на основе полевых опытов и модели. Однако при данных нормах азота раскрытие коробочек хлопчатника запаздывало, что календарно не совпадает с периодом, когда со стороны хлопкопринимающих организаций устанавливается наивысшая цена за качество волокна.

Общая эффективность использования азота была высокой для обеих культур (81-84 %) и значительная часть азота ^{15}N (соответственно 48 и 47 %) закрепилась в почве. Это указывает на существенное влияние процесса иммобилизации и/или азотного пула на связывание азота в почве. Фермерская практика использования N-удобрений обеспечила самый высокий урожай хлопчатника, но самый низкий вынос и коэффициент использования азота ^{15}N растениями (64 %). Внесение N-удобрений и проведение последующего полива на ранних стадиях развития хлопчатника способствовало значительному увеличению непроизводительных потерь азота. Дополнительное внесение N-удобрений в фазе колошения пшеницы обеспечило наибольший коэффициент (52 % и 53 % в биомассе растений и в почве, соответственно) использования азота ^{15}N растениями. Наивысшая эффективность использования азота пшеницей и хлопчатником достигнута при применении диаммофоса в предпосевном удобрении.

Качество хлопкового волокна в опыте было низким (в соответствии с узбекской классификацией, т.е. длиной в 31 мм, прочностью 25 г tex^{-1} и 4,08 micronaire) независимо от применяемых норм, сроков и форм N-удобрений. С применением рекомендованного количества азотного удобрения содержание протеина (12,3 %) и клейковины (23,0 %) в зерне пшеницы соответствовало критерию от «удовлетворительный» до «хорошо», а муки - «низкий» до «средний». Повышение норм N-удобрений способствовало увеличению содержание протеина в зерне зерне (15 % при норме азота 300 кг га$^{-1}$), но не повлияло на клейковину (25 %). Между содержанием протеина и урожаем зерна существовала обратная связь, что указывает на необходимость выведения или внедрения новых сортов пшеницы с суженной взаимосвязью качества и потенциала урожайности, приемлемой для орошаемых условий Узбекистана.

С использованием базового набора данных по хлопчатнику, собранных специально для модели CropSyst, было возможным с высокой точностью прогнозировать урожай хлопка-сырца (RSME 1,08 мг кг$^{-1}$). Симуляция показала, что газообразные потери азота могут быть сокращены путем понижения уровня грунтовых вод. Повышение урожайности хлопчатника без увеличения потерь азота считается возможным при точном соблюдении соответствия потребностей и обеспечения растений оросительной водой.

Отдача от вложенных средств на использование N-удобрений под хлопчатник была наибольшей (1069332 узбекских сумов га$^{-1}$ чистой прибыли) в случае с фермерской практикой применения удобрения и при применении низких норм азота (120 кг га$^{-1}$), способствовавших раннему созреванию урожаев первого и второго сборов хлопка-сырца. Экономически оптимальная норма азота, таким образом, не была вкупе с потребностями растений в азоте и существующими рекомендациями (200 кг га$^{-1}$). Экономически наиболее перспективной нормой азота на озимой пшенице было использование N-удобрений в соответствии с существующими практическими рекомендациями (180 кг га$^{-1}$), а также при перенесении части нормы N-удобрений в период цветения культуры (340669 узбекских сумов га$^{-1}$ чистой прибыли). Однако существующая в настоящее время система оплат на мукомольных комбинатах не предоставляет стимулы фермерам для производства более качественного зерна пшеницы.

В целом, эффективность использования азотных удобрений на хлопчатнике и озимой пшенице в условиях орошаемых почв может быть улучшена посредством усовершенствования методов орошения и управления грунтовыми водами, системы оплат на хлопковых заводах и мукомольных комбинатах с целью стимулирования использования совершенной практики применения N-удобрений и повышения качества продукции. Качество зерна может быть улучшено посредством внесения N-удобрений в поздние фазы развития культуры или выведения улучшенных сортов озимой пшеницы. Симуляционная модель CropSyst может продемонстрировать влияние различных агротехнологии на урожай и параметры почвы и, таким образом, стимулировать изменения в существующей системе возделывания культур.

Ключевые слова: хлопчатник, озимая пшеница, отзывчивость на азотные удобрения, коэффициент использования растениями азота, качество волокна, хлебопекарное качество, симуляция с помощью модели CropSyst, анализ затрат и доходов

АБСТРАКТ

УЗБЕКИСТОН РЕСПУБЛИКАСИНИНГ ХОРАЗМ ВИЛОЯТИДА ЭКИНЛАР АЗОТДАН ФОЙДАЛАНИШ САМАРАДОРЛИГИ ВА МАХСУЛОТ СИФАТИНИ ОШИРИШ

Ўрта Осиё суғориладиган тупроқлар шароитида азотли ўғитлар самарадорлигининг пастлиги ғўза (*Gossypium hirsutum* L.) ва кузги буғдой (*Triticum aestivum* L.) нинг хосилдорлиги ва фермер хўжаликларининг иқтисодини пасайишига олиб келади. Ҳозирги вақтда азотли ўғитларни қўллашнинг асосий мақсади Иттифоқ даврида ишлаб чиқилган тавсияномаларга асосланган бўлиб, экинлардан фақат юқори ҳосил олишга қаратилган. N- ўғитлар қўллашнинг замонавий услублари атроф муҳитни муҳофазалаш, юқори ва сифатли махсулотни таъминлаш, фермерларга барқарор ҳосил олишда ёрдам кўрсатишга қаратилган.

Мазкур тадқиқот 2004-2006 йиллар мобайнида Ўзбекистонинг Хоразм вилоятида ўтказилган дала тажрибаларимизга асосланиб, қуйидаги мақсадларга эриши учун олиб борилган: (i) кузги буғдой ва пахта ҳосили ҳамда сифатига N-ўғитларнинг таъсирини аниқлаш; (ii) фермер тажрибаси ва расмий тавсияномалар асосида N-ўғитлардан фойдаланиш самарадорлигини баҳолаш; (iii) CropSyst модели ёрдамида тупроқ азоти ва ҳосилдорликни азот меъёри ва суғоришга ҳамда сизот суви сатҳига боғлиқ равишда симуляция қилиш; (iv) Тажрибаларда N-ўғитлар қўллашнинг иқтисодий баҳолаш. Изланишларда ишлатилган минерал ўғит азотидан ўсимликларнинг фойдаланиш коэффициентини аниқлашда ^{15}N азот изотопидан фойдаланилди.

Изланишлар натижалари кўрсатишича, экинлар озиқланишида азот асосий чекловчи элемент хисоблансада, пахта ва кузги буғдой дони хосилига N-ўғитларнинг ортиб борган меъёрининг таъсири паст бўлди, бунда максимум ҳосил мутаносиб равишда 120 ва 180 N га$^{-1}$ қўлланилганда кузатилди. Буни тупроқ юзасига яқин жойлашган сизот ва суғориш сувлари таркибидаги ҳисобга олинмаган азот миқдорининг (5-61 кг га$^{-1}$) ҳосилга бўлган таъсири билан тушунтириш мумкин. Бизнинг дала тажрибаларимизда ва модел асосида аниқланган максимум ҳосилда ўсимликларнинг азот ўзлаштириши бўйича маълумотлар, N-ўғити меъёрлари 200 ва 180 кг га$^{-1}$ бўлганда, Ўзбекистон ИТИ тавсияномаларига тўлиқ мос келади. Бироқ, қўлланилган азот меъёрлари ғўза кўсакларининг етилиб пишишига нисбатан кечикади ва бу албатта пахта қабул қилувчи ташкилотлар томонидан тола сифатига бирмунча юқори баҳо белгиланган даврга тўғри келмайди.

Икки экин учун ҳам азотдан фойдаланишнинг умумий самарадорлиги юқори бўлди (81-84 %) ва ^{15}N азотнинг маълум бир қисми (тегишлича 48 ва 47 %) тупроқда бирикади. Бундан кўринадики, азот манбаси тупроқда азотнинг боғланишига ёки иммобилизация жараёнига жиддий таъсир кўрсатади. Фермер тажрибасига асосан N-ўғитлар қўлланганда энг юқори пахта ҳосилига эришилди, аммо ўсимликлар азот ўзлаштириши ва ^{15}N азотидан фойдаланиш коэффиценти жуда паст бўлди (64 %). Ғўза ривожланишининг илк даврида N-ўғитларнинг қўлланилиши билан дарҳол суғориш ўтказ амалиёти азотнинг беҳуда йўқолишининг кўпайишига сезиларли таъсир кўрсатди. Буғдойни бошоқлаш даврида қўшимча N-ўғит қўлланилиши, ўсимликлар ^{15}N азотидан фойдаланиш коэффицентини бирмунча ошишини таъминлади (52 % ўсимлик биомассасида ва 53 % туплоқда). Ғўза ва буғдойни азотдан фойдаланишининг энг юқори самарадорлиги экишдан олдин ўғитлашда диаммофос қўлланилганда кузатилди.

Тажрибада пахта толасининг сифати (ўзбекистон классификацияси бўйича узунлиги 31 мм, толанинг мустаҳкамлиги 25 г tex^{-1} и 4,08 micronaire) N-ўғитларнинг шакли, муддати ва қўлланилган меъёрига боғлиқ бўлмаган холда паст бўлди. Тавсия этилган азот ўғитининг миқдори қўлланилганда буғдой донида протеин (12,3 %) ва клейковина (23,0 %) миқдорлари мезон бўйича “қониқарли” дан “яхши” гача, ун эса “паст” дан “ўртача” га тўғри келди. N-ўғит меъёрининг ортиши дон таркибидаги протеин миқдорини ошишига сабаб бўлди (300 кг га$^{-1}$ миқдордаги ўғит нормаси қўлланилганда 15 %), лекин клейковинага таъсир қўрсатмади (25 %). Дон ҳосили ва протеин миқдори ўртасида тескари боғлиқлик бўлиб, Ўзбекистоннинг суғориладиган тупроқлари учун мос келадиган, сифати ва потенциал хосилдорлиги юқори янги буғдой навларини жорий этиш заруриятини кўрсатади.

Ғўза бўйича CropSyst модели учун махсус тўпланган маълумотлардан фойдаланиб, пахта ҳосилини юқори аниқликда (RSME 1,08 мг кг$^{-1}$) башорат қилиш имконияти мавжуд. Симуляция натижалари кўрсатишича, азотнинг газ шаклида йўқолишини сизот сувлари сатҳини пасайтириш йўли орқали камайтириш мумкин. Ўсимликни суғориш сувига талаби ва таъминланганлигига аниқ риоя қилинган ҳолда азотни беҳуда йўқолишини камайтириб, ғўза ҳосилдорлигини ошириш мумкин.

Фермер тажрибасига асосан N-ўғитлар қўлланганда ҳамда пахта ҳосилининг биринчи ва иккинчи теримларини эрта пишиб етилишига имконият яратувчи белгиланган меъёрга нисбатан кам бўлган N-ўғитлар (120 кг га$^{-1}$) қўлланганда харажатларнинг қопланиши энг юқори бўлган (1069332 узбек сўм га$^{-1}$ соф фойда). Шундай қилиб, ўсимлик учун азотнинг иқтисодий мақбул меъёри, унинг талаби ва мавжуд тавсияномалар билан бир хил бўлмади. Кузги буғдойда N-ўғитнинг тавсияланган 180 кг га$^{-1}$ миқдорини қўллаш тажрибаси ва N-ўғитлар меъёрининг маълум бир қисми экиннинг гуллаган даврида қўллаш тажрибаси иқтисодий жиҳаттдан энг истиқболли деб топилдилар (340669 ўзбек сўм га$^{-1}$ соф фойда). Бироқ, ҳозирги вақтда ун комбинатларидаги мавжуд тўлов тизимлари сифатлироқ буғдой донни етиштириш учун фермерларни рағбатлантирмайди.

Умуман, суғориладиган тупроқ шароитида етиштирилаётган ғўза ва кузги буғдойда маҳсулот сифатини ошириш, N-ўғитлар қўллашнинг амалда яхшилаш ва азотли ўғитлардан фойдаланиш самардорлиги ошириш масалаларни суғориладиган тупроқ шароитида сизот сувларини бошқариш ва суғориш услубларини, пахта заводларда ва ун комбинатларидаги мавжуд бўлган тўлов тизимларини такомиллаштириш орқали амалга ошириш мумкин. Кузги буғдойни яхшиланган навларини тадбиқ қилиш ёки ўсимлик ривожланишининг кейинги фазаларида N-ўғитларни қўллаш орқали дон сифатини яхшилаш мумкин. CropSyst модели ёрдамида экинларни етиштиришда мавжуд бўлган тизимнинг ўзгариш сабабларини, турли агротехнологияларнинг тупроқ кўрсаткичлари ва зироатлар ҳосилига бўлган таъсирини кўрсатиш мумкин.

Калит сўзлар: ғўза, кузги буғдой, азотли ўғитга талабчанлик, ўсимликнинг азотдан фойдаланиш коэффициенти, тола сифати, новвойлик сифати, CropSyst модели ёрдамида симуляциялаш, фойда ва харажат таҳлили.

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1 GENERAL INTRODUCTION

1.1 Problem setting

Shortly after its independence from the Soviet Union in 1991, Uzbekistan embarked on a wide range of unprecedented agricultural reforms. With the dissolution of the Soviet structure of the agricultural production system, the newly established farmers had to cope with substantial changes such as increasing privatization, new land-tenure regulations (Pomfret 2000, Spoor 2004, Müller 2006b), and increasing prices of fertilizers, pesticides and machinery (Kandiyoti 2004a). At the same time, they were still bound to contracts with the state to produce a fixed amount of crop produce on a given share of land (Trevisani 2005, Müller 2006b). Hence, farmers were stuck between the new agricultural legacies and the burden of ensuring their livelihood in view of increasing input prices and uncertain commodity markets (Trevisani 2007).

During the era of the Soviet Union, Uzbekistan's agriculture was developed primarily to supply the inner Soviet market with raw cotton (*Gossypium hirsutum* L.) (Trevisani 2008). Other agricultural products such as wheat were imported to Uzbekistan from other Soviet states (Rudenko 2008). After independence, increasing domestic winter wheat (*Triticum aestivum* L.) production became the declared strategy of the national administration to reduce the dependency on imports (Guadagni et al. 2005). Today, cotton and winter wheat are the most important crops in the Uzbekistan economy, contributing 30 % to the national GDP (Rudenko and Lamers 2006, Djanibekov 2008). However, although the country has achieved its goal in obtaining food security and is now independent of wheat imports (Guadagni et al. 2005), the domestically produced winter wheat does not meet the flour quality standards of the formerly imported wheat (Abugalieva et al. 2003a, Rudenko 2008).

Sufficient supply of nitrogen (N) to crops is essential to improve quality and sustain yields. In the irrigated areas of Uzbekistan, however, the efficiency of N-fertilizer use in cotton and wheat production is low, as N is frequently lost to the environment via denitrification or leaching (Ibragimov 2007, Scheer et al. 2008c). Due to heavy input subsidies during Soviet times, excessive use of fertilizers was common (Wegren 1989, Herrfahrdt 2004), and state and cooperative farms had little incentives to use fertilizers efficiently, pay attention to losses to the environment, or consider the cost-effectiveness of input management. Similarly, most fertility research before independence aimed at maximizing production rather than at promoting sustainable fertilizer use or improving the quality of cotton fiber or wheat flour.

Following the land reforms, Uzbek farmers remedy soil N deficiencies by applying the N fertilizers they can afford, which often differs from the N-fertilizer amounts recommended by Uzbek research institutions (WARMAP and EC-IFAS 1998, Djanibekov 2005). The constant mismatch between the N applied and removal of N with the harvested products will, however, eventually affect crop yield and quality due to the decline in soil fertility. In fact, declining cotton yields in Uzbekistan have already been reported (e.g., Herrfahrdt 2004), although the reasons for this trend are not fully understood. Given the on-going economic and agronomic changes in crop production in Uzbekistan, the N-fertilizer recommendations for irrigated cotton and wheat production need to be updated to meet the expectations of producers, minimize losses to the environment and improve or sustainably maintain soil fertility.

1.2 Research objectives

Considering the major legal and economic changes imposed on the agricultural sector and on the newly emerged private farmers after independence, the overall goal of this study was to identify N-fertilizer use inefficiencies under the current irrigated cotton and wheat production practices, to optimize its use while minimizing environmental impacts, to develop balanced N-fertilization strategies for those crops, and to provide appropriate management strategies to improve the efficiency and crop quality. The outcome is, therefore, expected to assist farmers in the irrigated regions in their decision making process regarding balanced N-fertilizer applications with respect to technical and economic optimization and environmental impact.

The specific research objectives were to:

1. Assess cotton and wheat yield response to increasing N-fertilizer application rates under the current management;
2. Evaluate N-fertilizer use efficiency under various N-management practices with special focus on fertilizer timing and N-fertilizer types;
3. Determine cotton fiber and wheat kernel quality at different N-fertilizer rates, and timing;

4. Simulate the effects of alternative N applications, irrigation water quantities and groundwater levels on N dynamics in the soil and on crop yield;
5. Determine the financial feasibility of different N-fertilizer management practices.

The German-Uzbek project of the Center for Development Research (ZEF) of the University of Bonn, Germany (www.khorezm.uni-bonn.de), has identified the Khorezm region south of the Aral Sea in Uzbekistan as a suitable pilot area for developing concepts for ecological and economic sustainable land use in the Aral Sea basin (ZEF 2001, ZEF 2003). This study was conducted in this region, which relies completely on irrigated agriculture with cotton and winter wheat as main crops in various rotations. Eventually, the research results may be used as orientation for regions of similar agro-climatic conditions in the Aral Sea basin.

The research involved three years of completely researcher-managed fertility management experiments conducted in close collaboration with local research structures in the Khorezm region. These studies were complemented with a series of researcher/farmer-managed on-farm experiments scattered across Khorezm to cover potential geographical and edaphological differences. In addition, this research was carried out in close collaboration with other on-going studies within the ZEF project.

1.3 Outline of thesis

The thesis consists of thirteen chapters. Following the general introduction, Chapter 2 comprises a literature review on the topics related to irrigated cotton and wheat production in Uzbekistan with special reference to the region-specific conditions of Khorezm, including the agricultural, economic and agronomic settings before and after independence, actual N-fertilizer use and recommendations, a theoretical background to N-use efficiency and cotton and wheat quality, and a comparison of crop-soil simulation models for cotton modeling. Details on the study region and the materials and methods used are provided in Chapters 3 and 4. The results are presented and discussed in Chapters 5 through 12. Chapters 5 summarizes the N-fertilizer effects on cotton and winter wheat yields from 2004-2006, and Chapter 6 describes the soil and groundwater nitrate dynamics. Plant-N uptake and ^{15}N recovery rates in cotton and wheat are presented and discussed in chapters 7 and 8. Chapter 9 comprises data on the quality of cotton fiber and seed and wheat kernels quality in relation to different N management. The parameterization and calibration of the crop-soil simulation model CropSyst for cotton and the simulation results for N dynamics under different fertilizer and irrigation practices are given in Chapter 10. A financial assessment and yield gap analysis between official statistical data and the research findings is provided in chapters 11 and 12. The thesis closes with a summary of the main outcomes of this research and the general conclusions further research and policy outlooks in Chapter 13.

2 LITERATURE REVIEW

2.1 Uzbekistan's agricultural setting

2.1.1 Cotton and wheat production

Cotton (*Gossypium hirsutum* L.) is the predominant crop in the agricultural production system of Uzbekistan. It had a central role in the country's economic development during Soviet Union time over the last 70 years (1924-1991), which has continued since the country's independence in 1991. With an annual raw cotton production of 3.55 million t in 2006 (FAOSTAT 2008), Uzbekistan is the 6th largest world cotton producer after China, US, India, Pakistan, and Brazil (FAOSTAT 2008). In 2004, it was the 2nd, in 2005 still the 4th largest producer of cotton lint (0.55 million t in 2005) after the US (3.40 million t in 2005), Australia and India (FAOSTAT 2008). The production of raw cotton per hectare (2.4 t ha^{-1} in 2006) was above world average (2.0 t ha^{-1}), but only 53% of the leading per-hectare-producer Australia (4.5 t ha^{-1}) (FAOSTAT 2008) .

The agricultural sector contributes around 26-30 % to the Uzbek gross domestic product (GDP) (FAO 2006, Rudenko and Lamers 2006), of which cotton alone accounts for ca. 13-18 % (Wehrheim and Martius 2008). Due to the high share to the foreign exchange revenues (25-50 % according to Saigal 2003, Guadagni et al. 2005, Martius et al. 2005) and as cotton is a substantial source of tax revenues (Guadagni et al. 2005), the "white gold" is considered the cash crop of Uzbekistan, and consequently still has a high economic and political priority in the country (Müller 2006b).

After Uzbekistan's independence in 1991, however, winter wheat (*Triticum aestivum* L.) gained increasing importance. Formerly imported from other regions of the Soviet Union, winter wheat then became a second strategic crop to supply domestic food needs (Guadagni et al. 2005). A national food self-sufficiency program was initiated to decrease imports from neighboring, former Soviet countries (Rudenko 2008), and the area of winter wheat increased rapidly. While in 1992 only around 0.62 million ha, mainly in the rain-fed areas, were cropped with winter wheat, in 2006 the wheat area had expanded to 1.45 million ha (FAOSTAT 2008) covering 31 % of the irrigated regions of Uzbekistan (FAO 2002).

Today, winter wheat ranks as the second most important crop after cotton (FAO 2002). In fact, with the impressive production increase from 1.0 in 1992 to 6.0 million t in 2006, and average yield improvements from 1.5 to 4.1 t ha^{-1} in the same time period (FAOSTAT 2008), the country has achieved its goals in obtaining food security, and is now independent of imports (Guadagni et al. 2005). On the other hand, the domestically produced winter wheat has not reached the quality standards of the formerly imported wheat and consequently smaller quantities are still imported to mix with the locally produced winter wheat to increase the baking quality (Rudenko 2008).

2.1.2 The state order

Production targets

Cotton and winter wheat are grown as state order crops, i.e., production targets are set by the state authorities (Müller 2006b, Rudenko 2008). Uzbek farmers are legally obliged to turn in a share of 25-30 % of the cotton and winter wheat harvest to the cotton ginneries and the state mills at a fixed price, and another 20-25 % share on a state-paid contractual basis (Guadagni et al. 2005, Rudenko 2008). The remaining share of the harvest usually can be sold freely, i.e., at the market at higher prices (Rudenko 2008). However, despite these declarations, Müller (2006b) and Rudenko (2008) reported no free competition on the Uzbek cotton market and only a very small private demand for cotton, so that in fact the state still buys the complete harvest. Similarly, the share of winter wheat handed in by the farmers is subject to deviations from the legal frame (Rudenko and Lamers 2006), as the percentage of wheat to be turned in to the state is in fact bound to the actual yield, so that in cases of low harvest farmers are obliged to submit as much as the total harvest (Rudenko and Lamers 2006).

Soil bonitet

The production goals imposed on the two strategic crops by the state are determined before sowing according to the soil “bonitation”, a classification system for soil fertility established in Soviet times, ranking land quality of particular soils on a 100-point scale depending on parameters such as groundwater depth, salinity levels, soil organic matter (SOM) and gypsum content in the soil (Soil Science Institute 1989, FAO 2003). Every score point equals a yield capacity of 0.04 t ha^{-1}, so that soils with a bonitet of 100 points are assumed to yield 4 t ha^{-1} cotton (FAO 2003). The official soil bonitet, however, often differs from the achievable harvest due to biases that influence the calculations for the yields that have to be handed to the government (e.g., Müller 2006b).

Subsidies

Aside from production targets, the government provides bank credits for cotton and winter wheat production at low interest rates, e.g., for the purchase of the required inputs such as fertilizers, fuel and seeds (Rudenko 2008). The inputs and irrigation water are supplied at low costs (Rudenko 2008). However, the state controls the prices of processing, irrigation water distribution and scheduling (Spoor 2004, Müller 2006b). Furthermore, the state provides an income security to the cotton producers by accepting practically all cotton handed in at the ginneries (Rudenko 2008).

Quality assessment

Cotton: The remuneration by the cotton ginneries varies with time of picking, and quality of the raw cotton (Rudenko 2008). The cotton quality is pre-assessed within half an hour of arrival of the raw cotton by laboratories owned by the cotton ginneries. The laboratories assign the quality classes and grades of the cotton based on the percentage of impurity and moisture in the raw cotton (State Ginnery laboratory staff, personal communications), which in turn depends on the time of picking. For each quality level, a different price is paid, ranging in 2004 from roughly 260 Uzbek soum per kg to 50 Uzbek soum per kg for the lowest quality. However, these preliminary quality classes are still subject to change, as the quality is frequently downgraded depending on the cleanliness and degree of moisture and pollution of the raw cotton (own observations).

Winter wheat: As bread products and pasta, produced by the state mills, are part of the state order system, the quality of the delivered winter wheat is determined upon delivery of the wheat (Rudenko 2008). Two laboratories are responsible for the quality check at the state mills. As they have different tasks, they follow different analysis standards. One is responsible for wheat quality analyses following the former Soviet Union and now national standard (GOST) for moisture and natural weight measurements, transparency, gluten content and quality analyses (e.g. GOST 13586.1-

68 and GOST 27186). The other laboratory conducts analyses for fodder quality measuring raw protein (e.g. GOST 134-96.4-4-84), heavy metal and pesticide content according to Uzbek standards. After analyses, the wheat is classified into four classes, with class 1 representing the best and class 4 the lowest quality (Khonka State Mill laboratory staff, personal communications) according to which farmers receive their payments. However, as for the cotton, the classes are still subject to changes after the laboratory analyses, as they may be downgraded depending on the cleanliness and the degree of pollution of the wheat.

2.1.3 Land reforms

Until independence, 80 % of the agricultural area was divided amongst state-owned (sovkhozes) and collective farms (kolkhozes) bound to state-set cotton production targets (Kandiyoti 2004a, Veldwisch 2008). Most of the remaining agricultural land was given to households as plots of less than one hectare, the so-called tamorkas, free of any state order and adjoining the house (Kandiyoti 2004b, Müller 2006b, Veldwisch 2008).

Shortly after independence, gradual agrarian reforms towards market economy (Wehrheim 2003) and partial foreign exchange and trade liberalization were implemented (Müller 2006b). State and collective farms were dissolved step by step during the land-tenure reform process, becoming joint-stock companies, so-called shirkats or farmers' associations (Müller 2006b).

In March 2003, a decree was passed that postulated the replacement of shirkats by private farms as main agricultural producers (Trevisani 2005, Trevisani 2008). The further transformation of shirkats into private/independent farms began with the incomplete dismantlement of the shirkats and was planned to be finished in 2010 (Trevisani 2005). However, this process was already completed to 55 % in 2004 and finally completed by 2007[1].

Despite the land tenure-reforms, the land remained state property, with private land-use rights (Pomfret 2000, Trevisani 2007, Trevisani 2008) based on a land lease for farmers for officially up to 50 years with the possibility for renewing the contract (Trevisani 2005, Müller 2006b). The farmers are obliged to produce a given quota of

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[1] For a detailed description of the land reform process see Trevisani (2008)

cotton and winter wheat on the given share of land (Trevisani 2005, Müller 2006b). The production of animal products, fruit and vegetables consequently shifted to the small-scale agricultural producers, who are free from any state order (Pomfret 2000, Wehrheim 2003, Müller 2006b, Rudenko 2008). Today, the arable land in Khorezm is to 100 % cultivated by farmers (Veldwisch 2008).

Politically, the land reform with its increasing privatization, land-tenure regulations, reduction of production area, etc., are an economic and organizational challenge to the recently emerging group of private farmers (Pomfret 2000, Kandiyoti 2004a, Spoor 2004, Müller 2006b, Trevisani 2007, Djanibekov 2008, Trevisani 2008). The newly established private farmers bound to the state contracts still have access to subsidized inputs such as seeds, fertilizer, fuel and others, which can be bought with credits of previous harvest benefits via bank transfers (Trevisani 2005). However, farmers now are accountable for losses in production where before the collective farm or shirkat took responsibility (Trevisani 2006, Trevisani 2007). If the plan is repeatedly not fulfilled, the land will return to the state and the lease contract ceases (Trevisani 2005). The farmers thus face the balancing act between the new agricultural policies/legacies with continuous state-order requests on the one hand and the burden of ensuring their own livelihood in view of increasing input prices on the other hand (Trevisani 2007). Trevisani (2006), therefore, describes the land privatization process as more a privatization of risk than of land.

2.2 Agriculture in the Khorezm region

2.2.1 Cotton and winter wheat production

In the Khorezm region, approximately 7-8 % of the Uzbek cotton (MAWR 2004a, OblStat 2004, FAOSTAT 2008) and 4-5 % of the total winter wheat are produced (OblStat 2004, FAOSTAT 2008). Between 1998 and 2003, around 60 % of the 275,000 ha of irrigated agricultural land in Khorezm was annually allocated to cotton and winter wheat: cotton covered around 45 % and winter wheat 21 % in 2003 (Djanibekov 2008) and agriculture produce accounted for 67 % of the regional GDP (45 % in 2005) (OblStat 2004, Djanibekov 2008) and to virtually 100 % of the export (Rudenko 2008). The remaining area is dedicated to rice, sunflower, maize, fodder crops, vegetables, fruits and others (OblStat 2004, Djanibekov 2008).

In the Soviet era, the area under cotton was higher. In the course of the country's food-security program in the early 1990's, however, the area under winter wheat in Khorezm more than doubled from 36,800 ha to 86,000 ha in the period 1990-2003 at the expense of fodder crops, while the area of cotton remained stable at around 100,000-110,000 ha (Figure 2.1) (OblStat 2005, Djanibekov 2008). As a result, the crop rotation scheme was significantly changed.

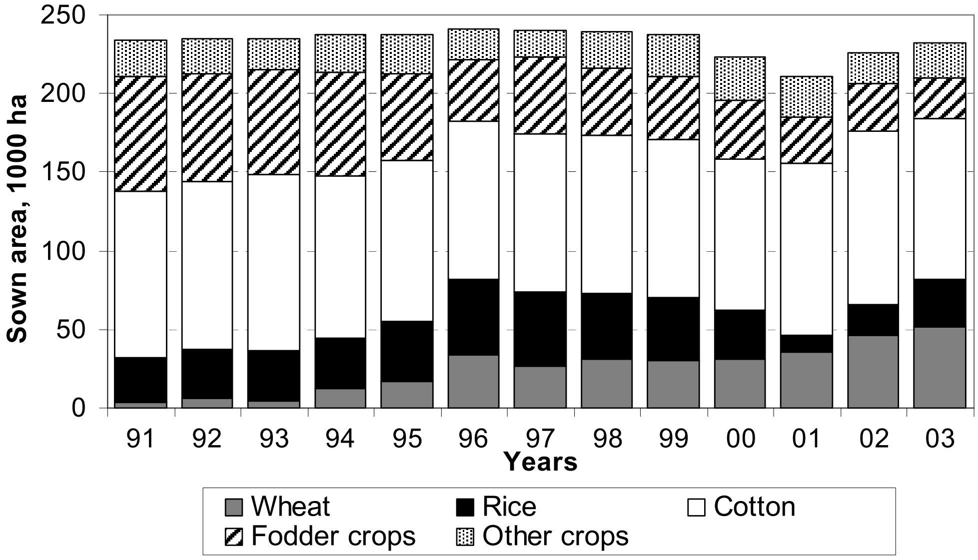

Figure 2.1 Area under cotton and cereals in Khorezm 1991-2003 according to the regional department of statistics 2004 (OblStat 2005, Djanibekov 2008).

2.2.2 Crop rotations

Before the invasion of the Russian army, agricultural production in Khorezm in the time of the Khan (around 1909) was very diverse. Winter wheat made up the largest share of the area (24 %) followed by alfalfa (16 %) and sorghum (14 %), as well as cotton (10 %) and rice (10%). Millet, melons, barley other crops were produced in smaller shares (N. Ibragimov, personal communications).

Already in the late 1930s, the area under cotton had expanded at the expense of cereal and alfalfa (Robertson 1938). During the Soviet period, the so-called "3:6" rotation was strongly enforced, a alfalfa-cotton-rotation where six years of cotton where cropped following three years of legume (Tursunkhodjiaev et al. 1977). Often, seven to nine (3:7, 3:8 or 3:9 rotation schemes) or even more years were consequently under cotton, up to the extent of complete cotton monoculture (Glantz et al. 1993). In the

1970s, the share of cotton amounted to more than two thirds of the irrigated area (Glantz et al. 1993).

After independence, this rotation was radically changed with the enforced introduction of winter wheat: The rotation scheme now usually involves one to three years of cotton followed by two years of winter wheat. Cotton is planted in April-May and harvested in September-November, while winter wheat is planted in September-October and harvested in mid June. In the remaining time after winter wheat harvest from July to October, summer crops such as rice, maize, sunflower or vegetables are sown.

The particularity of this rotation in Khorezm is that further extension of agricultural land was not possible without first investing in the extension of the irrigation and drainage network, which however ceased after independence. Hence, the pressure on land increased and, as a result, a cropping system similar to the Punjab regions in India was adopted (Byerlee et al. 1987) where in the first year after cotton, winter wheat is sown into not yet harvested cotton rows (Figure 2.2).

Figure 2.2 Winter wheat seeded into cotton rows in September.

2.2.3 Khorezmian cotton varieties and irrigation

Upland cotton (*Gossypium hirsutum* L.) is considered a salinity-tolerant crop (Ayers and Westcot 1985). No yield decreases were found due to salinity until saturated electrical conductivity levels (ECe) of 7.7 dS m^{-1} at germination, and 50 % yield decrease at 17.0 dS m^{-1} (Ayers and Westcot 1985, Rhoades et al. 1992). However, WARMAP data show yield reductions of 20-30 % already at medium salinity (ECe levels of 6 dS m^{-1}). Only during seed germination may salinity levels in the topsoil horizons constrain seed germination (Kent and Läuchli 1985, Chaudhry and Guitchonouts 2003). Therefore, Khorezmian farmers leach as often as necessary to bring the salt concentration well below the threshold.

The most widely cropped cotton variety in Khorezm is the local cultivar *Khorezm-127* (Table 2.1), covering 50-60 % of the area (OblStat 2004, OblStat 2006). It was introduced in 2000 by J. Yuladashev, O. Iskandarov, K. Matnazarov and others (Masharipov 2006). Its physiological features made it quite a popular cultivar in the region. The variety has a vegetation period of 125-135 days, which is shorter than those previously cultivated. It is more tolerant to the fungus Fusarium wilt (*Fusarium oxysporum* f. sp. Vasinfectum) than the previous cultivars such as variety *108-f*, variety *175-F* or varieties *Tashkent-1*, *Tashkent-2* and *Tashkent-3* (Djumaniyazov 2005); it has an open boll weight of 6.0-6.5 g and a fiber output rate of around 37 %.

Table 2.1 Area (ha, %) of cotton varieties planted in the Khorezm region in 2006, total raw cotton yield (t ha^{-1}) and total production (t) (OblStat 2006)

Variety	**Planted area**	**Planted area**	**Yield**	**Production**
	ha	%	kg ha^{-1}	t
Khorezm-127	51942	49.1	2.61	135722
Mehnat	31415	30.7	2.64	83080
Bukhara-6	8320	7.9	2.41	20079
Bukhara-8	7400	7	2.63	19454
AN-Bayaut-2	4567	4.3	2.47	11301
Khorezm-150	1985	1.9	2.64	5248
New varietes & lines	135	0.1		453
Total	105764	100 (45)		275337

The average irrigation norms for crops grown in Uzbekistan are calculated based on so-called hydro-module zones (MAWR 2000, HydroModRay 2003). These zones were established to forecast the approximate water demand from the Amu Darya river for the area under the respective crop. Nine hydro-module zones were identified according to groundwater depth, losses in the canals, soil properties including salinity, and the expected crop evaporation (Cotton Research Institute 1992). The most wide-spread zone in Khorezm is the hydro-module zone VII, covering the main soil types (i.e. sandy and sandy-loamy soils with groundwater table 1-2 m) (Cotton Research Institute 1992). For this zone, irrigation recommendations (Appendix 15.1) are given in accordance with the phenological growth phase of cotton, amounting to a total of 490-640 mm irrigation water per season (MAWR 2000, HydroModRay 2003). In Australia, cotton yields were maximum at total water application amounts of 700-750 mm (Roth et al. 2004).

2.2.4 Khorezmian winter wheat varieties and irrigation

Winter wheat (*Triticum aevestum* L.) can grow in moderately saline soil conditions if the irrigation water salinity level (ECw) does not exceed 4.0 dS m^{-1} during germination (Ayers and Westcot 1985, FAO 2008). At salinity levels in the soil of 6.0 dS m^{-1}, yield decreases are still negligible; however, 50 % of the yield will be lost due to salinity at levels of 13.0 dS m^{-1} (Ayers and Westcot 1985)

The length of the vegetation period for winter wheat is 180-250 days (FAO 2008). It is commonly planted in September and harvested in June. The Krasnodarian winter wheat cultivar *Kupava* is the most common variety in the region at present and covers 43 % of the area (Table 2.2) (FAO 2001). It is mainly used as bread wheat. It was registered in 1998 as soft wheat and released in 1999 after breeding the cultivars *Caucasus x Atlas 66* for special yellow rust resistance (FAO 2001). Average height is 90-100 cm.

For Soviet wheat, the FAO (2008) recommends “high yield with one full irrigation and one to four spring irrigations with soil water depletion in the first 1 m soil depth not exceeding 70 percent of the total available water”. The official Uzbek recommendations for irrigating winter wheat range from 250-450 mm for the growth season (Appendix 15.2) depending on the groundwater level (Mansurov et al. 2008). The FAO (2008), on the other hand, assumes water requirements of 450-600 mm for optimal yields depending on the environment.

Table 2.2 Seeded area (ha, %) of winter wheat varieties in the Khorezm region in 2006 (OblStat 2006)

Wheat variety	**Planted area**	**Planted area**
	ha	%
Kupava	13100	43.0
Kroshka	9500	31.1
Bozkala	4300	14.1
Polovchanka	1200	3.9
Intensivnaya	1000	3.3
New varieties	1400	4.6
Total	30500	100

* *Krasnodarkaya-99 and Andijan-2 will replace Kupava and Kroshka from 2008*

2.2.5 Fertilizer research history and recommendations

Due to the strong interest of the former Soviet Union and present Uzbek government in maximal production, crop-specific research institutes such as the Cotton Growing Research Institute, Wheat Research Institute, Rice Research Institute and their related regional branches were established during the time of the Uzbek Soviet Socialist Republic (Uzbek SSR). To meet governmental demands, fertilizer research has been conducted mostly to optimize yields by harmonizing fertilizer rates and timing to crop demand (Ibragimov 2007). Fertilizer uptake efficiency (section 2.3.4) has only become part of the research agenda in the past decades, and has only recently been thoroughly assessed by Ibragimov (2007).

Cotton

The Uzbek Cotton Growing Research Institute has 11 regional branches, where researchers conduct field experiments on fertilization recommendations and timing, cotton varieties and planting techniques (Djumaniyazov 2004). The Khorezm Cotton Research Station was established in January 1926 (Djumaniyazov 2004) and is still in place today.

In 1926, the Khorezm Cotton Research Station reported that fields receiving no fertilizer produced cotton amounts of 1.3-1.7 t ha^{-1} (Djumaniyazov 2004). Following the introduction of mineral N and P fertilizers[2] to the Uzbek SSR in the 1930s, first official recommendations, the so-called "Instructions of Narkozem Uzbek SSR about Chemical and Cake Fertilization on Cotton Lands", were published in 1935 recommending systematic N and P fertilizer use to increase cotton production (Ibragimov 2007). In the Cotton Grower's Guide, published in 1932 by Krivetz, an annual rate of 60 kg N ha^{-1} was advised. The distribution was to be in the center of the furrow in 10 cm depth and for soils with shallow groundwater in Khorezm and Karakalpakstan application before sowing or after crop emergence was recommended (Ibragimov 2007). Krivetz (1932) also listed the types of N fertilizer according to their effectiveness: ammonium nitrate (NH_4NO_3) was the most efficient, followed by urea, calcium cyan amide, and ammonium sulphate (Ibragimov 2007). Reported cotton yields from that time, with 90 kg N and 90 kg P ha^{-1}, were as high as 3.0-3.5 t ha^{-1} (Zverlin 1934 in Djumaniyazov 2004) (Appendix 15.3).

From 1951 until 1960, research focused more intensively on issues of effective use of N fertilizers, i.e., N-rate differentiation depending on stocks of NO_3-N in the soil (Ibragimov 2007). On fields with residual soil-NO_3 concentrations of 200-300 kg ha^{-1} down to 1-m depth, around 4 t ha^{-1} could be harvested without additional fertilizer, for soils containing 100 kg NO_3-N ha^{-1} in the profile, applications of 150 kg N ha^{-1} were recommended, and in case of 200 kg NO_3-N ha^{-1} an additional 50 kg N ha^{-1} applied during budding and flowering was advised (Ibragimov 2007).

Most of the research on N-fertilizer efficiency conducted in the 1950s and 60s was undertaken in the Tashkent region. In the Khorezm region, the first guidelines for a balanced fertilization comprising all three macro nutrients N, P, and K were developed by Khaitbayev in 1960 and 1963. He proposed rates of 100-120 kg N, 90-100 kg P and 40-50 kg K ha^{-1} to produce cotton yields of 2.9 and 4.2 t ha^{-1} (cotton variety *Khorezm-8*) (Djumaniyazov 2004). The N applications were to be split, applying 25-40 % before seeding, and depending on the total annual rate, the rest should applied at 2-4 leaves, budding and mid-flowering (Pershin 1961, Protasov 1961), as excessive basal N applications were found to increase undesired plant biomass and delay boll opening

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[2] In the following, the abbreviations P and K are used for phosphorous and potassium fertilizers. These acronyms stand for P_2O_5 and K_2O.

while reducing the economic efficiency of N fertilizers (Protasov 1961, Ibragimov 2007).

Application rates of NPK similar to those used today were developed only a few years later in the mid-1960s by researchers such as Yusupov, Ruzmetov, and Tahtashev (cotton variety *108-f*), who suggested 200-225 kg N, 150-200 kg P and 50-75 kg K ha^{-1} (Djumaniyazov 2004). These rates were kept to until 1970, with cotton yielding 4.3 to 5.3 t ha^{-1} at the Cotton Research Station in 1970 (Ruzmetov 1970, Yusupov and Tatashev 1970 in Djumaniyazov 2004).

From the mid-1970s onward, however, not only a new cotton variety was introduced (cultivar *Tashkent-1*), as the previous cultivar *108-f* had proven to be vulnerable to pests (N. Ibragimov, personal communications), but also the N rates used in the research studies increased to 300-450 kg ha^{-1} (Djumaniyazov 2004). In 1974 and 1976, Sabirov suggested N rates of 400 kg ha^{-1} for 4.5-5.1 t ha^{-1} cotton (Sabirov 1974, Djumaniyazov 2004), and in 1982, Nazarov recommended rates of even 450 kg N, 450 kg P and 225 kg K ha^{-1} to obtain around 4.7 t ha^{-1} cotton yield (Djumaniyazov 2004).

Only in 1983-84 where the N rates in the research studies were reduced again to 250-300 kg ha^{-1}, which coincided with the introduction of the new cotton cultivar *175-f* (Djumaniyazov 2004, Ibragimov 2007). However, based on the research results, the optimal N:P ratio of 1:0.7 is sill applied (Kadirhodjayev and Rahimov 1972, Cotton Research Institute 2007). Khodjizadaeva and Yakhina (1983) studied the effect of nitrification inhibitors on cotton growth, development and quality. While in the first year of the experiment no effect on raw cotton yield was observed, in the second year the cotton increase with inhibitors amounted to around 5 t ha^{-1}, and fiber quality had improved (Ibragimov 2007).

Atajanov (1984) and Tashpulatova (1985) proposed fertilizer norms of 250-350 kg N, 150-250 kg P and 100-140 kg K ha^{-1} to produce 4.0-4.9 t ha^{-1} cotton (Djumaniyazov 2004). Their suggestions are the basis of the fertilizer recommendations still used. For the cultivar *Khorezm-127* introduced in Khorezm after independence, a special committee revised those fertilizer guidelines in 2000, but the rates changed only slightly from the recommendations published in the 1980s (Djumaniyazov 2004, Masharipov 2006, Cotton Research Institute 2007, Ibragimov 2007). The experimental yields on the Khorezm Cotton Research Station for these fertilizer amounts ranged from 3.6-4.6 t ha^{-1} (Djumaniyazov 2004). Also, the most recent research work conducted by Sabirov and Rustamova (2002) and Masharipov (2004) documented cotton yields to be 3.8-4.0 t ha^{-1}, and 3.2-3.4 t ha^{-1} for applications of 200-250 kg N ha^{-1}, respectively (Djumaniyazov 2004). The latest fertilizer recommendations of the Cotton Research Institute (2007) (Table 2.3) do not deviate much from the established norms and can actually be dated back to the beginning of the 1980s (Ibragimov 2007).

Table 2.3 Average research-based application rates of mineral fertilizers according to soil nutrient status and yield (Cotton Research Institute 2007)

Amount available in the soil in 0-60 cm depth prior to seeding			**Fertilizer to be added for achieving the expected yield of**					
			3.0-3.5 t ha^{-1}			3.5-4.0 t ha^{-1}		
Content	**N_{min}* / P**	**K**	**N**	**P**	**K**	**N**	**P**	**K**
	mg kg^{-1}	mg kg^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
very low	0 - 15	0-100	**200**	**140**	**100**	**250**	**175**	**125**
low	16-30	101-200	175	100	80	225	120	100
medium	31-45	201-300	150	80	60	200	90	80
high	46-60	301-400	125	50	40	175	60	60
very high	> 60	> 400	100	25	20	150	45	40

* *N_{min} stands for soil mineral N content*

These fertilizer recommendations are valid for any cotton variety used in Uzbekistan, but adjustments should be made according to determined indices (i.e., for soil type, preceding crop, and nutrient status of the soil). These indices then should be multiplied with the fertilizer norm to give the final application rate (Cotton Research Institute 2007).

To overcome N, P and K limitations during the vegetation period, split applications are recommended. All P and K should be applied bere seeding together with 25-30 % of the annual rate of N (Masharipov 2006, Cotton Research Institute 2007). The remaining N should be applied in two splits with 35 % N at mid-budding and 35 % N at the beginning of flowering, directly followed by irrigation (Cotton Research Institute 2007). In case of the first N application being delayed, the share could also be applied at 2-4 leaves (Ibragimov 2007). Uzbek farmers prefer the latter timing, i.e., to apply the N fertilizers before seeding, at 2-4 leaves and at flowering, as the application then coincides with other agro-technical measures such as general cultivation and furrow shaping for irrigation (N. Ibragimov, personal communications).

The present official Uzbek cotton fertilization rates as well as the split-application and timing for N largely correspond to recommendations of other major cotton producers such as western USA: 180-200 kg N ha^{-1} (Hutmacher et al. 2004, IFA 2006); Pakistan (Punjab): 120-170 kg N ha^{-1} (FAO 2004); Egypt: 145-170 kg N ha^{-1} (FAO and IFA 2000, FAO 2005a); India: 150-300 kg N ha^{-1} (IFA 2006); and Iran (Khuzestan): 190 kg N ha^{-1} (FAO 2005b). For irrigated cotton produced in Australia, around 180-200 kg N ha^{-1} were found to be sufficient (Constable and Rochester 1988, Constable et al. 1992, CRC 2007).

Winter wheat

For winter wheat and summer crops, the development of guidelines for a balanced fertilization and production only started systematically after independence at the Wheat Research Institute and its regional branches (MAWR 1995, MAWR 1996)[3]. According to FAO (2003), the application rate in the past has been as high as 250 kg N ha^{-1}. The present research-based application recommendations for 5 t ha^{-1} winter wheat for soils of low nutrient status are 150-180 kg N, 90-100 kg P, and 60-70 kg K ha^{-1} (MAWR 2000). All P and K should be applied before seeding together with 30 kg N. The remaining N is to be applied in two split applications with 50 % at the beginning of tillering (Zadoks-25; Feekes-2 (Zadoks et al. 1974)) and 50 % at stem elongation (Zadoks-30; Feekes-4-5 (Zadoks et al. 1974) (MAWR 1996, MAWR 2000).

In Pakistan (Punjab), a similar amount of N is applied: 75-160 kg ha^{-1} (FAO 2004). Also, in Iran (Khuzestan) and Egypt, recommendations are in the range of those for Uzbekistan with 180 kg ha^{-1} (FAO 2005b) and 168-180 kg N ha^{-1} (FAO 2005a), respectively. However, to increase winter wheat flour quality, many authors also propose late applications of N at anthesis/flowering (Zadoks-60, Feekes-10.51 (Zadoks et al. 1974)) or kernel milk development (Zadoks-73, Feekes-11.1 (Zadoks et al. 1974)) (section 2.3.2) (Fowler and Brydon 1989, Woolfolk et al. 2002, IFA 2006), a practice uncommon in Uzbekistan.

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[3] Unfortunately, researchers of the Khorezm Wheat Research Station were reluctant to share latest research results with the author.

2.2.6 Actual yield trends in Khorezm

Cotton production has a long history in Central Asia as well as in Khorezm. The continuous expansion of irrigated cotton area in Central Asia since the late 1930s was due to the fact that the raw cotton was easily transportable, so that the plant could be cropped even at great distances from the location of the actual textile industry (Robertson 1938). With the exception of the war years, where cotton pickers were sent to the army, and the years of famine (1941-1947), Khorezmian cotton yields experienced a steady increase until 1983 (Figure 2.3). The record cotton yield of 6.1 million t on the national level was reached and celebrated in 1981. Highest yields in Khorezm were achieved in 1974 and 1980, where 4.5 t raw cotton ha^{-1} were harvested. Based on the findings, it can be assumed that since the mid 1970s, cotton yields continuously declined. With Uzbekistan's independence and the introduction of winter wheat on farm-level, winter wheat yields increased, while cotton yields continued to decrease.

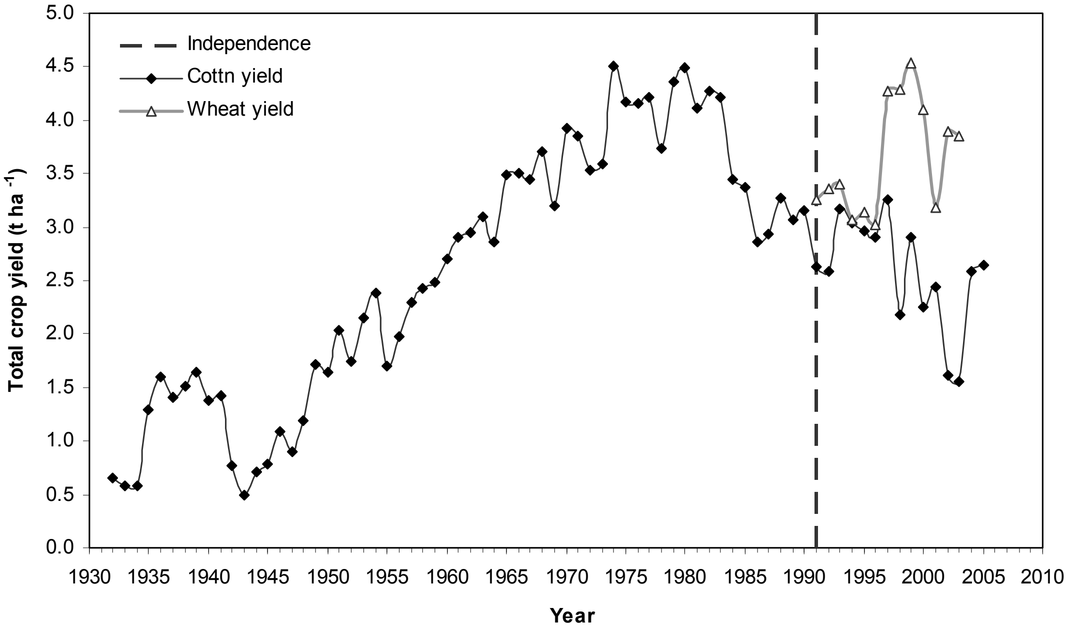

Figure 2.3 Yield of cotton and wheat (t ha^{-1}) in Khorezm 1932-2005 (official statistics).

However, it is unclear how trustworthy these official statistical data on cotton are, as over-reporting of cotton production was common (Trevisani 2007), and frequently pushed to a maximum as evidenced by the Cotton Scandal in the late 1970s and early 1980s, which revealed a major falsification of harvest data records during the period Sharaf Rashidov[4], the First Secretary of the Uzbek Communist Party in the Uzbek Soviet Socialist Republic (Uzbek SSR) (1959-1983). In the aftermath of the scandal, Mikhail Gorbachev demanded that all statistical documents be thoroughly re-checked and when necessary adjusted (Saiko 1995). Following the statistical corrections, the new officially recorded cotton yields were lower by 1 t ha^{-1} than those of the late 1970s, and have continued to decrease slightly until today. Due to the manipulated harvest data records until 1983, however, it remains unclear when the turning point in cotton yield actually occurred.

Nevertheless, there are indications that cotton yields in Khorezm have declined in recent years according to Glazovsky (1995), Brookfield (1999), Herrfahrdt (2004) and others. Reasons for the decline are repeatedly related to the extensive irrigation and cotton production campaigns of Premier Khrushchev in the late 1950s (Virgin Lands Program), which encouraged unsustainable agricultural practices, and cotton monoculture causing soil degradation, salinization, and waterlogging, which accumulated in the desiccation of the Aral Sea (Mickin 1988, Glantz et al. 1993, Saiko 1995, Spoor 1998, Brookfield 1999, Roll et al. 2006). On the other hand, the change in the economical setting after independence and political events such as the cotton scandal in 1983 or the agrarian reforms after independence (Glazovsky 1995, Herrfahrdt 2004) had a negative effect on the production dynamics of cotton in Uzbekistan.

2.2.7 Actual fertilizer trends in Khorezm

As for all crops, during Soviet times, cotton yields were firstly governed by fertilizer application. Mineral nitrogen fertilizers (N) were introduced to Khorezm in the 1930-1940’s during the so-called Period of Chemicalization (Ibragimov 2007) (Figure 2.4). For the 5-year-plan of that time, the amount of fertilizers was calculated based on the optimal rate for cotton production of 60 kg N ha^{-1} (Ibragimov 2007). Initiated in 1966 by Brezhnev’s plans to intensify agriculture, fertilizers, pesticides and other related inputs for cotton production were heavily subsidized (Wegren 1989, FAO 2003). Together with the input subsidies, this policy encouraged cultivation of even marginal

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[4] Sharaf Rashidov was First Secretary under Nikita Khrushchev (1953-1964) and Leonid Brezhnev (1964-1982)

and low-fertile lands, leading to substantial expansion of cotton production to areas such as the Hungry and Djizzak Steppe, as well as in the Karshi region (Sabirov 1974, Glazovsky 1995). An over-application of fertilizers was common (Wegren 1989, Herrfahrdt 2004), as employees of the kolkhozes and sovkhozes had little incentives to use fertilizers efficiently. The same applied to losses and to the pollution of the environment, and cost-effective management.

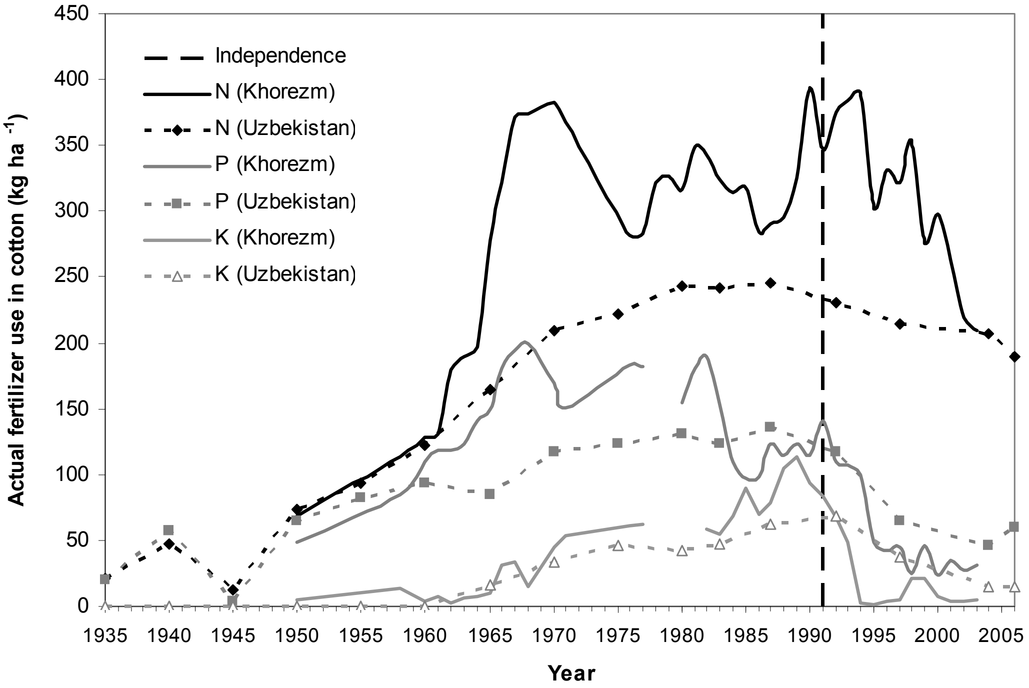

Figure 2.4 NPK fertilizer use in cotton production (kg ha^{-1}), 1935-2006 (official statistics). Lines indicate fertilizer use in Khorezm, dotted lines use on national level. Interruptions in the lines are missing data.

In 1991, Uzbekistan became independent from the Soviet Union. This was a political and economical turning point. The break-up of the Soviet Union and the declaration of independence brought about a breakdown in the supply of agrochemicals and cheap fertilizer, especially potassium (K), which was formerly imported from Kazakhstan and Byelorussia (Ibragimov 2008, personal communications). Also, the phosphorous (P) enterprises, built in the 1950-80s on South Kazakhstan territory and that usually supplied Uzbekistan, stopped working after independence (UZEX 2004). The statistics show that despite constructions of fertilizer plants, i.e. a new K-mining chemical plant was constructed in 1999 (UZEX 2004), and N fertilizer production within Uzbekistan was promoted again after 2002 (UZEX 2004, FAO 2006), the fertilizer application rates in cotton decreased steadily: N-fertilizer use declined considerably from around 400 kg N ha^{-1} in 1990 to 210 kg ha^{-1} in 2003. In the same period, the use of P and K fertilizers decreased from 115 kg P ha^{-1} and 95 kg K ha^{-1} to 31 kg ha^{-1} and 5 kg ha^{-1}, respectively (OblStat 2004).

One of the reasons for this development was mainly the price increase for mineral fertilizers (Figure 2.5), especially for P (single superphosphate, SSP), which increased twice as fast as the price of N and K fertilizers (WARMAP and EC-IFAS 1998, Kandiyoti 2004a, Rudenko 2005). Prices for fuel, seeds and pesticide also rose (Figure 2.6) (FAO 2002, Kandiyoti 2004a, Müller 2006b), leading to a significant decrease in input use and thus crop production (FAO 2003, Müller 2006b, Djanibekov 2008). An Uzbekistan-wide farm management survey conducted in the framework of a EU-Tacis-Project during the years 1996-1998 documented a misbalanced use of NPK fertilizers and an almost completely minimized pesticide use in cotton production for all regions (WARMAP and EC-IFAS 1998).

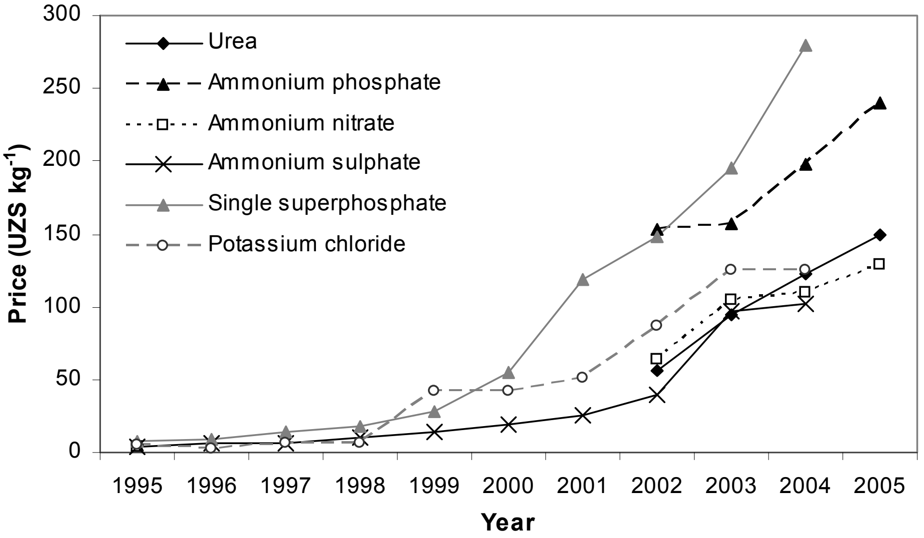

Figure 2.5 Average fertilizer prices (UZS kg^{-1}) in Khorezm (1995-2005) according to official statistics (Djanibekov, Rudenko and Bobojanov, personal communications).

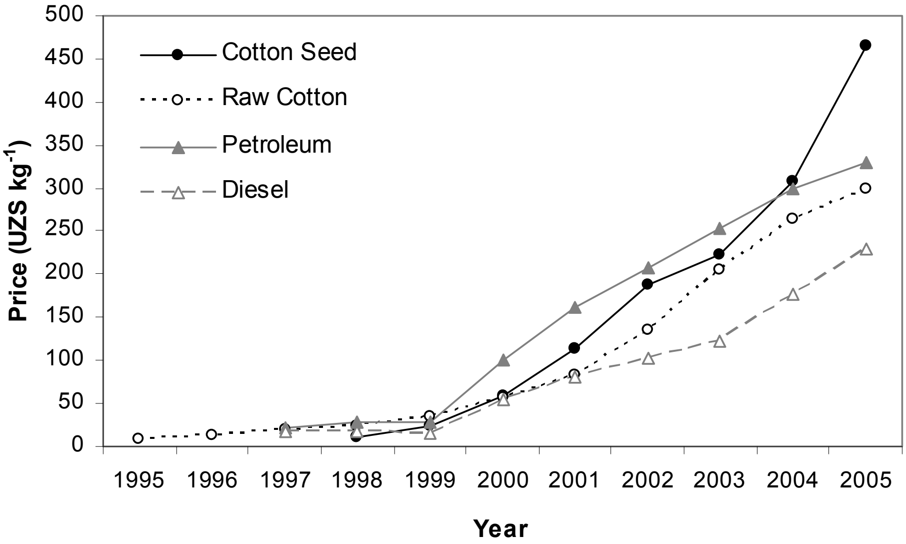

Figure 2.6 Input costs (UZS kg^{-1}) for cotton production in Khorezm (1995-2005) according to official statistics (Djanibekov, Rudenko and Bobojanov, personal communications).

At the same time, state prices for cotton and winter wheat yields did not keep pace with the increase in input prices such as for fuel, fertilizers or pesticides (Rudenko and Lamers 2006). Although inputs for state-ordered cotton production are still considered to be subsidized, in Khorezm in 2005, the costs for fuel, seeds and mineral fertilizer amounted to around 30 % of the total input cost for cotton production (Figure 2.7) (Rudenko 2005). The fertilizers were 17 % of the total farm expenditure in cotton production, ranking third after wages and mechanization service (paid to the machine tractor park) costs. In winter wheat production, the fertilizers are the most expensive input making up 32 % of the total costs, followed by seeds and mechanization services. Labor costs in wheat production are generally low, as there is only one harvest, and other labor resources are mostly the farmer’s family (Djanibekov 2008).

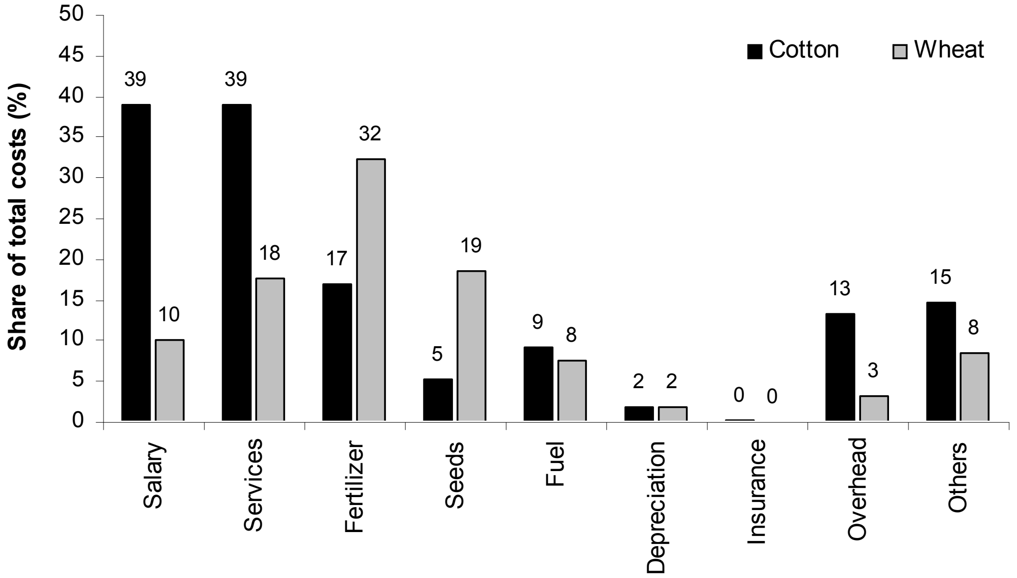

Figure 2.7 Share of total costs in cotton and winter wheat production in Khorezm (%) according to official statistics (Rudenko, personal communications).

However, this new situation is not reflected in the official fertilizer recommendations developed by Uzbek research institutions (section 2.2.5). A farm management survey conducted during 1996-1998 found large discrepancies in actual use of N, P and K fertilizers as opposed to the recommendations or norms (WARMAP and EC-IFAS 1998). Scientific research institutions such as the Institute of Soil Science and Agro-chemistry as well as the Ministry of Agriculture and Water Resources (MAWR) estimate the under-use of mineral fertilizers in cotton and cereal production as high as 20-30 % of the recommended rates (FAO 2003, FAO 2006).

Plotting the yields against the N fertilizer use in cotton for the two main time periods before and after independence (1950-1990 and 1991-2003) (Figure 2.8), one can observe a complete move downwards of the response curve after independence. Whereas in the years before independence, cotton yields still amounted to around 3.0 t ha^{-1} at the fertilizer rate of 200 kg N ha^{-1}, after 1991 the same fertilizer input yielded around 1 t less. Thus, assuming the recommended fertilizer rates for cotton and wheat production to be correct, the mismatch between actual and recommended fertilizer application practices is likely to have immediate effects on crop yield and quality and in the long run negatively affect soil fertility.

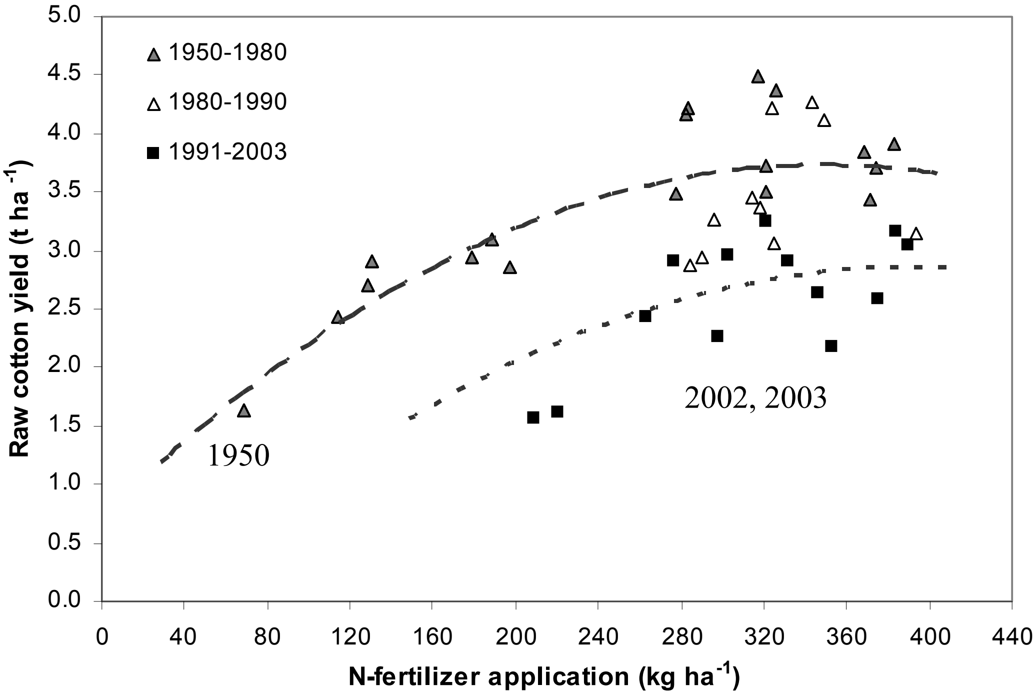

Figure 2.8 Raw cotton yield (t ha^{-1}) in relation to N fertilizer applied (kg ha^{-1}) in Khorezm 1950-2003 (official statistics). Data are split in years before Uzbekistan's independence (1950-1990) and after independence (1991-2003).

2.3 Nitrogen in plant-soil systems

2.3.1 Soil-nitrogen cycle

The soil-N cycle involves several N transformations, which essentially make soil-organic N or fertilizer-N usable for plants. Processes increasing plant available N are mineralization, nitrification and biological N_2 fixation, while processes such as ammonia (NH_3) volatilization, immobilization, denitrification and leaching foster temporal or permanent N losses from the plant rooting zone (Figure 2.9) (Scheffer and Schachtschabel 1998).

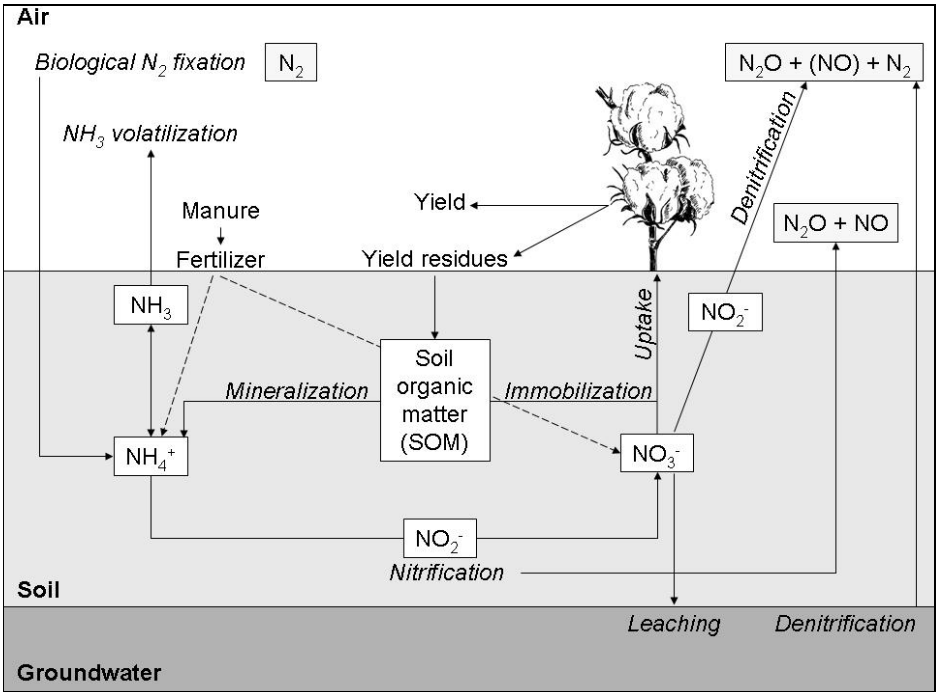

Figure 2.9 Simplified soil-N cycle (modified after Hofman and van Cleemput (2004) in van Cleemput and Boeckx 2005).

Nitrification, immobilization and mineralization

The dynamics of soil-N follow a continuous cycle of nitrification, immobilization and mineralization processes, and thus a continuous change of N between organic and inorganic forms of N (Jansson and Perssson 1982, Schmidt 1982). Nitrification processes are particularly promoted under higher soil temperatures and in well-aerated, moist soils (Schmidt 1982). In fact, Halevy and Klater (1970) assumed that most of the NH_4-fertilizer applied in Israel is taken up by cotton in the form of NO_3-N, since nitrification in the summer months is particularly high. Drawing on this, also for Khorezmian soils high nitrification rates can be expected, and low NH_4-N concentrations have been reported.

In case the mineral N supply (i.e., sum of NH_4-N and NO_3-N) in the soil is lower than the carbon (C) content, which is needed for microbial respiration energy, preferably NH_4-N (and only later NO_3-N) will be taken up by the microorganisms, transformed to organic N compounds and thus temporarily immobilized (Jansson and Perssson 1982, Jenkinson et al. 1985, Recous and Mary 1990). In case more mineral N is available than needed to satisfy the microorganisms, the remaining N will be subject to uptake or nitrification processes.

Mineralization, which is the reverse of the immobilization process, increases with increasing temperatures (Jansson and Perssson 1982) and is more or less independent of soil moisture, although changing patterns of drying and re-wetting also enhance the mineralization processes (birtch effect) (Birtch 1958, Vlek et al. 1981). The high temperatures prevailing during the summer period in Khorezm and the frequent wetting and drying cycles in the course of the irrigation events particularly boost mineralization during the vegetation period and create soils of low organic N content (Riskieva 1989).

Volatilization, denitrification and leaching

The process of volatilization comprises loss of NH_4-N, which is converted to gaseous NH_3, to the atmosphere. Especially (sandy) soils with low cation exchange capacity (CEC) and higher pH, and in conditions favoring high evaporation such as warm and windy weather, and low partial NH_3 pressure are susceptible to volatilization (Vlek et al. 1981, Stevenson 1982). Even though these factors prevail in the Khorezm region, volatilization losses have not yet been documented.

Denitrification, i.e., the conversion of NO_3-N into molecular N (N_2), takes place mainly under anaerobic conditions when the soil is saturated (>60% water-filled pore space) (e.g., Burford and Bremner 1975, Craswell 1978, Mahmood et al. 2000). For denitrification, microorganisms use easily accessible soil organic C (C_{org}) as an electron donor instead of oxygen (O_2), which in warm, irrigated environments is available from readily decomposable plant material due to high turnover rates (Mahmood et al. 1997), or from organic matter mineralizing in the course of wetting and drying cycles (Franzluebbers et al. 1994).

Denitrification rates in Khorezmian soils under current land-use practices have recently been studied in detail (Scheer et al. 2008a, Scheer et al. 2008b, Scheer et al. 2008c). The findings show that denitrification losses were especially pronounced in cotton production as opposed to winter wheat or paddy rice (Scheer et al. 2008c) due to the higher soil temperatures in summer. Both cotton and winter wheat showed highest losses when N-fertilizer application was concomitant with irrigation. These N_2 losses exceeded N_2O losses by far, which resulted in total gaseous losses of N ranging from 10-70 % of the total N applied (Scheer et al. 2008c). From the N losses, the N_2O

emissions were from 0.2-2.6% of the N fertilizer applied for all annual crops, while N_2 losses were estimated to be up to 40 % of the N fertilizer applied.

Frequent irrigation events with large amounts of water as well as heavy rainfall increase the potential for N losses below the rooting zone or even to the groundwater via leaching of the mobile fractions (Smika and Watts 1978, Young and Aldag 1982, Burkart and Stoner 2002, Ju et al. 2006). As it is not attracted by the negatively charged clay surfaces, NO_3-N is not retained by the soil particles (Scheffer and Schachtschabel 1998).

High concentrations of NO_3-N in the surface waters and aquifers are of concern regarding water quality (e.g., Addiscott 1996, Burkart and Stoner 2002, Ju et al. 2006, WHO 2006). More than 50 mg l^{-1} NO_3-N or 3 mg l^{-1} NO_2-N in the drinking water are reported to cause health hazards such as the blue-baby syndrome (*Methaernoglobinaernia*) and other chronic effects (WHO 2006, WHO 2007). In Khorezm, drinking water mostly comes from groundwater tube wells located close to intensively cultivated gardens (Herbst 2005) and from hand pumps installed near agricultural fields. Herbst (2005) found substantial fluctuations in the pollution of the drinking water in the tube wells, although the average NO_3-N concentrations did not exceed the critical drinking-water threshold (median 25 mg l^{-1}, range 0-250 mg l^{-1}). For drainage canals and lakes in the region, Shanafield (personal communications) reported low monthly NO_3-N levels of less than 1 mg l^{-1} and NH_4-N pulses in March and April of maximum 3 mg l^{-1}.

Khorezmian soils

The prevailing soils of the lower reaches of the Amu-Darya river are essentially light and medium loams (Rizayev 2004) originating from coarse-textured deposits of the ancient river delta during the tertiary era, which in turn are covered with 20-100 m finer textured alluvial sand layers from the quaternary (Tursunov and Abdullaev 1987, Riskieva 1989, Popov et al. 1992, Djumaniyazov 2006). Especially the sandy loams and loams (Figure 2.10) with their low to medium clay and silt content have a low cation exchange capacity (CEC) and ion adsorption capacity (Yuan et al. 1967, Miller 1970, Syers et al. 1970).

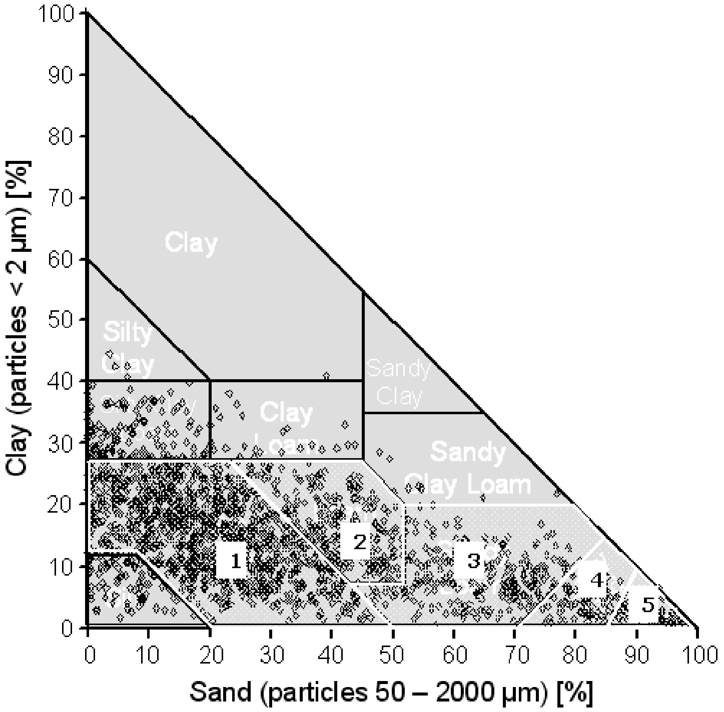

Figure 2.10 Particle size distribution (USDA classification) of soils in Khorezm (Sommer et al. 2008a). Modified after data from the Soil Science Institute Tashkent.
Main soil classes and their abundance: 1: silt loam (55 %); 2: loam (13 %); 3: sandy loam (12 %); 4: loamy sand (5 %); 5: sand (3 %)

The soils in Khorezm region are furthermore characterized by low amounts of soil organic matter (SOM, 0.33-0.60 %) and a high carbonate rock content (Riskieva 1989, Ibragimov 2007). The topsoil contains 1 % or less SOM, and SOM sharply decreases with depth (Figure 2.11) (Riskieva 1989, Soil Science Institute 2003, Sommer et al. 2008) owing to high temperatures and intensive irrigation and tillage practices, which enhance fast decomposition in the plowing layer (Vlek et al. 1981, Riskieva 1989, McGiffen et al. 2004). However, as the CEC in the loamy soils prevailing in the Khorezm region depends mainly on SOM content, its content is crucial for the nutrient holding and buffering capacity (Yuan et al. 1967, Miller 1970, Syers et al. 1970).

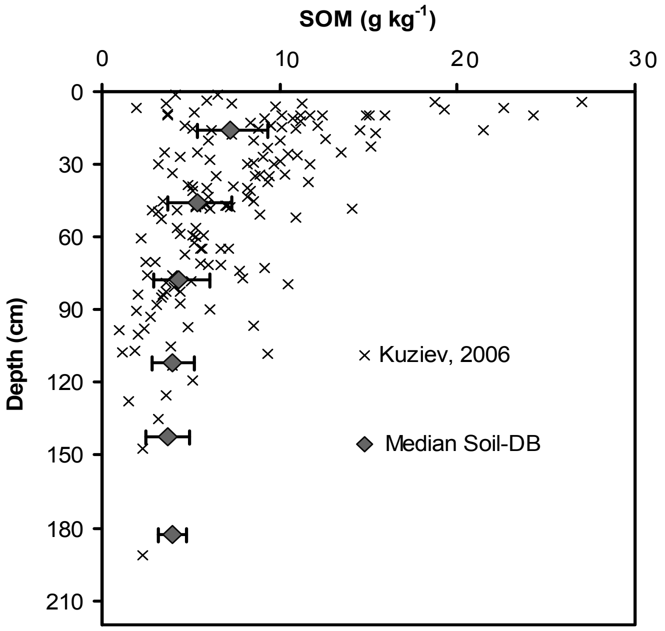

Figure 2.11 Soil organic matter (SOM) content (g C kg^{-1} soil) in Khorezmian soils (cm) (Sommer et al. 2008a). Modified after data from Soil Science Institute Tashkent.

In the Khorezmian soils, N is considered to be the most limiting nutrient (Ibragimov 2007). Total organic N (N_{org}) usually comprises around 90-95% of the soil total N content in the plowing layer of agricultural soils, and is closely associated with the SOM[5] (Vlek et al. 1981). For Khorezm, the N_{org}-content in the soils has been reported to vary from 0.012-0.073 % in 0-30 cm depth (Riskieva 1989, Soil Science Institute 2003, Ibragimov 2007).

While 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}) (Riskieva 1989, WARMAP and EC-IFAS 1998, Djumaniyazov 2004, Djumaniyazov 2006). 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 (Riskieva 1989, WARMAP and EC-IFAS 1998, Djumaniyazov 2004).

Riskieva (1989) found the quantity of NO_3-N in the Khorezmian soil profile to vary to a great extent depending on the time of soil sampling and on the amount of

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[5] SOM = 1.56 organic C (C_{org})

irrigation water applied. In the top 0-30 cm, the average residual NO_3-N content in several surveyed soil profiles was 25 mg kg^{-1} (range 6-96 mg kg^{-1}) and decreased to 8 mg kg^{-1} in 70-100 cm (range 4-17 mg kg^{-1}). NH_4-N on the other hand showed a rather homogeneous distribution in the soil with 10 mg kg^{-1} in the topsoil (range 6-20 mg kg^{-1}) and 9 mg kg^{-1} in 70-100 cm depth (range 3-16 mg kg^{-1}) (Riskieva 1989). These NO_3-N and NH_4-N concentrations were documented also by Kadirhodjayev and Rahimov (1972) and Tashpulatova (1974), who reported initial NO_3-N levels of 3 and 5 mg kg^{-1} in the plowing layer of a medium loamy soil, respectively, while Khodjizadaeva et al. (1978) and Nazarov (1985) found higher initial amounts of around 15 mg NO_3-N kg^{-1} and 7 mg NH_4-N kg^{-1}, respectively. These nutrient levels, therefore, generally demand an N application for the cultivation of cotton or winter wheat.

2.3.2 Plant-nitrogen cycle

Balancing crop N demand and supply from the soil is essential for sustainable crop growth and development (Olson and Kurtz 1982). Constant removal of N with the harvest or improper N management will eventually cause deficiencies and substantially reduce yields (Balasubramanian et al. 2004). For agronomists, therefore, “the challenge is to manipulate N availability before, during and after crop peak N demand” (Dinnes et al. 2002, p. 156) while minimizing N losses.

Once absorbed from the soil, N is readily transported to the leaves, where it is stored (CRC 2007). The N-deficiency symptoms often appear first as yellowing of older leaves or chlorosis, since a scarce N supply from the soil or fertilizers inhibits chlorophyll synthesis and decelerates photosynthesis (Epstein 1972). Other visible N-deficiency symptoms are reduced or weak growth and shorter height, while an excess N supply may encourage pest manifestations and late ripening (IFA 2006). In the case of cotton, N deficiencies will produce fewer branches and induce early fruit shedding and premature termination of fruit formation, while an excess supply can create rank growth and delay boll opening and maturity (Chaudhry and Guitchonouts 2003). The N deficiency during winter wheat growth has detrimental effects on the protein content and quality (section 2.3.2) (Olson et al. 1976), and will produce smaller ears and less kernels per ear, and decrease kernel weight (Langer and Liew 1973). High N supply to winter wheat can cause high plant densities due to intensive tillering (Strong 1986, Eck

1988), lodging and subsequent difficulties during harvest (Hucklesby et al. 1971, Hobbs et al. 1998).

Nitrogen uptake and fertilization

Most plant-N taken up during the vegetation period comes from the soil in the form of inorganic N, i.e., Nmin (soil-NO_3 and -NH_4). The relationship between pre-sowing mineral-N amounts in the soil and dry matter production and ultimately yield has been studied for various crops to estimate the N-fertilizer requirements.

The most common practice to mitigate the N status of agricultural soils is the use of mineral or organic N fertilizers. The first Russian researcher to declare that the fertilizer N supply should be adjusted to the soil-NO_3 was Balyabo in 1938 (Ibragimov 2007). For contents of more than 200-300 kg N ha^{-1} in the profile (1 m), no additional N was needed for obtaining cotton yields of 4.0 t ha^{-1}.

The rate of N-fertilizer uptake by plants depends on many factors, such as fertilizer application rates, timing, method, type of fertilizer, soil history and biological features of the crops (Olson and Kurtz 1982). Riley et al. (2001) compared farmers' practices with better plant-N uptake related applications and found that good timing of N in relation to crop demand is very efficient in reducing losses, i.e., adequate splits and also timing of splits. Also, meeting crop nutrient needs by applying the appropriate amount of N with the appropriate technique reduces losses and increases the N-use efficiency (NUE) (Wuest and Cassman 1992a).

Soil N deficiencies are met by Khorezmian farmers by applying available and/or most affordable straight N fertilizers such as ammonium nitrate ("selitra" containing 34 % N) and urea ("carbamid" or "mochevina" containing 46% N[6]) (FAO 2003). Also, N-containing fertilizers are used including ammonium phosphate ("ammofos", AP, 11-12 % N and 46 % P_2O_5), ammonium sulphate ("sulfat", 20.5-21.0 % N) and ammonium superphosphate ("ASF", 13-14 % N and 9 % P_2O_5) (FAO 2003). Other available N-containing fertilizers such as mono- or diammonium phosphate (DAP, 18 % N and 46 % P_2O_5) are uncommon in the region (own observations, WARMAP and EC-IFAS 1998, FAO 2006). The N fertilizers such as

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[6] Percentages estimated by the Cotton Research Institute (2007)

anhydrous ammonia which are favored in Australia (Constable and Rochester 1988) are not available in Uzbekistan.

Urea ($CO[NH_2]_2$) is favored in the world as N fertilizer as it is highly soluble (CRC 2007), and with 46 % N the highest concentrated N fertilizer, which makes it very attractive because of a good N per kg fertilizer ratio (FAO and IFA 2000). However, it has to be hydrolyzed to NH_4 and then nitrified before it can be taken up by most plants. During this time, it is subject to volatilization, and, therefore, it should be incorporated into the soil rapidly (FAO and IFA 2000).

Mono- and diammonium phosphate are frequently applied as starter fertilizers, as they accelerate early growth of seedlings (IFA 2006). The combination of both N and P at the onset has shown to be effective, as phosphate serves as a carrier for ammonium, which makes the latter better available for plants (Olson and Kurtz 1982).

Ammonium nitrate has hardly been used after the Oklahoma City bombing in the US in 1995 although it provides both ammonium and nitrate.

2.3.3 Nitrogen and crop quality

Cotton

The quality of cotton is generally related to its fiber. The fiber properties can be summarized in the terms shape and maturity. Fiber shape is described by length, diameter, etc., of the cotton seed hair, which is very much governed by its genetics (Bradow and Davidonis 2000). The realization of the genetic potential of cotton usually depends on the environmental conditions such as fertilizer and irrigation, temperature, day length, and solar radiation (Bradow and Davidonis 2000).

Fiber physical maturity and micronaire (fineness, fiber cross section and relative wall thickening), on the other hand, is more sensitive to environmental conditions and management (Bradow et al. 1997, Johnson et al. 2002), and is not so much affected by its genetic potential. Higher fiber maturity and micronaire can be expected with earlier picks, and decreasing properties with later picks (Bradow et al. 1997, Bradow and Davidonis 2000). The longer the opened cotton bolls remain in the field on the plant, the more likely is a change of color (especially weather strongly affects the color) and shrinking of fibers, which inevitably reduces the quality with respect to fiber length, strength and micronaire (Chaudhry 1997). Fibers of lower micronaire generally contain a higher percentage of less developed cellulosic secondary fiber walls (Bradow et al. 1997). These walls are more likely to collapse in the process of maturing, hence, increasing dye defects in yarn and fabric (Bradow et al. 1997). Therefore, cotton is usually picked 3-4 times in one season after the bolls have opened.

Aside from the harvest time, the nutrient supply influences the fiber quality. A low N supply, for example, causes weak and short fibers (Bradow and Davidonis 2000, Chaudhry and Guitchonouts 2003), while a high N supply causes immature and weak fibers, which is associated with lower micronaire, but greater length (Chaudhry and Guitchonouts 2003, Montalvo 2005).

On the international market, the fiber value increases with fiber color (whiteness), length, strength, and decreasing micronaire (Bradow and Davidonis 2000). Most problematic are very short fibers and a high content of immature and weak fibers. Also, high micronaire fibers are coarser and more uneven and thus problematic in the dying process (Bradow and Davidonis 2000, Montalvo Jr. 2005). Longer fibers yield a smoother and stronger yarn, and immature fibers give matted yarns that are difficult to handle during the spinning process (Martin et al. 1976). In addition, fiber length classes of upland fiber cotton differ between countries. The US, for example, uses the classification short fiber (<21 mm), medium (22-25 mm), medium-long (26-28 mm) and long (29-34 mm) (Bradow and Davidonis 2000). In Uzbekistan, the classes for fiber length are much closer, i.e., 31-33 mm, 33-35 mm, 35-37 mm, 37-38 mm and 38-41 mm (Ibragimov et al. 2008). Micronaire classes range from 3.0 to 5.0, and fiber is considered strong at 36 g tex^{-1} and weak at 33 g tex^{-1} (Ibragimov et al. 2008).

In Uzbekistan, the certification center for cotton quality, the Uzbek Center for Certification of Cotton Fiber (SIFAT), is a joint-stock company responsible for evaluating the fiber export quality. It was established after Uzbekistan’s independence and uses national certification standards that are in line with the USDA certification classes (SIFAT 2001, Rudenko 2008). According to SIFAT, the fiber length of the fiber cotton variety *Khorezm-127* is 33.6-35.0 mm (SIFAT 2005), the micronaire index (fineness) is 4.4, and the relative strength (measured by the stelometer) is 25.6-27.6 g tex^{-1} (SIFAT 2005, Masharipov 2006). This variety, therefore, is classified as middle-fiber (Bremen Cotton Exchange 2004).

Important for the fodder industry is the cotton seed weight. The Uzbek cotton cultivar *Khorezm-127* produces between 30 and 37 % fiber (Masharipov 2006, Rudenko 2008). Ginned seeds usually comprise 60-65 % of the total raw cotton weight, of which around 16 % are crude oil and 46 % are meal (Chaudhry and Guitchonouts 2003, Rudenko 2008). The seed serves as an important oil source when pressed. The residues from pressing, i.e., the cotton seed cake, serve as energy-rich fodder for livestock (Martin et al. 1976, DLG 1997). Seed weight increases with increasing N supply (Khaitbayev 1963).

Winter wheat

Around 60 % of the wheat production world wide is used for food (Gwirtz et al. 2007). Most widely grown is soft winter wheat (*Triticum aevestium* L.), which is especially used for cakes, biscuits and pastry (Oliver 1988, Fowler et al. 1990, Farrer et al. 2006). Hard winter wheat (*Triticum durum* L.) accounts for only 10 % of the total global production (Raiffeisen 2008) and is used mainly for pasta, bread and Chinese noodles (Oliver 1988, Habernicht et al. 2002). It is grown especially in the Mediterranean region and in the water-limited regions of the US (Great Plains) (Habernicht et al. 2002, Raiffeisen 2008).

Quality criteria for wheat include high flour protein, high water absorption, good dough extensibility and tolerance to mixing, and high loaf volume (Schofield and Blair 1937, Schofield 1994, Shewry et al. 1995, Bruckner et al. 2001). Wheat kernels at maturity, for example, may contain 8-20 % proteins (Johnson et al. 1973, Farrer et al. 2006). Providing viscosibility and elasticity, the gluten is responsible for the functionality of wheat flours and the processability into different foods (Shewry et al. 2002). A balance between viscosibility and elasticity is important, as highly extensible or too strong gluten will not produce the desired voluminous, fluffy, evenly pored dough (Shewry et al. 1995). Also, a low protein content will cause problematic starchy kernels (Fowler et al. 1989). The optimal ratio for bread making is provided at protein contents of 11.5-14.0 % (Oliver 1988, Panozzo and Eagles 2000).

Cereals are the main source of protein intake in the developing world after meat and diary products (Olson et al. 1976, Friedman 1996). Proteins are essential in the diets of humans, as they provide some essential amino acids, complex carbohydrates and many valuable vitamins (e.g., vitamin B) and minerals (Hucklesby et al. 1971, Pellett and Young 1980, Oliver 1988, Friedman 1996). Gluten and protein content are, therefore, key indicators for baking quality and food quality of kernels, and a measure for assessing the baking quality of wheat flour (Gupta et al. 1992, Shewry et al. 1995).

Hard wheat varieties grown in semi-arid environments are usually likely to have higher protein content than soft wheat varieties (Habernicht et al. 2002). Roughly, for bread wheat, the German classification distinguishes three protein and four gluten classes (Raiffeisen 2008): low protein (10.5 %), medium protein (12.5 %) and high protein (16.5 %) content; and little gluten (< 20 %), low gluten (20-23 %), medium gluten (24-27 %) and high gluten (> 28 %) content. The official Soviet standard for hard wheat provides a more detailed system for protein and gluten (Table 2.4) (Abugalieva et al. 2003b).

Table 2.4 Soviet wheat protein and gluten classification for hard and medium winter wheat varieties (Abugalieva et al. 2003b)

	Strong wheat types			**Value wheat types**	**Wheat filler**		**Weak wheat**
	Excellent improver	Good improver	Satisfactory improver		Good	Satisfactory	
Protein content, % (not less than)	16.0	15.0	14.0	13.0	12.0	11.0	8.0
Kernel gluten content, % (not less than)	32.0	30.0	28.0	25.0	24.0	22.0	15.0

The content of protein and gluten in the wheat kernels can be managed successfully by targeted N supply to the wheat crop (e.g., Farrer et al. 2006). Also, the kernel weight can be improved by applying higher N-fertilizer rates (e.g., Alaru et al. 2003). However, there is a natural limit above which increasing protein content is associated with decreasing yields, as protein content and yield are known to be negatively correlated (e.g., Olson et al. 1976, Alaru et al. 2003). Once the response curves for both protein content and yield for a given variety are known, breeders can narrow the ratio of yield-to-protein content beyond the potential by targeted selections of particular varieties (e.g., Terman 1979, Lanning et al. 1994, Ortiz-Monasterio R. et al. 1997, Fowler 2003).

Aside from increasing N rates, also NH_4-based fertilizers (IFA 2006) and the appropriate timing of N application significantly affects protein content (e.g., Farrer et al. 2006). By delaying N applications until the reproduction phase (i.e. the periods of maximum N assimilation or of maximum carbohydrate formation) e.g., prior to anthesis/flowering (Zadoks-60, Feekes-10.51 (Zadoks et al. 1974)), or after anthesis/at milk formation stages (Zadoks-73, Feekes-11.1 (Zadoks et al. 1974)), increased protein contents of the kernels can be achieved without affecting the vegetative growth. In fact, the efficiency of acquired N after anthesis was higher than for earlier N applications, as the partitioning of the absorbed N to the kernels was more effective (section 2.3.4) (Wuest and Cassman 1992b). On the other hand, during this growth stage the mineral N content in the soil is usually low (Smith and Whitfield 1990), which also may impact N efficiency.

Uzbek local winter wheat is reported to have gluten contents of less than 20 %, which is an overall low gluten quality, and often starchy kernels (Abugalieva et al. 2003a) caused by low protein content (Fowler et al. 1989). Given the genetic potential, it can be concluded that the winter wheat production practices in Uzbekistan provoke an under performance of its potential in terms of quality. Consequently the N-fertilizer management strategies need to be revised and adjusted should quality become a priority.

2.3.4 Nitrogen-fertilizer use efficiency

Knowing the fate of N applied as fertilizer is particularly important to improve its availability for crops, since inefficient fertilization may lead to nutrient losses to the environment via volatilization or leaching, while sacrificing crop yields and quality (section 2.3.1). The efficiency of crops to use the applied N from fertilizer depends on the uptake and the utilization efficiency. While the first can be managed by cultivation practices (section 2.3.4), the latter is genetically predetermined (Hirel et al. 2007). The labeled N (^{15}N) recovery and N uptake efficiency, in the following referred to as N-use efficiency (NUE), is high where losses to the environment are minimized.

The N-fertilizer use efficiency is usually assessed by two procedures: (i) by estimating the agronomic N-use efficiency (NUE_{AE}), which is also commonly referred to as the difference or apparent method, and (ii) by the use of the ^{15}N isotope dilution technique (Harmsen and Moraghan 1988).

For the first method, the yield increase in the economically important component (i.e., raw cotton, wheat kernels, etc.) per unit of N fertilizer applied is calculated (IAEA 2008) under the assumption that the N uptake is similar for fertilized and non-fertilized plants. Despite its widespread use, this assumption has been a subject for an on-going debate, in particular since root growth may differ depending on N input (Olson and Swallow 1984, Belford et al. 1987). The yield increase may also be expressed per increase of biomass N uptake (NUE_P), which is equivalent to the physiological efficiency (Hirel et al. 2007, IAEA 2008), or per N absorbed from the soil (Moll et al. 1982). However, Fritischi et al. (2004b) among others reported a high variability and contradicting tendencies with respect to increasing N rates in physiological N-use efficiencies. Moreover, some critics underline that the estimation of the NUE does not provide insight as to which part of the assimilated plant-N originated from fertilizers, or from other sources such as the soil or irrigation water (Smith et al. 1989).

The isotope dilution method, on the other hand, assesses the fate of ^{15}N, be it from the fertilizer (or soil, or irrigation water) by determining the recovery rates of the ^{15}N fertilizer in the plant tissue, soil and groundwater (IAEA 2001, IAEA 2008). An additional advantage is that this method does not need control plots (Krupnik et al. 2004), and permits the direct calculation of fertilizer- and soil-N used by the crop (Harmsen and Moraghan 1988). A disadvantage is the necessity for advanced and expensive laboratory equipment, a larger number of samples and the need for extreme accuracy during the work and computations.

Previous research shows that both methods may give different results, and this has fuelled a controversial debate. Hauck and Bremner (1976) stated that the difference method results in higher recovery rates as compared to the isotope dilution method when initial soil Nmin content is low or N-fertilizer application rates are high. Harmsen (2003a) confirmed these findings. The discrepancy between the two methods was also high under conditions promoting losses of fertilizer-N during fertilizer applications (Harmsen and Moraghan 1988, Harmsen and Gabaret 2003). Wheat kernel data analysis of Krupnik et al. (2004) proved the opposite - with the ^{15}N technique higher recovery rates were obtained - postulating that the results of this method may overestimate these rates whereas the difference method may underestimate them. However, when the information from the kernels was complemented with data on the N recovery in straw, Hauck and Bremner's findings could be confirmed (Krupnik et al. 2004). In a test with both methods, Olson and Swallow (1984) reported a good agreement between the two methods, although the data variability of the difference method was much greater. Fritischi et al. (2004a) also found no statistically significant differences between the methods. Comparing several continents and cropping systems, the two methods showed both directions of over- or underestimation of N recoveries (Harmsen and Gabaret 2003, Krupnik et al. 2004). Krupnik et al. (2004) reviewed the advantages and disadvantages of both methods and concluded that both are prone to errors due to circumstances that promote the so-called apparent and real "added N interactions" as defined by Jenkinson et al. (1985).

Added nitrogen interactions

Jenkinson et al. (1985, p. 426) termed the added N interactions of a given N pool or compartment as "any increase (or decrease) in the quantity of soil-derived N in that compartment caused by the added N". By differentiating between real and *apparent* interactions independent of the plants present, Jenkinson et al. (1985) extended the until then existing term "priming effect" of Bingeman et al. (1953): The mechanism underlying the term priming effect or apparent added N interaction is mostly a biological process, where inorganic fertilizer-N is immobilized by microbial activity and instead soil-derived N is taken up by plants (Jenkinson et al. 1985, Kuzyakov et al. 2000). This pool substitution and mineralization-immobilization turnover of soil-N was found to be the major cause of low fertilizer use efficiencies and the dominating phenomenon in soils (Harmsen and Moraghan 1988, Harmsen 2003b, Harmsen and Gabaret 2003), which is the more pronounced, the more high-energy organic matter was available (Craswell 1978, Jansson and Persson 1982, Hart et al. 1986). Although, to a lesser extent, apparent added N interactions also can be caused directly by plant uptake, denitrification or isotope displacement (Jenkinson et al. 1985). The latter, i.e., process of isotopic diffusion where ^{15}N incorporated into soil microbial biomass will subsequently release residual unlabelled N to the inorganic pool, can however be neglected (Jenkinson et al. 1985, Kuzyakov et al. 2000).

Altogether, the potential of apparent added N interactions taking place in the soil makes it difficult to accurately quantify the ^{15}N uptake by plants (Wuest and Cassman 1992a), as the amount of ^{15}N fertilizer taken up by the crop may frequently be underestimated (Krupnik et al. 2004).

The real added N interactions will occur where N-fertilizer applications directly enhance the rooting development of the crop (Jenkinson et al. 1985, Harmsen and Moraghan 1988). As plants with well developed rooting systems are able to extract N from deeper soil layers (Olson and Swallow 1984), with the difference method, crop available N is underestimated and consequently N recovery rates are overestimated (Harmsen and Moraghan 1988, Krupnik et al. 2004).

Irrigated cotton systems

The fate of N in irrigated systems has been intensively studied. Efficiency in cotton production settings similar to those in Uzbekistan has been described in detail by researchers in Australia (e.g., Rochester et al. 1997), in the US (e.g., Fritschi et al. 2004a, Hutmacher et al. 2004), in Pakistan (e.g., Mahmood et al. 2000), and in China (e.g., Hou et al. 2007).

In Uzbekistan, research on N balances in cotton using the difference method or ^{15}N technique dates back to the end of the 1970s (Ibragimov 2007). In the “Recommendations on Fertilization in Kolkhozes and Sovkhozes in the Uzbek SSR” published in 1980, a fertilizer-N uptake by cotton of around 40 % is assumed (Ibragimov 2007). Depending on the N rate, application method and crop management, Masharipov (1990), Rashidov (1990), Turdialiyev (1990), Khidirnazarov (1990), Kariyev (1991) found 28-55 % of the fertilizer-N applied in the plants. Also, in most recent ^{15}N research conducted by Ibragimov (2005a, 2005b) using lysimeters, the rate of urea-N uptake by the cotton plant amounted to 33-44 %.

These recovery rates are similar to those in other regions. For Australian cotton, Rochester et al. (1997) reported plant-N recoveries to be less than 50 %, Constable and Rochester (1988) found 40 %, and Freney et al. (1993) and Rochester et al. (1993) recovered less than 30 % of the N fertilizer applied. A recent cotton report estimated the recovery rate at around 33 % (CRC 2007). Plant recovery rates of fertilizer-N in the US ranged from 32-36 % (Silvertooth et al. 2001a) and 19-38 % (Chua et al. 2003). However, in Pakistan and China, Mahmood et al. (2000) and Huo et al. (2007) observed higher N recoveries than in Australia or the US with 39 % and 45 % N recovery, respectively.

Microplot experiments of Khajiyev and Bairov (1992), conducted from 1978-79 in the Tashkent region, showed different recovery rates depending on fertilizer type, with NH_4-containing fertilizers performing better than NO_3-based ones. Urea-derived N in the cotton plant was found to be around 33 %, ammonium sulfate fertilizer recovery was 31 %, and the recovery of calcium nitrate fertilizer was 28 % (Ibragimov 2007).

The N-recovery rates in the soil under irrigated conditions, however, vary widely in the literature. Silvertooth et al. (2001a), for example, found recovery rates of up to 60 % in the soil in the US, mostly in the top 0-60 cm. In China, Hou et al. (2007) recovered 27-34 % in 0-50 cm, while only 19 % remained in the soil in Pakistan (Mahmood et al. 2000). In Uzbekistan, Khadjiyev (1998) reported recovery rates for different soil types: fertilizer-derived N on an irrigated meadow soil, which also prevails in Khorezm, was 37-44 %, on a soil typical of the Tashkent region it ranged from 28-34 %, and on a light Tashkent soil it was only 21-31 % (Ibragimov 2007). Similarly, Fritschi et al. (2004a) found higher ^{15}N-recovery rates on clay loam soils (49 %) than on sandy loam soils (43 %), especially with increasing N rates. The clay loams also showed a better N response than the sandy loam (Fritschi et al. 2004a). Furthermore, of the total N fertilizer remaining in the soil at crop maturity, less than 3 % were fixed in mineral-N form, and 17-27 % in (slowly available) organic-N form (Khadjiyev 1998). Australian researchers found similar rates of 25 % remaining in the soil as organic N (CRC 2007).

Unaccounted N losses of 8-51 % observed in the Tashkent region of Uzbekistan (Ibragimov 2007) correspond with N-fertilizer inefficiencies found in other regions, e.g., 42-43% (Freney et al. 1993, Mahmood et al. 2000), 25-50 % (Chua et al. 2003), where N is assumed to be lost from the system through denitrification and leaching.

For the region of Khorezm, there has been little research on efficiency in cotton or winter wheat using the ^{15}N technique. Therefore, it is difficult to judge the efficiency of the farmers' current fertilizer management and to approximate hazards to health and the environment, and to give targeted recommendations.

Irrigated winter wheat systems

Similar to cotton, the fate of N in winter wheat systems has also been widely investigated. Raun and Johnson (1999), for example, estimated the overall world average N-use efficiency of cereal kernels to be 33 % (+ 9 % in the straw as corrected by Krupnik et al. (2004)), suggesting high inefficiency in global cereal management. Generally, also for irrigated production systems as in Pakistan (Hamid and Ahmad 1993, Mahmood et al. 2001), India (e.g., Krupnik et al. 2004), Australia (e.g., Smith and Whitfield 1990, Fischer et al. 1993), Argentina (e.g., Melaj et al. 2003), the US (e.g., Bronson et al. 1991, Wuest and Cassman 1992a, Ottman and Pope 2000), and Canada (e.g. Carefoot and Janzen 1997), fertilizer-N use efficiency varies around these levels.

Australian authors found 40-56 % fertilizer-N in the plants (Smith and Whitfield 1990, Fischer et al. 1993). Recent ^{15}N-recovery rates in above-ground matter of winter wheat published for Pakistan were as high as 48 % (Mahmood et al. 2001). Earlier publications, however, reported lower efficiency of N fertilizer in Pakistani wheat of 39 % (Mahmood et al. 1998) and 28-33 % (Byerlee and Siddiq 1994). The mean recovery efficiency of fertilizer-N in irrigated wheat in India was also in the range of 33-45 % (Krupnik et al. 2004). Similarly, Carefoot and Janzen (1997) observed 30-45 % fertilizer-N in winter wheat in irrigated Canadian soils, which depended on the straw and tillage treatments and on the timing of N applications. The plant-N derived from fertilizer in Argentina varied highly from 18-58 % depending on the tillage management and fertilizer timing, with lowest rates for the non-tilled treatments (Melaj et al. 2003). The efficiency of different N sources was nearly identical (Vlek et al. 1981, IFA 2006).

In the study of Hamid and Ahmad (1993), increasing N-fertilizer rates increased plant-N derived from fertilizer in steps of 25 % (N-0), 30 % (N-60), and 34 % (N-120). However, Ottman and Pope (2000) observed statistically insignificant increases in N recovery with increasing N rates, e.g., from 42 to 48 % for sandy loam. In contrast, the amount of soil-derived N decreased when more N fertilizer was applied. In fact, more frequently, decreasing recovery rates have been observed with higher N application rates (Wuest and Cassman 1992b, Krupnik et al. 2004). It was postulated that the decreased recoveries observed for increased N applications were due to increased potential for losses (Krupnik et al. 2004). Rather than large N amounts, late dressings at anthesis (Zadoks-60, Feekes-10.51 (Zadoks et al. 1974)) were shown to affect recovery rates of ^{15}N in plants (Ottman and Pope 2000). Of the total ^{15}N fertilizer applied before seeding, only 41-49 % was recovered in the plant, while at anthesis, uptake efficiency was on average 64-68 % (Wuest and Cassman 1992a, Ottman and Pope 2000).

Of the ^{15}N applied, Mahmood et al. (1998) found around 28 % remaining in the soil after harvest; Ottman and Pope (2000) found on average 24 %, while Bronson et al. (1991) found around 20 %. In Australian soils, less than 20 % fertilizer-derived N were recovered (Smith and Whitfield 1990). As for wheat, the largest share of ^{15}N fertilizer applied was found in the organic soil pool, indicating substantial fertilizer immobilization (Bronson et al. 1991, Mahmood et al. 1998). Losses generally ranged from 20-40 % (Smith and Whitfield 1990, Fischer et al. 1993, Ottman and Pope 2000), and did not decrease with delayed N applications (Smith and Whitfield 1990). Most of the ^{15}N was lost when fertilizer was applied prior to planting and while the crop was still small (Smith et al. 1989). Losses occurred mainly in the form of volatilization, denitrification or leaching (section 2.3.1). Mahmood et al. (1998), however, warned that the losses based on the ^{15}N balance are often higher than the directly measured denitrification losses. They assumed that this was due to an overestimation of NH_3-volatilization combined with an underestimation of denitrification losses.

2.4 Modeling cotton yield and nitrogen dynamics

Computer-based simulation tools for agricultural production have been in use for a long time. Based on mathematical equations, they are designed to mirror the complex processes in crop growth and development in a simplified but straight-forward way. Therefore, models are frequently used as aids in interpreting experimental results and as agronomic research tools (Whisler et al. 1986), as crop system decision management tools (Boote et al. 1996), or even for policy analysis (Boote et al. 1996).

For assessing agricultural sustainability and evaluating effects of changes in soil and management or weather on crops, system-dynamic models have been proven to be a good approach (Boote et al. 1996, Boulanger and Bréchet 2005). The models quantify the biophysical processes of complex cropping systems over time using feed-back loops and stocks and flows. Amongst them are crop-soil models, which generally are mechanistic and comprehensive based on the understanding of plants, soil, weather, and management interactions such as phenological development, photosynthesis and growth, stress effects (water, N, salt), and root water uptake (Whisler et al. 1986). For simulation runs, site-specific information about weather, soil chemical and physical properties, and initial soil status data give the local adjustment (Whisler et al. 1986).

Using the model as a research tool, crop responses to a particular factor or process information can be derived (Boote et al. 1996) that could not have been measured in the field or designed in field experiments. Crop-soil models also support the analysis of current or optimized crop management, examine the crop performance in a specific environment (Boote et al. 1996) or help to determine the optimum efficiency of irrigation and other agronomic practices (e.g., Pala et al. 1996, Clouse 2006). In this respect, models have become indispensable tools in quantifying the gap between potential and actual yields and forecasting changes as well as calculating leaching losses of chemicals and nitrate (Boote et al. 1996).

However, the models vary in their precision and data input requirements. Examples of single-crop models for cotton growth management include the model GOSSYM (Whisler et al. 1986, Wanjura and Barker 1988, Reddy and Baker 1990, Watkins et al. 1998) or its derivatives, COTONS (Jallas et al. 2000) and Cotton2K (Marani 2004, Clouse 2006, Haim et al. 2008). A research emphasis has been to integrate several crop sequences for applying management-oriented models also to multiple cropping systems (Stockle et al. 1994). In this respect, several scientifically acknowledged agronomic decision and planning support softwares are available, amongst which the following are the most frequently used: the Decision Support System for Agrotechnology Transfer (DSSAT) (Thornton and Hoogenboom 1994, Jones et al. 2003), the Agricultural Production Systems Simulator (APSIM) (McCown et al. 1996, Wang et al. 2002, Keating et al. 2003), the Root Zone Water Quality Model (RZWQM) (Hanson et al. 1998, Hanson et al. 1999), the ecosystem simulation model (ecosys) (Grant et al. 1993, Grant 1995, Grant et al. 2001, Grant et al. 2006), and the Cropping Systems Simulation Model (CropSyst) (Stockle et al. 1994, Stockle et al. 2003).

2.4.1 CropSyst

All of the above models have been applied in various systems. Also, CropSyst has already been tested for various crops, systems and environments including wheat-fallow systems in the US (Pannkuk et al. 1998), durum wheat varieties in Mediterranean Syria (Pala et al. 1996), several rice varieties in Italy (Confalonieri and Bocchi 2005, Confalonieri et al. 2006), rotations including barley, maize, and soybean or durum wheat, sunflower and sorghum in Italy (Donatelli et al. 1997), and alfalfa (Confalonieri and Bechini 2004), 3-year spring wheat rotation in China (Wang et al. 2006), various rotations in the semi-arid Murray-Darling Basin in Australia (Díaz-Ambrona et al. 2005), and conservation agriculture rotations in Mexico (Sommer et al. 2007).

CropSyst is quite popular because amongst the integrated models it is freeware and the one with the least requirements for inputs while providing a sound functional balance (Confalonieri and Bechini 2004). Furthermore, for the Khorezm region with changing groundwater tables and soil salinity hazards, CropSyst seemed the most appropriate software, as it can simulate crop yield and detailed N and SOM dynamics applying algorithms used in the CENTURY model (Parton et al. 1987, Parton and Rasmussen 1994) while considering fluctuating shallow groundwater tables and salinity stress (Ferrer-Alegre and Stockle 1999, Stockle et al. 2003).

CropSyst is a multiyear, daily time step model comprising several annual herbaceous crops, which is designed to simulate crop growth and yield responses to daily changes in the environment and agronomic management such as soil conditions, salinity levels, irrigation, N fertilization, tillage or residues (Stockle et al. 2003). It also simulates water and N budgets, i.e., leaching or denitrification losses, plant biomass production, root growth, residue accumulation and decomposition, and potential erosion (Stockle et al. 1994, Stockle and Nelson 2000, Stockle et al. 2003).

In addition, although no cropping routine for cotton growth has been implemented so far, the generic routine in CropSyst allows adaptation to any new annual herbaceous plants (Sommer et al. 2008b). Given that it calculates water transport for each soil node using a finite difference solution of Richards' equation (Stockle et al. 1997), results from Forkutsa (2006) and Forkutsa et al. (2009a) could be integrated in the parameterization.

The links between the module components for water budget, N budget and crop growth and phenology are numerous (Stockle et al. 1994) (Figure 2.12). The water budget accounts for precipitation, irrigation, soil evaporation, canopy and residue interception and transpiration, runoff, surface storage and ponding, infiltration and deep percolation (Stockle et al. 1994, Stockle et al. 2003). In the modeling process, daily crop growth and development are limited by light, temperature, water and N (Pala et al. 1996, Stockle et al. 2003). Therefore, crop growth is determined by potential transpiration, transpiration use efficiency, radiation use efficiency, temperature, water and N supply and vapor pressure deficit (Sadras 2002, Stockle et al. 2003). Model details for the water budget and crop growth and development are described elsewhere (e.g., Stockle et al. 1997, Jara and Stockle 1999, Stockle and Nelson 2000, Sadras 2002, Fuentes et al. 2003, Stockle et al. 2003, Bechini et al. 2006).

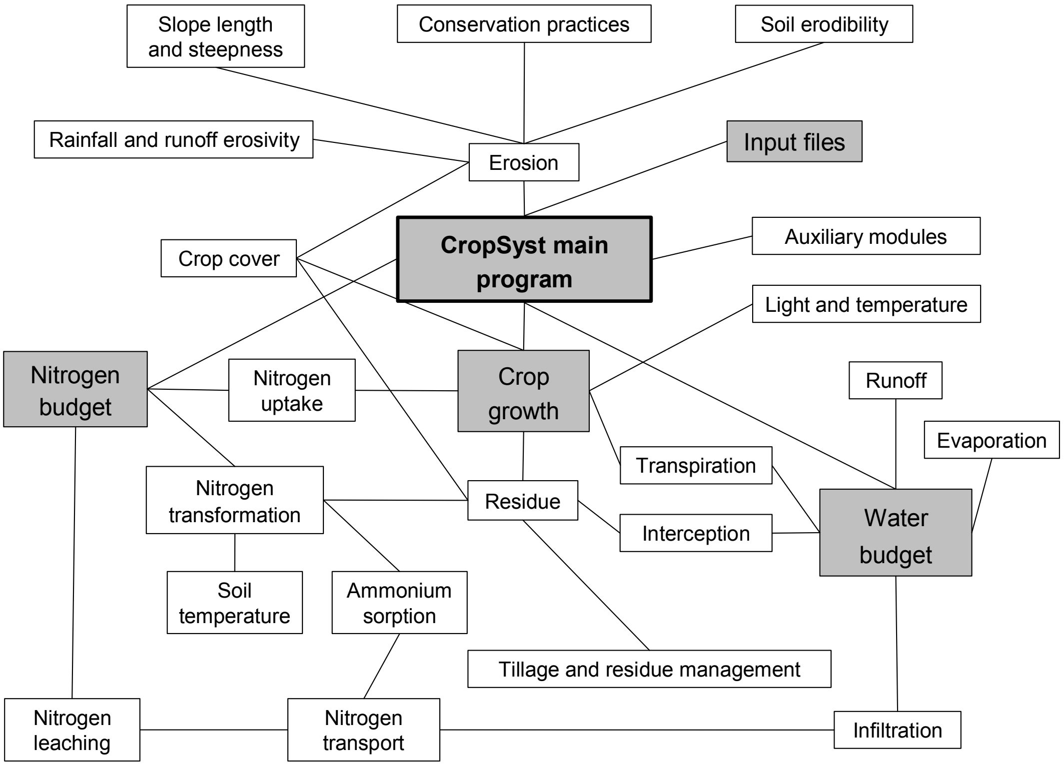

Figure 2.12 Flow diagram of CropSyst (Stockle et al. 1994)

Crop nitrogen uptake

CropSyst has been used to assess N balances (e.g., Pala et al. 1996, Stockle and Debaeke 1997, Peralta and Stockle 2001, Sadras 2002, Fuentes et al. 2003). Included in the balance are N transformations (i.e., net mineralization from organic matter and crop residues), losses (i.e., leaching, volatilization, denitrification), NH_4-N sorption, symbiotic N_2 fixation, and crop demand and acquisition (Stockle et al. 1994, Stockle et al. 2003). The model further differentiates between NO_3-N and NH_4-N in the N budget calculations, and N movement in the soil is driven by the interactions between the water and N components (Stockle et al. 2003). The crop quality, however, is not considered (Stockle and Debaeke 1997).

The N availability for a given crop is determined by soil N status, moisture and root distribution throughout the growing season (Hansen et al. 1991, Stockle et al. 1994, Stockle and Debaeke 1997). Although the daily uptake rate for cotton is estimated to be around 4.3 kg N ha^{-1} day^{-1} (Boquet and Breitenbeck 2000, CRC 2007), crop N uptake is not constant during the growing season (Stockle and Debaeke 1997, Boquet and Breitenbeck 2000, Ooesterom et al. 2001). In cotton, for example, the N demand is highest during the period of fastest growth; i.e., from flowering to boll filling (Boquet and Breitenbeck 2000, CRC 2007). During this time, uptake is also fast. As the crop matures, the uptake rate decreases (Boquet and Breitenbeck 2000, CRC 2007).

Thus, N requirements for a given crop are driven by the minimum N demand and the maximum potential uptake (Stockle et al. 2003). In CropSyst, as in APSIM or DSSAT, until flowering the concept of growth dilution is applied, where the maximum, critical, and minimum plant N concentration are in relation to the above-ground biomass accumulation (Stockle and Debaeke 1997, Ooesterom et al. 2001). Plant growth is not N limited for concentrations above the critical level; below this growth will be reduced. Maximum or luxury uptake occurs for concentrations higher than the critical N content, and at the minimum concentration growth is stopped (Stockle and Debaeke 1997, Ooesterom et al. 2001).

Beyond flowering, all concentrations are linearly decreased to match the observed/specified N concentrations at crop maturity (Stockle and Debaeke 1997). Stockle and Debaeke (1997) found this approach to be more satisfactory than, for example, relating N uptake to growing degree days as in the Danish N-simulation model DAISY (Hansen et al. 1991).

The plant N concentration (%) in CropSyst is, therefore, determined by equation (2.1):

$$N = a \times B^{-b} \tag{2.1}$$

where a and b are fitted parameters, and B is the accumulated biomass (kg ha^{-1}) (Stockle and Debaeke 1997). The maximum N plant uptake rate per unit of root length during early growth is a required input and allows for crop- or cultivar-specific calibration (Stockle and Debaeke 1997, Stockle and Nelson 2000).

The daily potential uptake N_{up} (kg N ha^{-1} day^{-1}) directly governs crop growth and plant N demand. Knowing the Nmin concentration in the soil solution, it is calculated for each soil layer. The potential uptake follows equation (2.2):

$$N_{up} = N_{up-max} \times L_R N_{avail} \times PAW^2 \tag{2.2}$$

where N_{up-max} is maximum uptake per unit root length (kg N day^{-1} m^{-1}), L_R the root length (m ha^{-1}), and PAW the plant available water factor (dimensionless, 0-1) (Stockle et al. 1994, Donatelli and Stockle 1999). N_{avail} is the dimensionless N availability factor (0-1), a function of N in the bulk soil (Stockle et al. 1994, Donatelli and Stockle 1999).

The actual N uptake (N_{act}) is then a function of potential uptake, N_{up}, and the actual crop demand, N_d (kg ha^{-1}). N_{act} is driven by the maximum crop N demand and the potential plant N uptake, i.e., the sum of deficiency demand and N demand for new growth (equation (2.3)) (Stockle et al. 1994):

$$N_d = \left(N_{p-max} - N_p\right) \times B_c + N_{p-max} \times B_t \tag{2.3}$$

where N_{p-max} is the maximum plant N concentration or demand (kg N kg^{-1} biomass) and N_p is the current N concentration before new growth (kg ha^{-1}) (Stockle et al. 1994, Donatelli and Stockle 1999). B_c is the current cumulative biomass consisting of top and root biomass (kg ha^{-1}), while B_t is the potential biomass to be produced today comprising new top and root growth (kg ha^{-1}) (Stockle et al. 1994, Donatelli and Stockle 1999).

N-limited growth (B_N) is simulated by a linear decrease in response to N stress (equation (2.4)):

$$B_N = B \times \left\{1 - \frac{N_{p-crit} - N_p}{N_{p-crit} - N_{p-min}}\right\} \tag{2.4}$$

where B is the growth limited by radiation or water, $N_{p\text{-}crit}$ is the critical plant N concentration, and $N_{p\text{-}min}$ is the minimum plant N concentration (Donatelli and Stockle 1999).

Soil nitrogen transformation

CropSyst is designed to simulate microbial N transformation, i.e., mineralization, nitrification and denitrification, for the top 30-50 cm of the soil profile based on first-order kinetics (equation (2.5)) (Stockle et al. 1994, Donatelli and Stockle 1999):

$$\mathrm{N}\,\Delta\mathrm{t} = \mathrm{N}_0 \times (1 - e[-K \times \Delta t]) \tag{2.5}$$

where NΔt is the transformed fraction of N in time t (kg m^{-2} t^{-1}), and N_0 is the initially available N (kg m^{-2} t^{-1}). In CropSyst, the rate constant in CropSyst is a fixed value (Stockle and Nelson 2000). However, as the transformations are temperature and moisture dependent, changes in temperature and soil water capacity in the rate constant K (t^{-1}) are accounted for (Stockle et al. 1994, Stockle and Nelson 2000). CropSyst furthermore provides multipliers (0-2) that change the rate constant to adjust it to the natural variation in the specific environment, i.e., a multiplier of 2 will increase the rate constant 2 times as coded in CropSyst (Stockle and Nelson 2000). However, changing the nitrification rate has no direct effect on the N balance (Donatelli et al. 1997). Losses via NH_4-volatilization are estimated based on gas concentration gradients for surface-broadcast fertilizer applications (Donatelli et al. 1997, Donatelli and Stockle 1999).

Organic matter was considered as single mineralizing organic matter pool fed by residue decomposition (Stockle and Nelson 2000), as the routine with different pools (labile, meta-stabile and passive) had not been implemented at the time of this study. The amount of organic matter N mineralized is calculated by equation (2.6):

$$\mathrm{Min} = \mathrm{Min}_{\mathrm{pot}} \times (1 - \mathrm{MF} \times \mathrm{e}(-\mathrm{M}_{\mathrm{rate}} \times \Delta\mathrm{t})) \tag{2.6}$$

where Min (kg ha^{-1}) is the amount of organic N mineralized to NH_4 in time t (day), and Min_{pot} (kg ha^{-1}) is the potential amount of organic N available for mineralization (Donatelli and Stockle 1999). MF is a soil moisture function dependent on the fraction of pore space containing water (equation (2.7)).

$$\mathrm{MF} = \begin{cases} 1.11 \times \mathrm{DS} \;\; \text{if DS} \le 0.9 \\ 10.0 - 10.0 \times \mathrm{DS} \;\; \text{if DS} \ge 0.9 \end{cases} \tag{2.7}$$

with DS being the degree of saturation (0-1) obtained by equation (2.8):

$$\mathrm{DS} = \frac{\mathrm{WS}}{1 - \frac{\mathrm{BD}}{2.56}} \tag{2.8}$$

The M_{rate} (day^{-1}) is the mineralization rate constant computed according to equation (2.9):

$$M_{rate} = \frac{1}{7} \times e\left[17.753 - \frac{6350.6}{T_s + 273}\right] \tag{2.9}$$

where T_s (ºC) is the soil temperature (Donatelli and Stockle 1999).

Nitrogen leaching is related to water movement in the soil (concentration of N in the water), which is determined by the amount of soil water in each soil layer and free movable Nmin in the profile and the soil CEC (Stockle et al. 1994, Donatelli and Stockle 1999). Simulations of infiltration and water redistribution in the profile are done via the cascade approach (Sadras 2002). NO_3-N is not retained by the soil matrix, and NH_4-N movement is dependent on the absorption capacity of the solid soil matrix as described by Langmuir (equation (2.10)) (Stockle et al. 1994):

$$X - NH_4 = \frac{k \times q \times [NH_4]}{1 + k \times [NH_4]} \tag{2.10}$$

where X-NH_4 is the amount of NH_4-N absorbed by the exchange sites (kg kg^{-1}), [NH_4] is the concentration of NH_4 (g l^{-1}) in the soil solution, and k and q are constants (kg kg^{-1}). Effects of diffusion and hydrodynamic dispersion are not considered (Stockle et al. 1994). The total soil NH_4-N is then calculated by using soil bulk density (BD, kg m^{-3}) and the gravimetric soil water content ω (kg kg^{-1}) (equation (2.11)) (Donatelli and Stockle 1999):

$$\text{Total soil } NH_4 = [X - NH_4 + \omega \times NH_4] \times BD \tag{2.11}$$

Although CropSyst is not a new model, the performance of the nitrogen routine has not been thoroughly tested yet for irrigated systems on field scale.

3 STUDY REGION

3.1 Geographical location

This research work was carried out within the framework of the German-Uzbek ZEF/UNESCO project (ZEF 2003) in 2004-2006 in the Khorezm region of Uzbekistan. The Khorezm region (60.05°-61.39°N latitude, 41.13°-42.02°E longitude) covers about 6,200 km² and is situated in the northwest of Uzbekistan on the lower left and right bank of the Amu-Darya river; the largest part of the region is on the left bank (Figure 4.1). It is part of the northern Turan lowlands of Central Asia and surrounded by deserts: to the north and east by the Kyzylkum desert, while in the south it borders on the Karakum desert (Yagodin and Betts 2006). The topography of the region is characterized by flat slopes (Djumaniyazov 2006) with a slight inclination from north-west towards south-east (Mukhammadiev 1982) and an elevation of 90-138 m above sea level (Katz 1976).

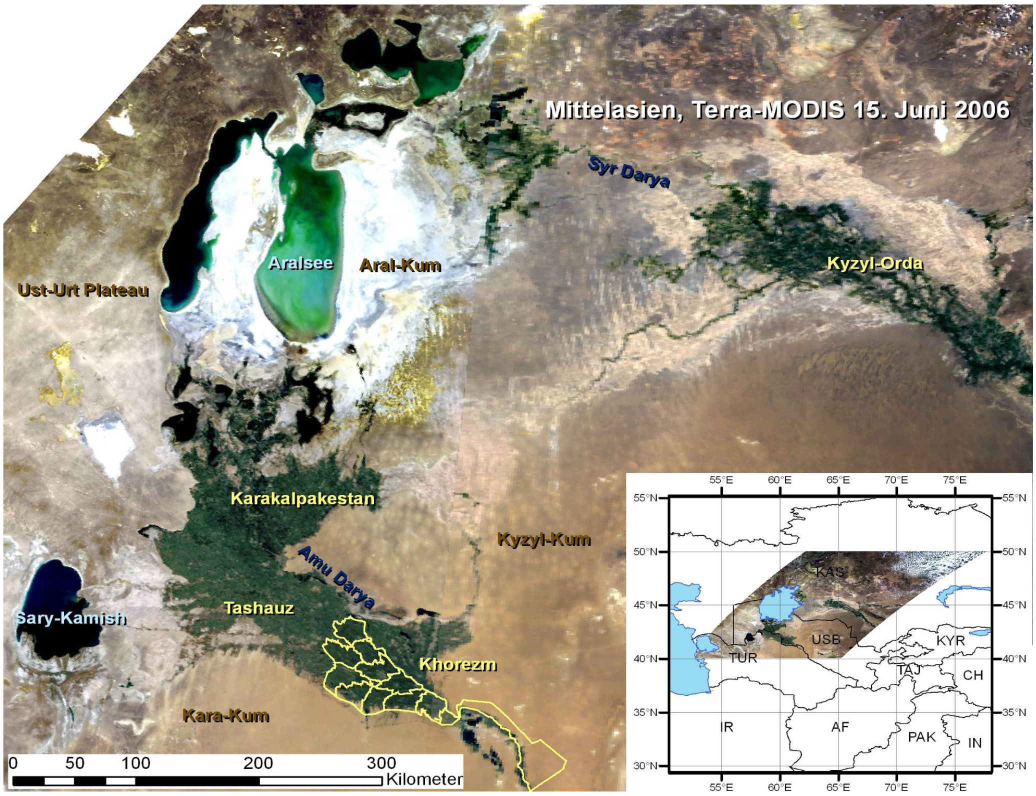

Figure 3.1 Terra-MODIS satellite image of the Aral Sea region, and the project region (outlined in yellow), June 15, 2006 (Conrad, personal communications)

Administratively, the region borders on the Amu Darya district of the autonomous Republic of Karakalpakstan in the north and east, while in the west and south the Dashauz region of the Republic of Turkmenistan is located. With a total population of 1.5 million in 2005 (OblStat 2006), it is administratively subdivided into 10 districts, i.e., Bogot, Gurlen, Khazarasp, Khiva, Khonka, Kushkupir, Pitnjak, Shavot, Urgench, Yangibozor, and Yangiaryk.

Cotton production in Uzbekistan is in the extra-arid (desert) and arid (semi-arid) climatic zones (Umarov 1975). The cotton belt of Uzbekistan is located in flat and mountainous areas – Chimbay and Termez are north and south borders.

3.2 Climate

According to Köppen-Geiger climate classification, the Khorezm region has a typical sharply continental, cold arid desert climate (BWk) (Kottek et al. 2006) with long hot summers and cold dry winters. The meteorological station in Urgench reported a mean annual temperature of 13.4°C with a minimum in February (-9°C) and a maximum in June/July (40°C) for the last 30 years (Glavgidromet 2003). Mean annual rainfall during the same period amounted to 90 mm (Figure 3.2). Maximum precipitation usually occurs in April and November (Glavgidromet 2003, UNEP 2005, Forkutsa 2006).

The climatic conditions favor the cultivation of annual, warm-season crops such as cotton, since this plant grows in frost-free regions with high temperatures, high solar radiation and little precipitation (Chaudhry and Guitchonouts 2003). The average cotton growing period in the Khorezm region spans from April to October. However, the desiccation of the Aral Sea, once the natural meteorological buffer against the cold Siberian winds during winter time (Chub 2000), has caused the frost period to stretch longer into spring and start earlier in autumn, thus decreasing the number of frost-free days from 220 to 170 (Vinogradov and Langford 2001, Ibragimov 2007). Cotton sowing dates are delayed by 1-2 weeks, causing frost-induced damage (seed quality reduction) at harvest time (Chaudhry and Guitchonouts 2003). The temperatures during winter wheat harvest in mid June regularly exceed the 20-year average air temperature (1980-2000) of 27.1°C (GIS-Lab, ZEF). The maximum temperatures for the years of this study were 40.2°C (18.06.04), 43.0°C (15.06.2005) and 42.0°C (13.06.06) (own climate data recordings, see section 4.4.1).

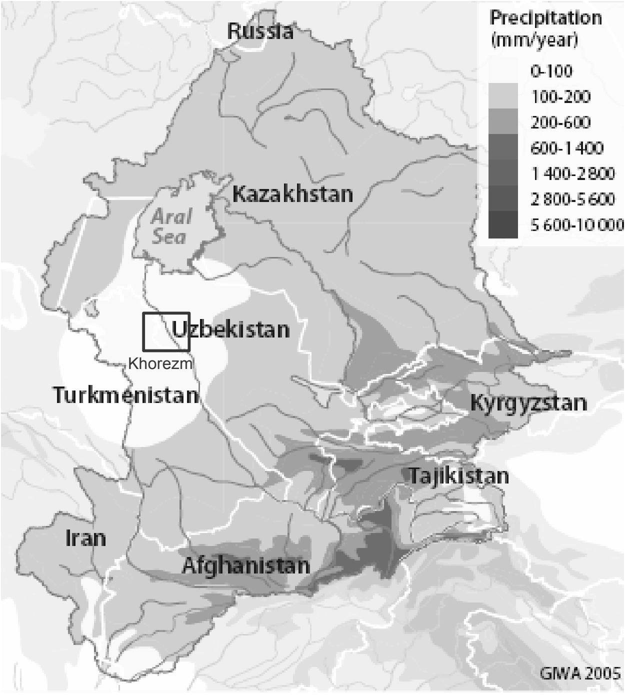

Figure 3.2 Annual precipitation in the Aral Sea region (UNEP 2005)

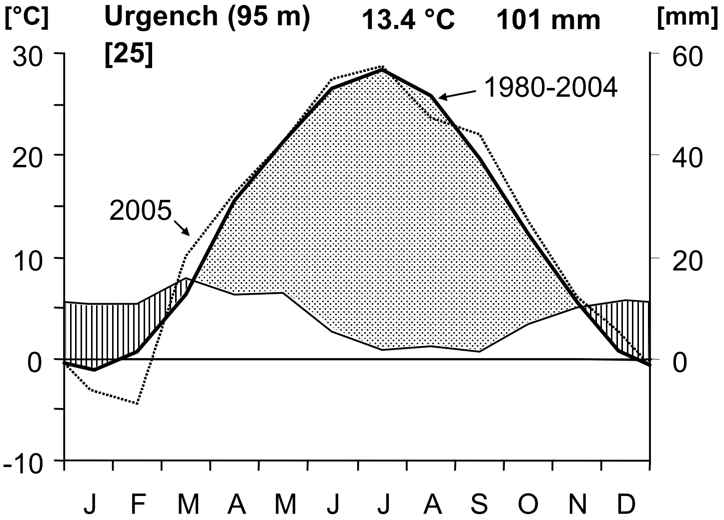

Figure 3.3 Climate diagram for Urgench, Khorezm, Uzbekistan, according to Walter and Leith (1967)

The Walter-Leith diagram (Walter and Leith 1967) shows high temperatures and radiation as well as low relative humidity and an evapotranspiration of 1400-

1600 mm per year that exceeds precipitation during almost every month of the year (Figure 3.3).

3.3 Groundwater, irrigation water and salinity

Already in 1940, due to the extension of the irrigated area, a systematic increase in the groundwater level was reported for the lower reaches of the Amu-Darya river (Djumaniyazov 2006). Despite the step-wise construction of the drainage network that was more or less completed in 1975, the area with groundwater tables of less than 1.0 m increased (Figure 3.4) due to rising irrigation amounts, thus influencing the salt dynamics (Jabborov 2005). Jabborov reported that only in the early 1980s when irrigation amounts were reduced, did the groundwater tables also decrease.

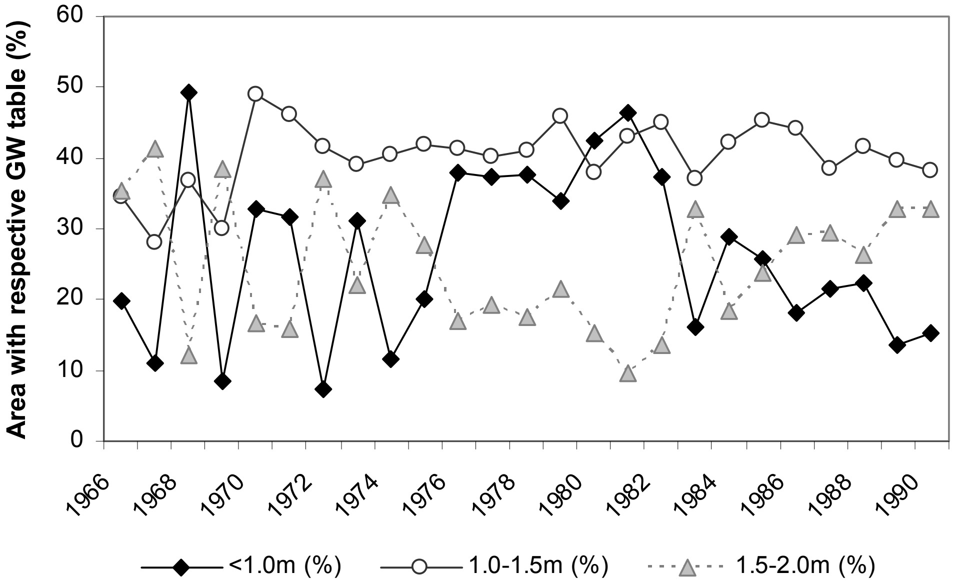

Figure 3.4 Dynamics of irrigated areas (%) for three groundwater depths (GW; < 1.0 m; 1.0-1.5 m; 1.5-2.0 m) in Khorezm during the period 1966-1990, adapted after (Jabborov 2005).

Lateral groundwater flow is slow with only 19-26 mm per year (Katz 1976). Fast movement of the groundwater is experienced in the riverbeds only. Groundwater dynamics for the Khorezm region throughout the year are described in detail by Ibragimov (2004). The shallowest groundwater table of around 1.25 m was observed during the vegetation period (July). After cotton harvest and thus closure of the irrigation canals (September to October), the groundwater table was the deepest (average 1.82 m). During the winter period, the groundwater level usually drops below 2 m (Katz 1976). The critical groundwater depth for cotton growth is around 1.5 m below the ground surface (Rakhimbaev in Shmidt 1985, Riskieva 1989, Ibragimov 2007), as under the present cultivation practices, 25-49 % of the cotton water demand is taken from shallow groundwater (Forkutsa 2006).

Groundwater salinity in the region ranges between 1.0 and 3.0 g l^{-1} (Ibragimov 2004, Forkutsa 2006), which is considered low, and tolerable for cotton growth (FAO 1979). Only at times of elevated evapotranspiration does the upward movement of saline groundwater and thus salts thus lead to topsoil salinization (Abdullaev 2003, Ibragimov 2004), a process which has affected more than 60 % of the irrigated lands in the region (Letunov 1957, Ibragimov 2004). A survey show that chloride (Cl) ions are the dominating form of salinity in the lower reaches of the Amu-Darya river (WARMAP and EC-IFAS 1998). The survey findings indicate that the chloride-sulfate type of salinity is common, with one third chloride and one third sulfate ions in the soil solution. Soil saturated electrical conductivity (ECe) measured in spring 1996-1998 ranged from 0.7 to 8.8 dS m^{-1} with an average of 3.4 dS m^{-1} (WARMAP and EC-IFAS 1998).

To reduce the salinity level in the topsoil, the fields are generally leached three times with water from the Amu-Darya river prior to sowing (Forkutsa 2006). Leaching prior to cotton cultivation takes place between March and April, whereas for winter wheat, the fields are leached in September. The leaching includes a complete flooding of the bare soil and drying for at least one week. During the vegetation period, the field crops in the Khorezm region are irrigated several times. The water is supplied via a sophisticated system of extended irrigation channels, while the outflow leaves the fields via drains (Conrad 2006). The irrigation and drainage network dates back to the years 1938-1940, constructed during the Uzbek leadership of Usman Yusupov (Teichmann 2006) and the early Krushchov era (1950s) (Wegren 1989). The salinity of the irrigation water during the last decade was below 1 g l^{-1} (Ibragimov 2004), which is still tolerable for cotton and wheat cultivation (FAO 1979).

3.4 Soils

The Khorezmian soils are of alluvial origin. According to Russian and Uzbek literature, the main soil type found in the region is the so-called irrigated alluvial meadow soil covering about 60 % of the area (Rasulov 1989, Djumaniyazov 2006). Other soils such as boggy-meadow (covering 16 % of the area), takyr-meadow (15 %), boggy (5 %), grey-brown (2 %) and takyr soils are also common in the Khorezm region (Sabirov 1980, Rasulov 1989). The FAO classification (Figure 4.1) (FAO 2003), in comparison, gives a rather rough description. As it does not capture the detailed characteristics of the Uzbek soil classification, it will not further be used in this study.

Along the delta of Amu Darya river and on the first river terrace, mainly hydromorphic meadow soils are found due to continuous shallow groundwater (1-3 m) (Riskieva 1989). Floodplain alluvial soils were formed in the floodplains, terraces and the present delta of the river, where meadow soil development was constrained by periodical flooding followed by rapid drainage. After the cessation of the floodings, the so-called virgin meadow alluvial soils formed, which are rich in carbonate rocks (Riskieva 1989). Newly irrigated meadow alluvial soils, mostly found in North Karakalpakstan and the present delta of Amu Darya, differ from the virgin meadow alluvial soil by a plow layer, i.e., the agro-irrigative horizon, covering the alluvium (Riskieva 1989). Those soils with a long history of irrigated agriculture are called old irrigated meadow alluvial soils as they lack turf and sub-turf horizons. They have a thick surface layer of monotonic color, i.e., agro-irrigative horizon (sediment), according to which the soil is separated into three groups depending on the thickness: thin – < 30 cm; thick – 30-70 cm; very thick – > 70 cm. The stratified alluvium is generally not visible in the soil profile (Riskieva 1989).

In the district of Yangibozor, around 80 % of the soils consist of light and medium loamy textures, in Urgench, Khonka and Bogot district ca. 70 %, and in Kushkupir district ca. 60 % (Rizayev 2004). In the southern districts Khiva, Khazarasp and Yangiaryk, soils are composed of finer particle sizes, with only around 40 % light and medium loams (Rizayev 2004) (see also section 2.3.1).

4 MATERIALS AND METHODS

4.1 Statistical cotton yield and fertilizer data

Official statistical records for cotton yield trends and fertilizer use in cotton production for Khorezm (OblStat 2004, OblStat 2005, OblStat 2006) were compiled from 1950 to 2003 for fertilizer use and from 1932 to 2005 for cotton yields. Additionally, fertilizer use in cotton production on the national level was collected 1935-2006 (Djumaniyazov 2004, FAOSTAT 2008).

4.2 Experimental setup

4.2.1 Minus-1 and nitrogen-fertilizer response experiments

The most limiting nutrients for cotton and wheat grown in the Khorezm region were examined by implementing so-called minus-1 experiments in the years 2004 and 2005. For the macro minerals N, P and K four different treatments were set up (Table 4.4, Table 4.5). In addition, N-fertilizer response experiments were established in 2004 and 2005 (Table 4.6, Table 4.7) to determine the optimal crop growth and yield. Both sets of experiments were planned as joint farmer-researcher-managed experiments. The researcher did not interfere during the management except for providing the fertilizer and the fertilization scheme.

Site selection for cotton experiments

The sites for the minus-1 experiments were selected to cover the three prevailing soil textures of irrigated alluvial meadow soils in the region: light, medium and heavy loam (Rizayev 2004). With the help of the German Agro Action (GAA)[7], 11 collaborative farmers in 7 districts near Urgench city were identified. During the growth period, four sites had to be excluded from the study for several reasons. The particular farmers either had forgotten to exclude the experimental site during fertilizer application or fertilized all plots, or they did not feel comfortable having nutrient-deficient yellow plants standing close to the road, or they used other fertilizers than provided. Therefore, in the

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[7] German Agro Action (Deutsche Welthungerhilfe (DWHH)) has been working in this region for a long time and has conducted extensive experiments with farmers. The farmers in this study were selected from their list of farmers.

following analyses, only data from the remaining 7 sites were used (Table 4.1, Figure 4.1). Two N-fertilizer response experiments were established in the Urgench district, one on a medium loamy soil and the other on a light loamy soil (Table 4.1).

Table 4.1 Cotton minus-1 and response experiments in 2004. LL: light loamy soil; ML: medium loamy soil; HL: heavy loamy soil.

Experiment	**Location**	**Shirkat**[8]	**Farmer**	**Soil texture**	**Name/Code**
Minus-1	Khonka	Sharaf Rashidov	Kurramboy Rajabov	LL	Khonka
Minus-1	Kushkupir	Nezagas	Farhod Rakhimov	LL	Kushkupir-LL
Minus-1	Kushkupir	Nezagas	Farhod Rakhimov	HL	Kushkupir-HL
Minus-1	Shavot	Sohibkor	Bekhtemir Boltaev	LL	Shavot
Minus-1	Urgench	Amir Temur	Maksud Jumaniyasov	ML	Urgench
Minus-1	Yangibozor	Modanyiat	Haylulla Rakhimboyev	HL	Yangibozor
Minus-1	Yangiaryk	Khorezm	Shavkat Abdullaev	HL	Yangiaryk
Response	Urgench	Amir Temur	Ruzemboy Yuldashev	ML	Response-ML
Response	Urgench	Amir Temur	Ruzemboy Yuldashev	LL	Response-LL

Site selection for winter wheat experiments

The sites for the wheat minus-1 experiments were implemented at four farms. Unfortunately, at wheat harvest, the site in the Kushkupir district had to be excluded from the study as the farmer harvested the wheat early (still green) in order to plant rice in time. Analogous to the cotton experiments, the wheat response experiments were established in a factorial design in the Urgench district. The same farmers were involved as during the cotton experiments (Table 4.2, Figure 4.1).

Table 4.2 Winter wheat minus-1 and response experiments in 2004/05. LL: light loamy soil; ML: medium loamy soil; HL: heavy loamy soil.

Experiment	**Location**	**Shirkat**	**Farmer**	**Soil texture**	**Name/Code**
Minus-1	Urgench	Amir Temur	Maksud Jumaniyasov	ML	Urgench-ML
Minus-1	Urgench	Amir Temur	Maksud Jumaniyasov	LL	Urgench-LL
Minus-1	Yangibozor	Modanyiat	Haylulla Rakhimboyev	HL	Yangibozor
Response	Urgench	Amir Temur	Maksud Jumanyasov	ML	Response-ML
Response	Urgench	Amir Temur	Maksud Jumanyasov	LL	Response-LL

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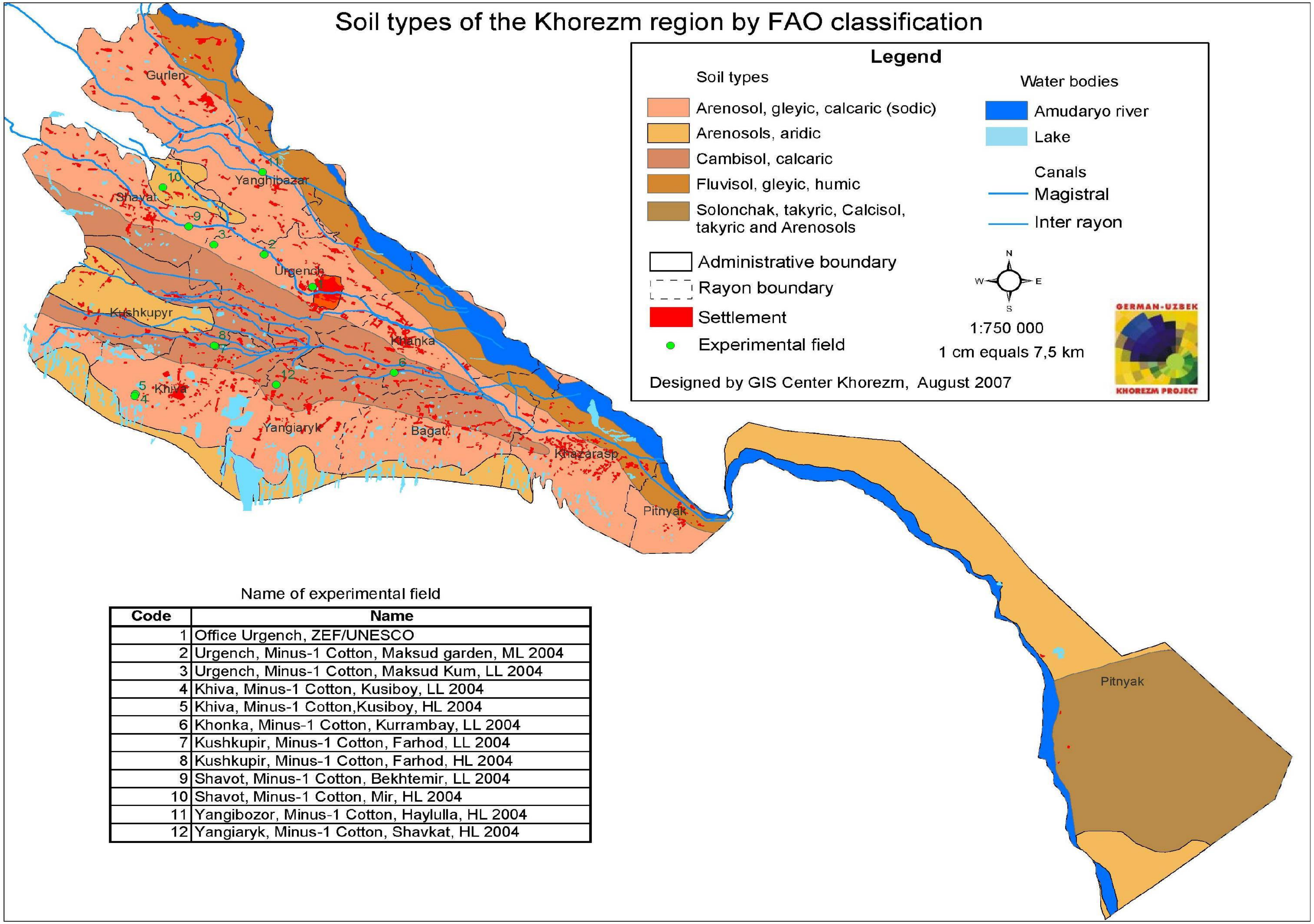
[8] Joint-stock companies (shirkats), which had not completely been dissolved in 2004 (see section 2.1.3).



Name of experimental field

Code	Name
1	Office Urgench, ZEF/UNESCO
2	Urgench, Minus-1 Cotton, Maksud garden, ML 2004
3	Urgench, Minus-1 Cotton, Maksud Kum, LL 2004
4	Khiva, Minus-1 Cotton, Kusiboy, LL 2004
5	Khiva, Minus-1 Cotton,Kusiboy, HL 2004
6	Khonka, Minus-1 Cotton, Kurrambay, LL 2004
7	Kushkupir, Minus-1 Cotton, Farhod, LL 2004
8	Kushkupir, Minus-1 Cotton, Farhod, HL 2004
9	Shavot, Minus-1 Cotton, Bekhtemir, LL 2004
10	Shavot, Minus-1 Cotton, Mir, HL 2004
11	Yangibozor, Minus-1 Cotton, Haylulla, HL 2004
12	Yangiaryk, Minus-1 Cotton, Shavkat, HL 2004

Figure 4.1 Spatial distribution of the cotton minus-1 experiments in the Khorezm region. Sites in brackets had to be excluded during the growing period. Soil types in the Khorezm region according to FAO classification (GIS-Lab, ZEF)

Fertilizers and treatments

For cotton and wheat, the official fertilizer recommendations of the Cotton Research Institute (CRI) and the Wheat Research Institute (WRI) were followed (see section 2.2.5). Single compound fertilizers were applied as ammonium nitrate (AN), single super phosphate (SSP), and potassium chloride (KCl) (Table 4.3).

Table 4.3 Nutrient content of applied fertilizers.

Fertilizer type	**N**	**P**	**K**
	%	%	%
Diammonium phosphate (DAP)	18	46	
Monoammonium phosphate (AP)	11	46	
Urea [$CO(NH_2)_2$]	46		
Ammonium nitrate (AN)	34		
Single superphosphate (SSP)		16	
Potassium chloride (KCl)			58

For the cotton and wheat minus-1 experiments, N, P and K fertilizers were combined in four treatments (“-N”, “-P”, “-K” and “NPK”) (Table 4.4, Table 4.5). For the response experiments, the application levels of N were varied in equal steps (Table 4.6, Table 4.7). Recommended P and K rates were equally applied to each treatment.

Total doses of P (single superphosphate) and K (potassium chloride) were applied before sowing along with the first dose of N (ammonium nitrate). The remaining splits of N (ammonium nitrate) were applied during the season. Nitrogen was applied in three splits for both crops:

Cotton: 30 % before seeding, 35 % at budding and 35 % at flowering-fruiting stage (square formation; around 104 days after sowing (DAS)).

Wheat: 20 % before seeding, 40 % at tillering and 40 % at booting stage.

Following fertilizer application, the soil was chiseled and cotton was seeded. During the vegetation season fertilizers were applied manually, and each application was directly followed by irrigation.

Table 4.4 Cotton fertilization scheme for minus-1 experiment

Treatment	N	P_2O_5	K_2O
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
-N	0	140	100
-P	200	0	
-K		140	0
NPK			100

Table 4.5 Winter wheat fertilization scheme for minus-1 experiment

Treatment	N	P_2O_5	K_2O
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
-N	0	100	70
-P	180	0	
-K		100	0
NPK			70

Table 4.6 Cotton fertilization scheme for response experiment

Treatment	N	P_2O_5	K_2O
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
N-0	0	175	125
N-80	80		
N-120	120		
N-160	160		
N-200	200		
N-250	250		

Table 4.7 Winter wheat fertilization scheme for response experiment

Treatment	N	P_2O_5	K_2O
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
N-0	0	100	70
N-120	120		
N-180	180		
N-240	240		
N-300	300		

Experimental layout

The size of the experimental sites and hence the necessary fertilizer amounts were adjusted according to the machinery and field size of the farmers' fields. Four replications of each treatment were set up in a complete randomized block design.

Cotton. Each plot consisted of 8 rows spaced at 0.60 m with a plant to plant distance of 0.15 m average. Gross plot size was 4.8 m x 30 m (total 144 m²). Only the Shavot site was seeded with 0.90 m row spacing. Gross plot size was 7.2 m x 30 m (total 216 m²).

Wheat. The size of the minus-1 winter wheat basins were 15 m x 15 m (total 225 m²) in Yangibozor, and 15 m x 18 m (total 270 m²) in Urgench (LL and ML). Plot size of the response experiments was 15 m x 18 m (total 270 m²).

4.2.2 ^{15}N-fertilizer experiment

The ^{15}N-fertilizer experiment for cotton and winter wheat was located in the Urgench district, 16 km west of the regional capital Urgench in the farmers' association "Amir Temur". The experimental site (Figure 4.2) was entirely researcher managed, with the exception of irrigation water allocation and electricity provision for pumping, which could only be managed by the farmer himself.

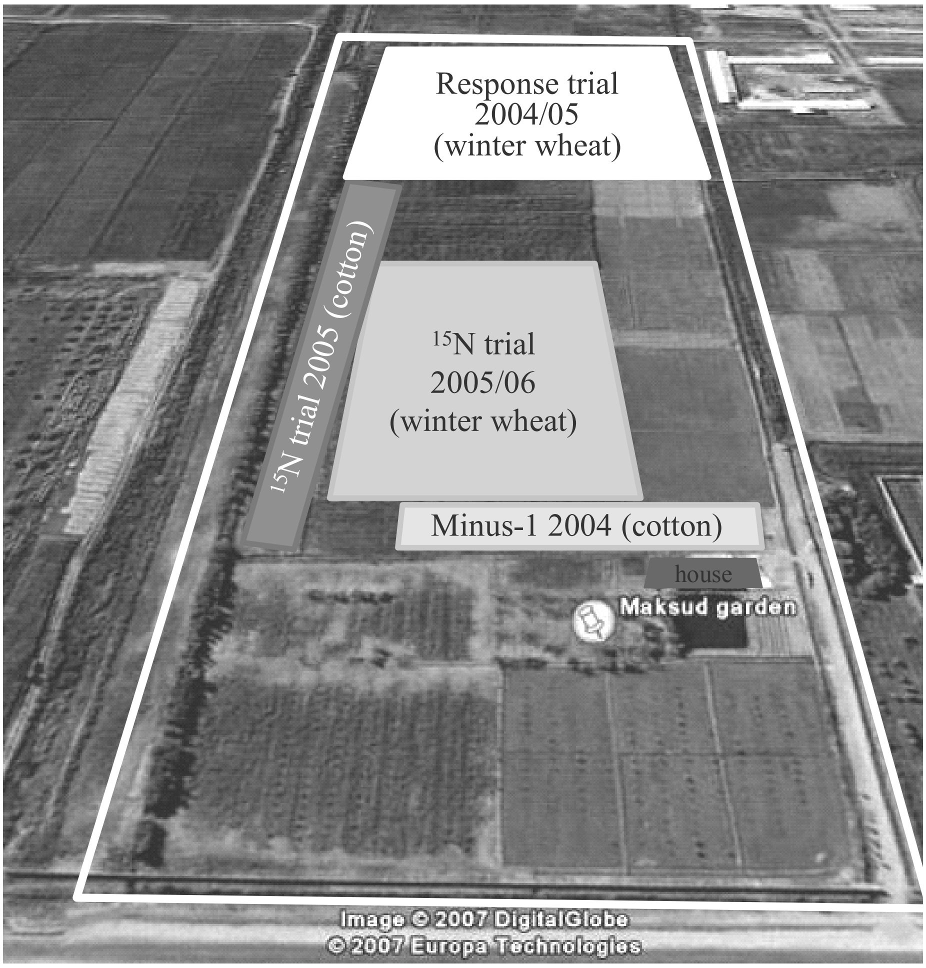


Figure 4.2 Maksud Garden research site (10 ha) in the farmers' association Amir Temur in the Urgench district; locations of the minus-1 experiment (2004), response experiment (2004/05), and ^{15}N experiments with cotton (2005) and winter wheat (2005/06). Adapted from Google-Earth©, 2007.

Cropping history

Prior to the cotton seeded for the ^{15}N-fertilizer experiment in 2005, the experimental field Maksud Garden had been seeded with cotton fertilized with approximately 270 kg N ha^{-1} (Table 4.8).

Table 4.8 Cropping history of Maksud Garden from 1988-2005

Year	**Crop**	**Fertilization**	
1988-2002	apple trees, cut in 2002	no	
2002/03	winter wheat	no	
2003	maize	400 kg AN*	(= 130 kg N)
2004	cotton	700-800 kg AN	(= 250-290 kg N)
2005	cotton	own	

* *AN: ammonium nitrate*

Main plots

For the N-fertilizer response cotton and wheat were fertilized with SSP and KCl as P and K fertilizer. The timing and form of the N fertilizer were varied using monoammonium phosphate, urea and ammonium nitrate.

For cotton, rates of 175 kg P ha^{-1} and 125 kg K ha^{-1} were used. Increasing rates of N fertilizer were applied (Table 4.9). Winter wheat was fertilized with 100 kg P ha^{-1} and 70 kg K ha^{-1}, while the N steps were increased from 0 to 160 kg N ha^{-1} (Table 4.10); N fertilizer was hand-broadcasted throughout the vegetation season.

Cotton

For the cotton experiment, three split applications and four fertilization regimes were implemented (Table 4.9). The timing allowed the comparison between the officially recommended ("DUUr") (Cotton Research Institute 2007) and the farmer's fertilizer management ("DUUf") (N. Ibragimov, pers. comm.), and included the growth stages before seeding, 2-4 true leaves, budding and flowering.

- AP – Urea – Urea, timing according to recommendations ("DUUr")
- Urea – Urea – Urea, timing according to recommendations ("UUU")
- AP – AN – AN, timing according to recommendations ("DAA")
- AP – Urea – Urea, timing according to farmers' practice ("DUUf")

Table 4.9 Cotton ^{15}N-fertilizer treatments according to rate (kg ha^{-1}), split (%) and timing of N fertilization, 2005.

Treatment	**Fertilizer regime**	**N rate**	**N split according to growth stage (%)**			
		kg ha^{-1}	before seeding	2-4 leaves	budding	flowering
			29.05.	11.06.	25.06.	11.07.
1	NPK-0	0	-	-	-	-
2	N-0	0	-	-	-	-
3	DAP*	(40)	100	-	-	
4	DUUr	80	25	-	35	40
5	UUU		25	-	35	40
6	DUUf		20	50	-	30
7	DAA		25	-	35	40
8	DUUr	120	25	-	35	40
9	UUU		25	-	35	40
10	DUUf		20	50	-	30
11	DAA		25	-	35	40
12	DUUr	160	25	-	35	40
13	UUU		25	-	35	40
14	DUUf		20	50	-	30
15	DAA		25	-	35	40

* *for the main plots AP was used as no DAP was available, but for simplification this treatment will be called DAP as in the microplots labeled DAP was used*

Wheat

For the winter wheat experiment, three split applications and four fertilization regimes were implemented (Table 4.10). The timing allowed the comparison between the currently recommended (“DUUr”) and the hypothetically more appropriate fertilizer management (“DUUf”) (IFA 2006), and included the growth stages before seeding, tillering (F-2-3), booting (F-9-10) and heading (F-10.1). A later N fertilization at growth stage F-10.51 was not possible due to the lack of spraying equipment.

- AP – Urea – Urea, timing according to recommendations (“DUUr”)
- Urea – Urea – Urea, timing according to recommendations (“UUU”)
- AP – Urea – Urea – Urea, timing according to IFA (2006) (“DUUu”)
- AP – AN – AN, timing according to recommendations (“DAA”)

Table 4.10 Winter wheat ^{15}N-fertilizer treatments according to rate (kg ha^{-1}), split (%) and timing of N fertilization, 2005/06.

Treatment	**Fertilizer regime**	**N rate**	**N split according to growth stage (%)**			
		kg ha^{-1}	before seeding	tillering	booting	heading
			25.09.05	18.03.06	04.04.06	03.05.06
1	-	0	-	-	-	-
2	-	0	-	-	-	-
3	DAP	(24)	100	-	-	-
4	DUUr	80	20	40	40	-
5	UUU		20	40	40	-
6	DUUu		20	30	30	20
7	DAA		20	40	40	-
8	DUUr	120	20	40	40	-
9	UUU		20	40	40	-
10	DUUu		20	30	30	20
11	DAA		20	40	40	-
12	DUUr	160	20	40	40	-
13	UUU		20	40	40	-
14	DUUu		20	30	30	20
15	DAA		20	40	40	-

Experimental layout

The 15 treatments of the cotton and wheat experiments were set up in a randomized block design with four replications. The fertilizer amounts were adjusted to the size of the plots.

Cotton

Each cotton treatment plot had 8 rows with 60-cm spacing. The 4 center rows were used for phenological observations, plant sampling at harvest and cotton yield determination. With a plot length of 10 m, a total plot size of 48 m² was obtained, while the harvested plot size was 24 m².

Wheat

The size of the basins was 11 m x 12 m.

Microplots

The N uptake pathway was monitored by isotopes as tracers, an appropriate method to assess N uptake efficiency of fertilizers (IAEA 2001). The use of ^{15}N as tracer allows the determination of the real rate of N use by plants.

Microplots were established within the main plots and fertilized with 120 kg N ha^{-1} (T8 – T11) to secure ^{15}N fertilizer uptake by the crop, avoid fertilizer losses via irrigation and mixing with the plot fertilizer (Follett et al. 1991, Silvertooth et al. 2001b).

The N-fertilizer amounts in the microplots were split and timed as in the main plots. Around 5%-enriched ^{15}N-labeled fertilizer pellets of DAP [$(^{15}NH_4)_2PO_4$]) and urea [$CO(^{15}NH_2)_2$] were used, and 99%-enriched liquid AN ($^{15}NH_4{}^{15}NO_3$) from Georgia, which was diluted to 5% enrichment, was applied to the microplots following the IAEA (2001) scheme. Each microplot received one dose of ^{15}N-labeled fertilizer in the course of the vegetation period. Meanwhile, for the other fertilization events, regular N fertilizer was used (Table 4.3). This allowed the calculation of partial fertilizer use efficiency of the respective split (Table 4.11, Table 4.12).

Cotton

Three microplots (A, B, and C) of 2.4 m x 1.2 m size (2.88 m²) were installed. The microplots thus enclosed four rows of cotton (Figure 4.3) of which the two center rows were used for plant sampling and yield determination at the end of the vegetation period. Roofing cardboard (tar paper) was inserted on all sides of the microplots to 50 cm depth for protection.

Wheat

The winter wheat microplots were of 0.9 m x 0.9 m size (0.81 m²) (Figure 4.4). Ridges were made out of soil around each ^{15}N treatment to secure the uptake of the marked fertilizer.

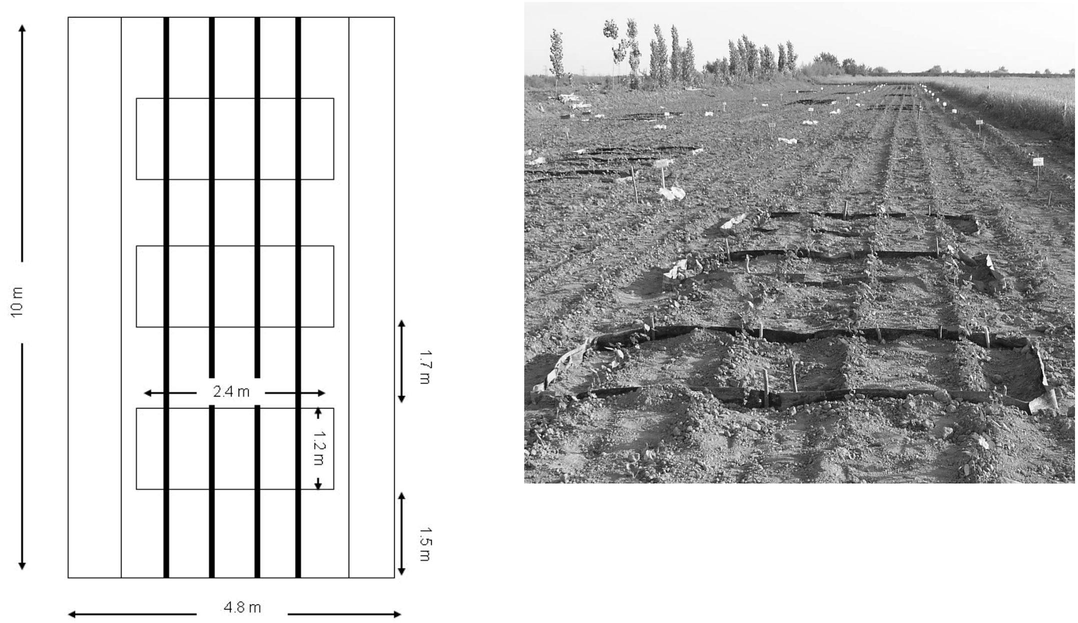


Figure 4.3 Experimental plot with microplots for cotton, Maksud Garden, 2005

Table 4.11 Timing of ^{15}N application (adapted after IAEA (2001)) in the cotton microplots, 2005; bold numbers denote the ^{15}N-labeled plots

Treatment	**Fertilizer regime**	**Microplot**	**N split according to growth stage (%)**			
			before seeding	2-4 leaves	budding	flowering
			29.05.	11.06.	25.06.	11.07.
				50 DAS**	64 DAS	81 DAS
8*	DUUr	A	25	-	35	40
		B	25	-	35	40
		C	25	-	35	40
9*	UUU	A	25	-	35	40
		B	25	-	35	40
		C	25	-	35	40
10*	DUUf	A	20	50	-	30
		B	20	50	-	30
		C	20	50	-	30
11*	DAA	A	25	-	35	40
		B	25	-	35	40
		C	25	-	35	40

* *Fertilization rate for these treatments was 120 kg N ha^{-1}*

** *DAS: days after sowing*

Figure 4.4 Experimental plot with microplots for winter wheat, Maksud Garden, 2005/06

Table 4.12 Timing of ^{15}N application (adapted after IAEA (2001)) in the winter wheat microplots, 2005/06; bold numbers denote the ^{15}N-labeled plots

Treatment	**Fertilizer**	**Microplot**	**N split according to growth stage (%)**			
			around seeding	tillering	booting	heading
			25.09.05	18.03.06	04.04.06	03.05.06
				185 DAS	202 DAS	231 DAS
8*	DUUr	A	20	40	40	-
		B	20	40	40	-
		C	20	40	40	-
9*	UUU	A	20	40	40	-
		B	20	40	40	-
		C	20	40	40	-
10*	DUUu	A	20	30	30	20
		B	20	30	30	20
		C	20	30	30	20
		D	20	30	30	20
11*	DAA	A	20	40	40	-
		B	20	40	40	-
		C	20	40	40	-

* *Fertilization rate for these treatments was 120 kg N ha^{-1}*

** *DAS: days after sowing*

4.3 Agronomic measurements

4.3.1 Cotton growth

The Uzbek cotton variety *Khorezm-127* was seeded in all experiments to allow comparisons across the years and experiments. Seeding density for all experiments was around 200 kg ha^{-1}. Cotton in the minus-1 experiments was seeded between April 3 and April 30, 2004 (Appendix 15.4). The response experiments were seeded with cotton on April 10, 2004. Reseeding occurred on April 28 due to heavy rain on April 15.

In April 2005, the ^{15}N experimental field was chiseled and leveled before seeding, and the fertilizers surface-applied to the treatment plots. ^{15}N-cotton was seeded on April 22, 2005 (Appendix 15.5). Due to low initial soil moisture and subsequent irregular germination rates and plant stand, reseeding was conducted on May 12, 2005.

After 15-20 DAS, the cotton rows of all experiments were thinned manually in all plots to achieve a uniform plant population. Plant to plant distance was then 0.15 m average, giving a plant density of 8 plants per m².

4.3.2 Winter wheat growth

The Uzbek winter wheat variety *Kupava-R2* was seeded in all experiments. Seeding density was 220 kg ha^{-1}. Wheat of the minus-1 experiments was seeded between September 24 and October 8, 2004 (Appendix 15.6). The response sites were sown on September 25, 2004 (ML-site) and on October 8, 2004 (LL-site). The wheat for the ^{15}N experiment was seeded on September 14, 2005.

4.3.3 Phenological cotton observations

Phenological measurements were carried out only on the cotton plants. Wheat observations were conducted by PhD student Yulduz Djumaniyazova and will be available in her dissertation (Djumanyiazova forthcoming). 60 cotton plants of the four central rows of the main plots and all plants in the microplots were observed throughout the vegetation period. Data of the phenological growth stages 2-4 leaves, budding, fruiting, flowering and maturity were collected from each treatment (Appendix 15.4). This information was partly used to calibrate the model CropSyst.

4.3.4 Weed, pest, and growth control

Minus-1 and yield response

Cotton

Weeds on the cotton minus-1 and response experiments were removed by tractor-driven machines (farmers' practice) twice during the vegetation period. Unfortunately, low temperatures in 2004 led to a high infestation of the cotton plants with pests (thrips, *Frankliniella fusca* Hinds, and cotton aphids, *aphis gossypii* Glover). Consequently, most of the farmers sprayed a small amount of concentrated urea-water mixture (carbamid, 5-6 kg ha^{-1}) and the organophosphorous insecticide Phosalone[9] ($C_{12}H_{15}ClNO_4PS_2$, CAS-Nr. 2310-17-0 (EPA 2007)).

Cotton growth was controlled by manually cutting off the tips of the plants (pruning) during the fruiting-flowering stage once the cotton plants had reached the height of 1 m (farmers' practice) to reduce void growth and enhance fruit formation rates.

To facilitate the harvest, a recommended defoliant (from China, magnesium chloride, $MgCl_26H_2O$, at a rate of 8-12 kg ha^{-1}) was sprayed when 60% of the cotton bolls were open. World wide, cotton plants frequently are sprayed with defoliants to encourage artificial leave-shedding (Eaton 1955, Chaudhry 1997) by stopping respiration temporarily and forcing an early ripening of the plant (Eaton 1955). In Australia and Israel, application of defoliants is common (100%), while in Uzbekistan, only around 70 % of the cotton area is treated with defoliants (Chaudhry 1997).

Wheat

Weeds on the wheat plots were removed manually by local labor every two weeks.

^{15}N experiments

Weeds were controlled with a hand hoe to prevent uptake of ^{15}N by weeds. Biological insect control measures against the cotton bollworm (*Helicoverpa armigera* Hübner) were implemented during the growing period by releasing egg parasitoids of the genus *Trichogramma* spp. to the field after sunset, following the common augmentative release programs of the former Soviet Union (Luttrell et al. 1994). Also pheromone traps were set up as biological control measures.

Cotton growth on the minus-1 experiments was controlled by applying a common chemical growth regulator (from South Korea, Mepiquat chloride, CAS-Nr.

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[9] Since 2006 banned in the EU (EU 2006, http://eur-lex.europa.eu/LexUriServ/site/de/oj/2006/l_379/)

24307-26-4 (EPA 2007)). The liquid was foliar-applied twice to enssure complete plant samples at harvest time.

4.4 Weather and water measurements

All experimental fields were leached 2-3 times prior to seeding according to common practice in Khorezm. However, water amounts required for leaching were not recorded for the experiments. Irrigation amounts for the minius-1 and response experiments were not documented, as the management was left to the respective farmer. Meteorological data were obtained from the weather stations of the project.

4.4.1 Meteorological station

Close to the ^{15}N experiments at Maksud Garden, a meteorological station (WatchDog Model 2700 Weather Station, Spectrum®) was set up 1.5 m above ground. It automatically recorded maximum and minimum air temperature (°C), relative humidity (%), precipitation (mm), and solar radiation (W m-^{2}) on an hourly basis.

4.4.2 Soil moisture, water content

Cotton

Five pF-meters (GeoPrecision, Germany ecoTech® 2004) were installed at 10, 20, 40, 60, and 80 cm depth in the ^{15}N-experiment plots T7-R1 and T12-R1 (later reinstalled at T14-R1). These sensors recorded the soil pressure head in the range of pF 0 to pF 7 by measuring the molar heat capacity irrespective of soil salinity level (ecoTech 2007b).

Furthermore, 15 Frequency Domain Reflectometry (FDR) sensors (ThetaSonde ML2x Eijkelkamp® theta probe, Delta-T Devices, UK) were installed at 20, 40, 60, 80 and 100 cm depth in the profiles of the plots T13-R1, T14-R1 and T15-R1. The FDRs allow the quantification of volumetric water content in the range of 0-50 % with a precision of 2 Vol.-% (ecoTech 2007a), by measuring the dielectric constant and conductivity, thus, eliminating salt interference (Pinto and Liu 1996). The pF-meters and FDR sensors were connected to a logger, and data were automatically recorded on a 30-min basis.

Data from both pF-meters and FDR sensors were used to adjust the water balance of the model CropSyst to the particular soil conditions (see section 10.1).

Wheat

The same set of pF meters and FDR sensors was installed in the ^{15}N wheat experiment. The pF meters were placed in plots T2-R2 and T15-R2, next to the FDR sensors in 20, 40, and 80 cm depth. Five FDR sensors were installed at plots T2-R2, T15-R2 at 20, 40, 60, 80, and 100 cm depth. A further 3 FDR sensors were positioned at plot T14 in 20, 40, and 80 cm depth.

4.4.3 Leaching and irrigation

At the ^{15}N experimental site, a submersible pump was installed down to 9 m depth to guarantee irrigation water at all times.

Cotton

Prior to cotton sowing, the^{15}N field was leached 3 times. During the vegetation season, it was irrigated 5 times. Irrigation was scheduled to keep 70-70-60 % of the field capacity (Ibragimov et al. 2007b), where 70 % was used from cotton germination to budding stage, 70 % from budding to flowering-fruiting, and 60 % during maturation of the cotton bolls.

For approximation of irrigation water application rates at plot level, two sharp-crested quadratic weirs (12 cm x 12 cm) and two flumes (RBC flume (Eijkelkamp 2001) and SANIIRI flume were installed (Figure 4.5). The plots were chosen to match the installation of the pF and FDR sensors (T7-R1, T12-R1 (later reinstalled at T11-R1), T13-R1 and T15-R1).

a) quadratic weir b) RBC flume c) SANIIRI flume

Figure 4.5 Discharge measurement devices at plot level

Calculations of irrigation water discharge for the quadratic weirs followed equation (4.1) (USDA 1997):

$$Q_n\left[\mathrm{l\,s^{-1}}\right]=\frac{2}{3}\times C_d\times b_c\times\sqrt{(2\times g)}\times\left(\frac{h_l}{100}\right)^{1.5}\times 1000 \tag{4.1}$$

where Q_n is discharge, C_d the coefficient of discharge (0.61 (USDA 1997)), b_c the weir width (12 cm), g the acceleration caused by gravity (9.81 m s^{-1}) and h_l is the head measured above the weir crest (cm). For the RBC flume, equation (4.2) was applied to determine the irrigation water discharge (Eijkelkamp 2001):

$$Q_n\left[\mathrm{l\,s^{-1}}\right]=\frac{7}{10^7}\times(h\times 10)^3+\frac{626}{10^6}\times(h\times 10)^2+\frac{1569}{10^5}\times(h\times 10)-\frac{665}{10^4} \tag{4.2}$$

where Q_n is the discharge, and h is the water level (cm). The SANIIRI flume had been previously calibrated and allowed readings representing the given discharge per time unit (Forkutsa 2006). The total irrigation amount of the respective weirs and flumes was then computed according to equation (4.3):

$$\text{Irrigation amount (mm)}=\frac{\sum\left(\frac{(Q_n+Q_{n+1})}{2}\right)\times dt_{n+1}}{\text{Plot size}} \tag{4.3}$$

where dt is the time interval observed; plot size was 24 m² for the first irrigation (inter-row irrigation) and 48 m² for all following irrigation events.

Groundwater level and salinity were monitored in 10 observation wells with piezometers. These consisted of 2.2-m long poly-ethylene pipes of 4-cm diameter. The pipes were blocked at the bottom, and the lower half of the pipe was perforated. To protect the perforated holes from clogging, the pipes were wrapped in fine synthetic fiber. The groundwater and salinity data were used to approximate groundwater table dynamics throughout the season; the data were later used in the modeling. The groundwater had an EC of 2.1 dS m^{-1} and fluctuated only little throughout the season. Average depth was 1.1 m below the surface. Irrigation water and groundwater salinity were on average 1.2 dS m^{-1} and 2.2 dS m^{-1}, respectively.

Wheat

Prior to wheat sowing, the ^{15}N field was leached 3 times. Throughout the vegetation season, it was irrigated 8 times. Irrigation was initiated when field capacity dropped below 70 %. The EC of the irrigation water was around 1.2 dS m^{-1}. Groundwater data were recorded by PhD student Yulduz Djumaniyazova, and will be available in her dissertation (Djumanyiazova forthcoming).

4.4.4 Nitrate content in irrigation water and groundwater

Nitrate content in the irrigation water and groundwater was only measured after the cotton and wheat harvest in 2007. Four piezometers were installed in July 2007 in a transect towards the drainage canal in the summer crops (carrots, cabbage and maize) following the ^{15}N wheat and cotton experiment. After harvest, all piezometers were removed to allow for winter wheat seeding. In February 2008, four new piezometers were installed in the wheat field perpendicular to the drainage at 20, 40, 80 and 100 m distance from the drain.

Water samples were taken from the irrigation and groundwater when research assistants were available. In the summer crop, water depth and nitrate was measured 4 times (20.07., 31.07., 20.08., and 07.09.2007). The groundwater under winter wheat in 2008 was measured more frequently until April 19, with higher frequency after fertilization and irrigation events. After this date, the groundwater level fell below the detectable limit of the piezometer, and measurements became impossible.

Nitrate content in the water was determined 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).

The upward flux of nitrate-containing groundwater was assumed to not be adsorbed in the soil but to contribute to the nitrate content in the rooting zone of cotton (Burns 1980). The upward movement of nitrate was thus estimated according to equation (4.4)

$$\text{Contribution} = 355\,\text{l}\,\text{m}^{-2} \times 8\,\text{mg}\,\text{l}^{-1} = 2.84\,\text{g}\,\text{m}^{-2} = 28.4\,\text{kg nitrate ha}^{-1} \qquad (4.4)$$

using the simulated groundwater contribution of 355 mm (see section 10.2) and an average nitrate concentration in the groundwater of 8 mg l^{-1}. The equivalent NO_3-N amount (in kg ha^{-1}) was obtained by multiplying the respective amount of nitrate with 0.2259 (i.e. atomic mass of N divided by atomic mass of nitrate).

A more detailed contribution to the subsoil nitrate content for the cotton vegetation period was computed using the daily water balance simulations from the model CropSyst (section 10.2). The bottom flux (Vbot) was calculated using equation (4.5) and equation (4.6):

$$\mathrm{V}bot = \mathrm{F} - \mathrm{E}Ta - \Delta W \tag{4.5}$$

$$\mathrm{F} = \mathrm{P} + I - R - Pi - Pm \tag{4.6}$$

where F is the infiltration (mm), ETa the actual evapotranspiration (mm), ΔW the storage change, P the precipitation (mm), I the irrigation amount (mm), R the surface runoff (mm), Pi the crop interception (mm) and Pm the mulch interception. The storage change was calculated as the daily water fluctuation in the soil between the rooting zone and the groundwater table. The daily nitrate concentration during the season was approximated by interpolating from groundwater nitrate measurements in 2007 and 2008 taking into account the groundwater table dynamics in 2005 (section 10.2).

4.5 Harvest

4.5.1 Cotton

Sampling and preparation for harvest

The cotton in the four central rows of each treatment was hand-picked for determining the total seed cotton yield. It was first picked in the second half of September when 30% of the bolls were open with a second, third and fourth picking in approximately 3-week intervals (Appendix 15.7). Fresh weight of cotton was determined in the field with a mechanical balance to the nearest gram. Dry matter was determined following drying to constant weight at 70°C in the drying oven. Total (dried) raw cotton yield per hectare was calculated by adding all harvested cotton yields.

Microplot sampling

Prior to harvest, three average plants were selected from the four central rows of each treatment according to the last phenological measurement. Plants were sampled on September 7/8, 2005. From the ^{15}N microplots, four central plants were taken.

The cotton plants were weighed (fresh weight). Then, leaves, fruit elements, and mature raw cotton from open bolls were removed, and the unopened cotton bolls were cracked open to allow further ripening. Next, the plants were air dried, and once the remaining bolls were ripe, the fiber, squares, and stems were separated (see Table 4.14).

All plant parts were oven dried at 105°C to constant weight, except for the cotton fiber, which was oven-dried at 70°C. The harvest index (HI) was calculated as the ratio of raw cotton to total biomass (equation (4.7))

$$\mathrm{HI} = \frac{\text{Raw cotton}\left[\text{g plant}^{-1}\right]}{\text{Total biomass}\left[\text{g plant}^{-1}\right]} \tag{4.7}$$

The weighed samples (leaves, stems, squares, and fruit elements) then were milled to pass through a 1-mm sieve and analyzed for total N and ^{15}N following Buresh et al. (1982). For ^{15}N-determination, the cotton fiber was separated from the seeds before grinding.

Picking

Following the harvest of the sub-samples, the four central rows of each treatment were hand-picked for determining the total seed cotton yield. For the ^{15}N microplots, all four rows were harvested.

Cotton was first picked on September 13, 2005, when 30% of the bolls were open with a second, third and fourth picking in approximately 3-week intervals (Appendix 15.8). Total raw cotton yield per hectare was calculated by adding all harvested cotton yields.

The computer software ArcGIS was used to display the spatial layout of the respective yields in the field. As cotton was harvested in several picks, only the averaged sum of yields was allocated to the respective plot.

4.5.2 Winter wheat

Winter wheat samples for all experiments were taken at harvest time (June 15-21, Appendix 15.9). For analysis, 3 samples of 1 m² each of each treatment was harvested using a quadrant, and the yield component data of those three sub-samples were averaged for statistical analysis.

The wheat samples were further divided and processed to determine yield components such as average kernel weight per m^2, spikes per m^2, weight of kernels per spike and 1000-kernel weight (TKW). Additionally, fresh and dry (105°C) weight of total biomass, stems, spikes, and chaff, the length of plant and spikes, and plant density (number of plants with spikes per m^2) were measured for each m^2. The harvest index (HI) was calculated as the ratio of kernel weight to total biomass (equation (4.7)).

Because of lacking information on weed-specific N uptake and weed density, weeds were treated like winter wheat with regard to N uptake characteristics. It was thus assumed that wheat N uptake in the same treatments did not differ despite the differences in plant density.

In order to account for differing plant density of the sub-samples (e.g., Appendix 15.23) as result of different seeding and germination rates, and weed manifestation when comparing wheat yields across the years, the overall plant density mean of all sub-samples was calculated to be 354 plants with spikes m^{-2}. The yield per wheat sub-sample was divided by the observed plant density of the respective treatment to calculate the yield per plant. This value then was multiplied with the overall plant density mean (354 plants m^{-2}) to obtain the density-adjusted yield for all treatments.

For those samples where the number of plants was not counted, the missing values were estimated using the regression equation of plant number vs. stem weight (see also section 4.10.3). The computer software ArcGIS was used to display the spatial layout of the respective yields in the field.

4.6 Soil Sampling

4.6.1 Minus-1 and yield response

From all minus-1 and response experiments, soil samples were taken prior to seeding and after harvest at 0-30, 30-50 and 50-70 cm depth. Soil samples were taken as bulk samples combining 4 points on the field. Sampling after harvest was conducted in one replication only.

The samples were air-dried and passed through a 0.25-mm and 1-mm sieve for chemical analysis. They were then analyzed in Tashkent, Uzbekistan, at the Soil Science Institute for SOM, total N, NH_4-N and NO_3-N content, total and available P, and total and exchangeable K (section 4.6.3).

4.6.2 ^{15}N experiment

Before seeding

Cotton. On February 4, 2005, three sites were selected in Maksud Garden. Soil was sampled at three depths (0-30, 30-50 and 50-70 cm) and analyzed by the Cotton Research Institute, Tashkent, for total and available forms of N, available P and exchangeable K, and C content, and for soil texture (section 4.6.3).

Furthermore, soil salinity was checked between the second and final leaching event to determine whether the values were below the threshold of 7.7 dS m^{-1} for cotton germination and growth (Ayers and Westcot 1985, Rhoades et al. 1992).

Wheat. For winter wheat, soil samples were taken from three sites prior to seeding. Unfortunately, however, the soil samples before wheat seeding were lost during transport from the field to the laboratory.

After harvest

After harvest, three soil profiles were dug to 1.4 m depth to determine soil bulk density every 10 cm. The microplots were sampled at 0-10, 10-20, 20-30, 30-40, and 40-60 cm depth. The samples were air dried at 40°C and milled to pass through a 1-mm sieve. The samples were analyzed at the Soil Science and Cotton Research Institute in Tashkent, Uzbekistan for EC, total N, NH_4-N and NO_3-N content, and for available P and exchangeable K (section 4.6.3). At the Institute of Crop Science and Resource Conservation of the University of Bonn, the soil samples were analyzed for total N and atom% ^{15}N content (section 4.7.3).

Furthermore, visible cotton and wheat roots in the soil samples of 0-10 cm depth (and 10-20 cm for cotton) were removed from the soil, dried at 105°C, ground to pass through a 1-mm sieve, and analyzed for total N and atom% ^{15}N in Bonn, Germany.

4.6.3 Soil analysis

Soil samples were analyzed at the Soil Science and Cotton Research Institute in Tashkent, Uzbekistan. Soil chemical analyses in the Uzbek institutes usually differ slightly from the international methods. The methodology applied in the Uzbek laboratories is mostly based on established Russian soil analysis methodologies (e.g., Cotton Research Institute 1977, Durynina and Egorov 1998). The chemicals used, however, are in many cases no longer used in international soil laboratories, which means that results are difficult to compare.

Uzbek soil texture determination according to Karchinksy (1980) follows the pipette method of Köhn as described in the German DIN 19683, part 2. However, particle size classes have different upper and lower limits. Therefore, the seven Uzbek size classes with the diameters 0.25, 0.1, 0.05, 0.01, 0.005, 0.001 and <0.001 mm according to Kachinsky were converted to the USDA system.

The EC (dS m^{-1}) was measured in a 1:1 soil:water extract in 2 replications for all samples in the ZEF/UNESCO laboratory in Urgench using a hand-held EC measurement device (Shirokova et al. 2000). The conversion from $EC_{1:1}$ to EC_e (FAO standard) was calculated by the empirical equation (4.8):

$$EC_e = \kappa \times EC_{1:1} \tag{4.8}$$

where κ is the calibration factor empirically determined by the Regional Chemical Laboratory of Uzbekistan (Shirokova et al. 2000), which can range from 3.3 to 3.7. For this study, the coefficient $\kappa = 3.5$ was used.

SOM (%) was determined according to Tyurin (Cotton Research Institute 1977, Durynina and Egorov 1998), which is a modified Walkley-Black (Nelson and Sommers 1982) method[10]. Total N was analyzed by Kjeldahl method[11] (Bremner and Mulvaney 1982). The NO_3-N content (mg kg^{-1}) was analyzed calorimetrically with phenol disulphonic acid according to the modified method of Granval-Lajoux from 1886 (Silber 1913, Haper 1924, Durynina and Egorov 1998), and NH_4-N content (mg kg^{-1}) was examined by the Nessler reagent (Yuen and Pollard 1952, Yuen and

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[10] Acidification of humus carbon with a solution of chromic anhydride in the presence of sulphuric acid, and titration of unused chromic anhydride with ferrous ammonium sulfate/ $Fe(NH_4)_2(SO4)2*6H_2O$

[11] Wet oxidation of soil organic matter using sulfuric acid

Pollard 1954, Durynina and Egorov 1998). Available P_2O_5 (mg kg^{-1}) and exchangeable K_2O (mg kg^{-1}) were analyzed according to the method described by Machigin-Protasov[12], which can be compared to the Olsen methodology (Olsen and Sommers 1982).

4.7 Plant analyses

4.7.1 Plant quality

Raw cotton from the four picks was analyzed for fiber quality at the Cotton Research Institute in Tashkent. The raw cotton bolls were analyzed for fiber length, gin turnout, 1000-seed weight, micronaire (indicator for air permeability, an indirect measure for linear density/fineness and maturity), fiber linear density, fiber ripeness coefficient, and the relative breaking strength of fiber (Stelometer) (Cotton Research Institute 1977). Sub-samples of wheat kernels were analyzed for gluten and protein content, transparency, and gluten quality at the local Khonka State Mill. As no national standard for protein analysis of wheat available at the mill laboratory, the author provided a copy of the Uzbek standard procedure (GOST 10846-91) for analysis of winter wheat kernels and their products for protein. According to this standard, protein content should be determined using the Kjeldahl method.

4.7.2 Critical nitrogen level

To determine the critical concentration of N (protein = N x 5.7) “above which there is luxury consumption and below which there is poverty adjustment” (Macy 1936, p. 751), the method of Pierre et al. (1977) was used. First, the relationships of N rate/yield (equation 1) and N rate/protein content (equation 2) were expressed by quadratic functions. From the first equation, the maximum yield was derived, and percentages of the maximum and the associated N rates were calculated. Substituting these N rates into the second equation, the protein levels associated with the relative yield levels were derived.

The percentage of maximum yield (relative yields) were plotted on the y-axis against the protein content (Cate and Nelson 1971, Pierre et al. 1977, Goos et al. 1982) .

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[12] Extraction of P and K compounds with 1%-solution ammonium carbonate, pH 9.0, flame photometer

4.7.3 Analyses of the ^{15}N-enriched plant and soil samples, and fertilizers

All harvested plant materials were analyzed by mass spectrometry for total N and ^{15}N at the Institute of Crop Science and Resource Conservation, Dept. Plant Nutrition of the University of Bonn. Total fertilizer-N and atom% ^{15}N (abundance) content of DAP and urea was also determined (Table 4.13).

Table 4.13 Total N and atom% ^{15}N (abundance) content of the labeled fertilizers (n = 2). The standard deviation is given in brackets.

Fertilizer type	**Total N, %**	**^{15}N, %**
Diammonium phosphate (DAP)	18.52 (±0.11)	5.52 (±0.00)
Urea	42.84 (±0.26)	5.68 (±0.00)
Ammonium nitrate (AN)	34	95.4

Isotope ratio mass spectrometer (IRMS)

The principle of the isotope ratio mass spectrometer (IRMS) is based on ionizing atoms and molecules with an ion source, separating them according to their mass-to-charge ratio in a mass analyzer, and recording them in an ion collector (Buresh et al. 1982, IAEA 2001). The IRMS (GC-MS, PDZ Europe now SERCON Ltd., Crewe, Cheshire, UK, 1998) used for this study was located in the Institute of Crop Science and Resource Conservation, Dept. Plant Nutrition of the University of Bonn.

Depending on total N content in the plant tissue or soil sample, 6-30 g finely milled substrate were weighed into zinc tin capsules and placed in the elemental analyzer (GC-MS). Each sample was measured twice. Four samples were used as standards. Subsequently, total N and atom% of ^{15}N (abundance) were determined.

Freezer mill

Cotton fiber, cotton seed samples, and winter wheat kernels could not be grinded well enough with the conventional mill for analysis with the IRMS. Therefore, a freezer mill (SPEX CertiPrep 6750 Tiefkühl-Schlagbolzen-Mühle, C3 Prozessanlysentechnik GmbH, München, 2006) was used. This mill has successfully been used for other substances such as plant and muscle tissue, hair, polymers, etc. (C3 PA GmbH 2006).

Liquid nitrogen (boiling point -195.8°C) served as a cooling agent to deep-freeze the sample material prior to and during milling. Two magnetic inductors magnetically move a striker (impactor) inside the milling container, pulverizing the deep-frozen sample material (C3 PA GmbH 2006). By grinding at such low temperatures, chemical and organic structures and properties are preserved (C3 PA GmbH 2006).

Around 2 g of the plant samples were filled into the milling container, pre-cooled for 7 min and milled for 2 min at a frequency of 10 beats per second. The finely ground material was filled into plastic bags and used for the analyses in the IRMS.

4.8 Agronomic calculations

4.8.1 Nitrogen response

Mean raw cotton yield data and the harvest index (HI) for the main plots of the ^{15}N experiments were grouped according to the respective N step. For the crop modeling, the NPK-0 and N-0 treatments were averaged to become N-0* as did not differ significantly. Also the mean cotton harvest indices derived from this grouping were used in the crop modeling.

4.8.2 Calculation of plant-nitrogen uptake

For plant N uptake estimation, the N content (%) was multiplied with the respective dry weight of the plant component (DM) (equation (4.9))

$$\text{N uptake}\left[\text{kg ha}^{-1}\right] = \text{DM yield}\left[\text{kg ha}^{-1}\right] \times \%\text{N} \tag{4.9}$$

Total plant biomass, above-ground biomass and exported biomass were calculated as the sum of the respective plant parts (Table 4.14), i.e., cotton stems, leaves, squares, fiber, seed, fruit elements, and roots from 0-20 cm depth. For winter wheat, the total plant biomass comprised stems, kernels and roots from 0-10 cm depth. As the weight of total root biomass was neither measured for cotton or wheat, simulation results from CropSyst were used to estimate total dry weight and the root weight in the soil layers 0-10 and 10-20 cm (see Forkutsa et al. (2009a) and Djumaniyazova et al. (2010)).

Table 4.14 Weight of plant parts included for calculations of total, above-ground and exported biomass (kg ha^{-1})

	Cotton	**Winter wheat**
Total dried biomass (kg ha^{-1})	• Stems • Leaves • Squares • Fiber • Seed • Fruit elements • Roots (0-20 cm)	• Stems • Chaff • Kernels • Roots (0-10 cm)
Above-ground biomass (kg ha^{-1})	• Stems • Leaves • Squares • Fiber • Seed • Fruit elements	• Stems • Chaff • Kernels
Exported biomass (kg ha^{-1})	• Stems • Squares • Fiber • Seed	• Stems • Kernels

4.8.3 Estimation of nitrogen recovery (isotope dilution method)

Data obtained from the IRMS were used to calculate the N recovery derived from applied ^{15}N fertilizer following modified equations of Hauck and Bremner (1976), Cabrera and Kissel (1989), and IAEA (2001). Nitrogen-recovery values are based on total dry weight of the plant and soil parts and their total N and ^{15}N content. The excess enrichment of the labeled ^{15}N fertilizer (atom %) was calculated by equation (4.10))

$$\text{atom \% } ^{15}\text{N}\left(\text{excess}\right) = \text{atom\% } ^{15}\text{N}\left(\text{abundance}\right) - \text{atom \% } ^{15}\text{N}_{\text{nat}} \qquad (4.10)$$

where atom% ^{15}N$_{nat}$ is the assumed natural abundance (0.366 atom% ^{15}N (IAEA 2001)). The N derived from fertilizer (Ndff) was estimated as the ratio of atom% ^{15}N (excess) in the soil and plant sample divided by the atom% ^{15}N (excess) in the fertilizer (equation (4.11)):

$$\text{Ndff}\left[\%\right] = \frac{\text{atom \% } ^{15}\text{N}\left(\text{excess}\right)_{\text{sample}}}{\text{atom \% } ^{15}\text{N}\left(\text{excess}\right)_{\text{fertilizer}}} \times 100 \qquad (4.11)$$

The fertilizer-N recovery rates from plant and soil samples were calculated using equation. (4.12) and equation (4.13):

$$\text{N yield}\left[\text{kg ha}^{-1}\right] = \text{DM yield}\left[\text{kg ha}^{-1}\right] \times \frac{\%\text{N}}{100} \qquad (4.12)$$

$$\text{Fertilizer N yield}\left[\text{kg ha}^{-1}\right] = \text{N yield} \times \frac{\text{Ndff}}{100} \qquad (4.13)$$

where DM yield is dry-matter yield and %N the total N content in the sample. The partial fertilizer N recovery for the respective soil or plant sample was calculated (equation (4.14)) as fertilizer-N yield per rate of labeled fertilizer:

$$\text{Fertilizer N recovery}\left[\%\right] = \frac{\text{Fertilizer N yield}}{\text{Rate of labelled fertilizer}} \times 100 \qquad (4.14)$$

Summing up the fertilizer N recovery yielded the total N recovery derived from fertilizer for the different plant parts and soil layers.

For comparing the recovery rates of the different fertilizer treatments, the values were weighted based on the different quantities applied at different times.

4.8.4 Estimation of nitrogen-use efficiency (difference method)

The agronomic N-use efficiency (NUE_{AE}, kg ha^{-1}) was calculated according to Good et al. (2004) (equation (4.15)):

$$NUE_{AE} = \frac{(Y_F - Y_C)}{N_F} \qquad (4.15)$$

where Y_F is the yield with fertilizer (kg ha^{-1}), Y_C is the yield of the unfertilized control (kg ha^{-1}), and N_F is the N fertilizer applied (kg ha^{-1}). For the rate of 0 kg N ha^{-1}, the treatments NPK-0 and N-0 (T1 and T2) were averaged and used as reference. Furthermore, the apparent N recovery (NUE_{AR}, %) was computed following Good et al. (2004) (equation (4.16)):

$$NUE_{AR} = \frac{(N_F\ \text{uptake} - N_C\ \text{uptake})}{N_F} \times 100 \qquad (4.16)$$

where N_F uptake is the N content of the plants from the fertilized plots (kg ha^{-1}), and N_C uptake is the N content in the plants from the unfertilized control (kg ha^{-1}). The calculated NUE_{AR} rates were then compared to the rates derived from the ^{15}N isotope dilution method.

4.8.5 Financial assessment

Financial assessment of fertilizer use in cotton and winter wheat production were conducted for the main plots of the ^{15}N experiment. A partial crop budget analysis (CIMMYT 1985, Perrin et al. 1988) was employed to estimate the profitability of cotton production for the different fertilizer applications.

The partial budget method considers only the total costs that vary (TCV) across experiments and the benefits. Variable costs include the fertilizer and other costs associated with fertilizer transportation or/and application, while assuming that the other costs do not differ between treatments (i.e., general farm overhead). This technique allows tracking the direct influence of different fertilizer levels on the profit (Perrin et al. 1988). Hence, recommendations for farmers can be developed and alternative fertilization practices selected that are based not only on the profitability of the alternative practice, but also on the marginal rate of return being greater than the acceptable minimum rate of return (Evans 2008).

For the beneficial sites, the average yields and prices according to quality were considered. The total gross field benefit for cotton and winter wheat (GB, UZS[13] ha^{-1}) was calculated for the respective harvest product, i.e., cotton of different picking times, cotton stems and oil and oilcake, wheat kernels and wheat straw (equation (4.17)):

$$\mathrm{GB} = \sum_{j=1}^{a}\sum_{i=1}^{n}\left(h_i \times p_i\right) \tag{4.17}$$

where h_i is the harvest product (quantity), and p_i the market price (UZS) for the respective h_i. The TCV (UZS ha^{-1}) of fertilizers, transport and harvest labor were estimated using equation (4.18):

$$\mathrm{TCV} = \sum_{j=1}^{a}\sum_{i=1}^{n}\left(c_i \times p_i\right) \tag{4.18}$$

where c_i is the cost of the respective activity. The gross margin or partial budget net benefits (NB, UZS) and the rate of return (RR, UZS) were determined (equation (4.19 and equation (4.20)):

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[13] UZS stands for the Uzbek currency Soum; the average exchange rate in 2005 was approximately 1114.5 UZS / 1 US dollar

$$\mathrm{NB} = \mathrm{GB} - \mathrm{TCV} \tag{4.19}$$

$$\mathrm{RR} = \frac{\mathrm{NB}}{\mathrm{TCV}} \tag{4.20}$$

To assess the economically most profitable fertilizer practices, a dominance analysis was performed. First, the data were sorted in an increasing order from the lowest to the highest TCV and listed with their respective net benefit. In a next step, the lowest and next higher costs and respective net benefit were compared to identify the dominating fertilizer treatments that cost more than the previous but yielded higher net benefit (CIMMYT 1985, Perrin et al. 1988). Those fertilizer treatments, for which the difference in TVC exceeded the difference in net benefit, were excluded from further analysis (dominated treatments). For the remaining treatments, the marginal rate of return (MRR) was determined giving the minimum acceptable rate of return (Perrin et al. 1988), i.e., the return for one additional applied unit of input.

All parameters such as input and output prices and quantities were acquired through official agencies such as the Committee on Demonopolization and Entrepreneurship Support in the Khorezm region. The provided inputs had been calculated as value of sold fertilizers divided by volume (Table 4.16, Table 4.17). Information on cotton class price was obtained from the cotton ginneries in the Khorezm region (Table 4.15). One bale of cotton stems was 50 UZS per bale, with one bale being 2.5 kg of stems (Tursunov, personal communications).

Table 4.15 Official state price (Uzbek soum, UZS) per ton of raw cotton according to class and sub-class, 2005 for cotton varieties *Khorezm-127* and *Khorezm-150* (Ys PCT 615-94)

Class	Sub-class	State price per ton, UZS
1	1	299,080
	2	291,320
	3	233,160
2	1	258,490
	2	250,740
	3	230,580
3	1	239,360
	2	219,000
	3	150,700
4	1	17,830
	2	138,290
	3	105,720
5	3	74,190

Source: OblVodKhoz (Khorezm Province Agriculture and Water Management Office)

Table 4.16 Fertilizer, salary and transportation prices per unit used for the partial budget calculation (Uzbek soum, UZS), 2005

Input prices per unit in 2005*		
Fertilizer		
Urea	173	UZS kg^{-1}
Ammonium nitrate (AN)	122	UZS kg^{-1}
Monoammonium phosphate (AP)	305	UZS kg^{-1}
Single superphosphate (SSP)	75	UZS kg^{-1}
Potassium chloride (KCl)	217	UZS kg^{-1}
Salary (cotton harvesting)		
Pick 1	35000	UZS harvested ton^{-1}
Pick 2	35000	UZS harvested ton^{-1}
Pick 3	38000	UZS harvested ton^{-1}
Pick 4	42000	UZS harvested ton^{-1}
Transportation		
Transportation cost	170	UZS t^{-1} km^{-1}
Transportation distance	20	km

* *Fertilizer prices taken from OAO "Kishlakkhudjalikkime"(calculated by the Committee on Demonopolization (value of sold fertilizers divided by volume))*

Table 4.17 State, negotiated and market prices (UZS) for winter wheat kernels (kg) for the respective quality class in 2004, and prices for wheat straw transportation

Quality class	**State price**	**Negotiated price* (state price + 20 %)**	**Average market price****
	UZS kg^{-1} wheat kernels		
1	102.57	123.08	130
2	87.23	104.68	
3	75.10	90.12	
4	67.18	80.62	
Sale share, %	50	25	25
Straw, UZS $truck^{-1}$			5000
Straw, t $truck^{-1}$			6

* *according to the accountant of the Khonka State Mill*

** *taken from interviews in 2004*

4.9 Crop modeling

For this study, the crop-soil simulation model CropSyst (version 4.09.05) was selected. It is freeware (http://www.bsyse.wsu.edu/cropsyst/) and programmed in C++ (object-oriented).

Model parameters needed for CropSyst were either estimated from the ^{15}N cotton field measurements or adjusted for cultivar characteristics based on literature data. Most of the components necessary for the water balance were measured in the field (i.e., irrigation water, precipitation, soil water fluxes) in 2005. Those parameters not measured in the field were estimated using the model HYDRUS 1-D (see also Forkutsa et al. (2009a, 2009b). Runoff was negligible as the soils were fairly leveled.

4.9.1 Scenarios

After the model had been calibrated, several settings were altered to mimic changes in current management practices and allow estimations of non-measured parameters.

First, the observed yields of the ^{15}N cotton experiment were compared to the predicted yields using the measured harvest indices. Then, the outcome of the water balance simulations was used to estimate potential and actual evapotranspiration in relation to the irrigation management. In a next step, the N dynamics for increasing fertilizer amounts and different N-fertilizer sources were modeled, and plant N uptake, yields and losses via leaching, volatilization and denitrification were estimated.

Following these results, management practices were modified to increase yields while reducing gaseous losses. Two N fertilizer levels, 120 kg ha^{-1} (T10) and 250 kg ha^{-1} (T18), of treatment DUUf were selected as base treatments. The yields and emissions of these base treatments were compared to the several scenarios. First, the timing of the second fertilizer split was varied and the number of splits was increased. Second, the irrigation management of the base treatments was modified. Amounts of 40 mm or 30 mm were automatically applied every 14 days (Table 4.18) thereby subsequently reducing the total amount of water from 280 mm (observed) to 240 mm (treatments auto-10.1 and auto-18.1) and 180 mm (treatments auto-10.2 and auto-18.2). Additionally, the automatic irrigation events were set to start 11 days earlier (treatments auto-10.3 and auto-18.3) or 16 days later (treatments auto-10.4 and auto-18.4) than the base treatments (observed).

Table 4.18 Observed and simulated (automatic irrigation every 14 days) irrigation events during the ^{15}N experiment in 2005.

Irrigation	**Observed**	**Automatic (simulated)**			
Treatment	10 / 18	auto-10.1 / 18.1	auto-10.2 / 18.2	auto-10.3 / 18.3	auto-10.4 / 18.4
Amount per event	individual	40 mm	30 mm	30 mm	30 mm
Total amount	280 mm	240 mm	180 mm	180 mm	150 mm
Day after seeding				14	
	25	24	24	28	
		38	38	42	41
	55	52	52	56	55
	72	66	66	70	69
	88	80	80	84	83
	106	94	94		97

* *treatment 10: DUUf, 120 kg N ha*$^{-1}$
treatment 18: DUUf, 250 kg N ha^{-1}

4.10 Data validation and statistical analysis

4.10.1 Data pre-testing

For data pre-testing, Moore and McCabe (2006) were followed. For sample sizes larger than 40, no test of normality is necessary, even if the distribution would clearly be skewed (Moore and McCabe 2006). A pre-test on the equality of variance, e.g., the Levene's Test, should be avoided (Underwood 1998). Furthermore, parametrical tests as analysis of variance (ANOVA) are robust against departures from homoscedasticity (Underwood 1998, Moore and McCabe 2006). In case of heteroscedacity, the ANOVA would give most conservative results. For cases of largely unequal standard deviations, however, and for non-significant model results, simultaneous confidence intervals (90 %) were displayed to facilitate data interpretation (Gardner and Altman 1986, Tukey 1991, Almond et al. 2000, Hoenig and Heisey 2001).

4.10.2 ANOVA and post-hoc procedures

The ANOVA was carried out with the statistical programs SAS for Windows version 9.1 (SAS Institute 2005) and SPSS for Windows version 14.0 (SPSS Inc. 2005).

The ANOVA was handled in the classical linear form (general linear model) and as a special case of the generalized linear model (GLM) according to the more recent theory of McCullagh and Nelder (1999). The statistical program STATA for Windows version 9.2 (StataCorp 2007) was then used for the GLM-ANOVA for running maximum likelihood ratio tests (model checking), bootstrapping (robustness tests) and permutation tests (non-parametric) as described in Moore and McCabe (2006). The maximum likelihood test in STATA was used to confirm that the reduced model was sufficient. Using GLM has the advantage that an objective test for model checking can be used, i.e., maximum likelihood ratio test.

Means of factors were separated (least significant difference, LSD) by multiple comparisons (post-hoc procedure) at the 10 % level of significance using F-tests (Tukey's Honestly Significant Difference (HSD) test (Tukey 1953)). For unbalanced designs, the conservative Tukey-Kramer F-test was used (Kramer 1956, Hayter 1984). The threshold significance level of $p<0.25$ was used to exclude effects of factors or interactions from further analysis (Winer et al. 1991).

4.10.3 Outliers and missing values

An outlier is an individual observation that is located outside the particular pattern of a distribution (Good and Hardin 2006, Moore and McCabe 2006). However, straightforwardly correcting or deleting outliers from the data sets is problematic, as the outlier is always relative to a pattern of the expected data (i.e., a model). Thus, first detecting outliers by assuming a model to be true and then later testing that model with the same data just corrected would be rather controversial. Such a flaw was avoided by using disjoint hypotheses, i.e., the assumption that was used to check for irregularities was not tested later.

To validate the soil N_{tot} and ^{15}N data for cotton and wheat obtained from the laboratory, the simple assumption was that the concentration of surface-applied N (N_{tot} and ^{15}N) decreases exponentially with soil depth due to enhanced mineralization in the top layer (equation (4.21)) (Ottman and Pope 2000, Gastal and Lemaire 2002):

$$N = A \times e^{-B \times \text{depth}} \tag{4.21}$$

where A und B are parameters describing the surface concentration and the half-life characteristic of the soil.

Influential observations, therefore, are those singular extreme points that, by pulling the regression line towards them, distinctly change the parameter estimates (Belsley et al. 1980, Good and Hardin 2006, p.158, Moore and McCabe 2006, p. 162). There are two main measures that could be used to describe such data irregularities from this simple pattern: residuals and dfbetas (Belsley et al. 1980). Rather than using residuals, i.e., the difference between the observed and the predicted value of the regression line (Moore and McCabe 2006, p. 154), the measure dfbeta was chosen to detect putative outliers[14]. A size-adjusted cutoff of dfbeta values $\geq \frac{2}{\sqrt{n}}$, with *n* being the number of sample observations, was applied to reject those influencing cases (Belsley et al. 1980). For the determination of dfbeta values via linear regression, the data were log-transformed ($\ln(N_{tot}, {}^{15}N)$). Those calculated dfbeta values were selected that were larger than $\frac{2}{\sqrt{20}} = 0.45$ (n = 4 fertilizer treatments x 5 soil depth steps). Declared influential outliers were excluded from further analysis and were replaced by imputation (replacement by means of the remaining group replicates).

For outliers in the wheat plant data, the relationship between plant number per m² (plant density) and total dry stem weight per m² of the original complete data set[15] was checked with the regression (equation (4.22)):

$$P = m \times StW \tag{4.22}$$

where P is the expected plant density, m is the slope, and StW the measured stem weight. Those plant density measurements differing more than the 90% confidence interval from the calibrated values were corrected by halving their difference (measured-expected) towards the calibration line. Missing values were imputed by their calibration values multiplied with 1 %.

Similarly, missing values in the data sets were substituted by means of the remaining replications (e.g., yield data of the ${}^{15}N$ experiment: replication 1, T2, T3 and T8).

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[14] "The dfbeta statistics are the scaled measures of the change in each parameter estimate and are calculated by deleting the ith observation: In general, large values of dfbetas indicate observations that are influential in estimating a given parameter" (Belsley et al. 1980). This diagnostic was preferred over the residuals as criterion as a small residual value might still be an influential data point (i.e., large dfbeta) (Cook and Weisberg 1982, Agresti 1990, Williams 19878)

[15] Non-averaged data, i.e., all sub-plots of all treatments

4.10.4 Evaluation of model performance

The model performance can be evaluated by indicators such as the root mean square error (RMSE) of the observed vs. simulated results (e.g., Stockle et al. 2003). The RMSE gives the variance of the estimates (also standard error of the estimates), i.e., the distance of the observations from the regression line, and is calculated following equation (4.23) (Underwood 1998):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left[M(t_i) - S(t_i, b)\right]^2}{n - 1}} \tag{4.23}$$

where $M(t_i)$ is observed value at time t_i, $S(t_i,b)$ is predicted value at time t_i, and n is the total number of parameters. When relating the RMSE to the observed mean, the relative magnitude of the standard error can be derived (Stockle et al. 2003). Yields from the ^{15}N experiment and from the response experiments were used for the model evaluation.

5 FERTILIZER EFFECTS ON YIELD

5.1 Cotton experiments (2004-2005)

5.1.1 Cotton minus-1 experiments

The average total raw cotton yield from the minus-1 experiments was 4.5 t ha^{-1}. The ANOVA[16] was significant for the main factors location ($p = 0.00$) and treatment ($p = 0.00$). Also, the interaction location x treatment were significant ($p = 0.09$), reflecting the fact that not all locations had the same cropping and fertilization history, seeding date and management. (Table 5.1). For all locations except Kushkupir-LL, the treatment without N application (-N) was always amongst the lowest-yielding treatments. However, it did not differ significantly from the fully fertilized treatment (NPK), except at location Shavot. Significant differences were only found in relation to the treatment without K fertilizer (-K), i.e., at the locations Shavot, Yangiaryk and Yangibozor. The treatments at locations Khonka, Kushkupir-LL, Kushkupir-HL and Urgench did not differ significantly.

The post-hoc test shows that from all experimental locations, highest yields were achieved at Shavot (4.6 ± 0.8 t ha^{-1}) and Kushkupir-HL (4.5 ± 0.6 t ha^{-1}). Significantly lower cotton yields were harvested at Kushkupir-LL (3.8 ± 0.4 t ha^{-1}), Urgench (3.6 ± 0.6 t ha^{-1}), Yangibozor (3.7 ± 0.4 t ha^{-1}) and Yangiaryk (4.0 ± 0.6 t ha^{-1}).

Total raw cotton yield for the treatment without N application (-N) was significantly lower (mean: 3.6 ± 0.5 t ha^{-1}) than for all other treatments. Yields of -P and -K treatments did not significantly differ from the yields of the fully fertilized treatment (NPK, mean: 4.2 ± 0.6 t ha^{-1}).

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[16] The ANOVA model used was $\text{yield} = \mu + \text{loc} + \text{treat} + \text{loc} \times \text{treat} + \varepsilon_0$; in the following only models differing from this will be noted.

Table 5.1 Average total raw cotton yield (t ha^{-1}) for the minus-1 treatments at seven locations in Khorezm (n = 4) in 2004.

Location	**Treatment**	**Mean**	**SE**	p**<0.1**	**NUE$_{AE}$**
		kg ha^{-1}			kg kg^{-1}
Khonka	-N	3.9	0.3	-	
	-P	4.4	0.1	-	
	-K	4.3	0.1	-	
	NPK	3.9	0.1	-	0.5
Kushkupir HL	-N	4.3	0.2	-	
	-P	4.4	0.3	-	
	-K	5.0	0.4	-	
	NPK	4.4	0.1	-	0.6
Kushkupir LL	-N	3.9	0.3	-	
	-P	3.8	0.3	-	
	-K	3.9	0.2	-	
	NPK	3.7	0.1	-	-0.9
Shavot	-N	3.6	0.1	a	
	-P	4.4	0.2	a	
	-K	5.0	0.3	b	
	NPK	5.3	0.4	b	8.3
Urgench	-N	3.1	0.1	-	
	-P	3.8	0.4	-	
	-K	3.7	0.4	-	
	NPK	3.8	0.3	-	3.6
Yangibozor	-N	3.4	0.2	a	
	-P	3.6	0.2	ab	
	-K	4.0	0.0	b	
	NPK	3.8	0.2	ab	1.9
Yangiaryk	-N	3.3	0.1	a	
	-P	4.0	0.4	ab	
	-K	4.4	0.2	b	
	NPK	4.1	0.2	ab	4.0
Mean (n = 28)	-N	3.6	0.1	a	
	-P	4.1	0.1	b	
	-K	4.3	0.1	b	
	NPK	4.2	0.1	b	2.6

Means with the same letter in the column are not significantly different according to the Tuckey test; “-“= model not significant, no significant differences

The agronomic N-use efficiency (NUE$_{AE}$), i.e., the yield increase for each kg N applied, was calculated only for treatment NPK using the -N treatment as the base treatment (the treatment NPK in the minus-1 experiments was fertilized with 200 kg N ha^{-1} (see section methods, Table). The average NUE$_{AE}$ for this treatment was 2.6 kg kg N^{-1}.

The different locations show different increases in yield between the unfertilized -N treatment and the NPK treatment. In Shavot, the NUE$_{AE}$ was highest with 8.3 kg yield increase per kg N applied followed by Yangiaryk and Urgench, where treatments show little increases of 4.0 and 3.6 kg kg^{-1}, respectively. The NPK treatment in Yangibozor also yielded more cotton than the -N treatment, although only with a very low NUE_{AE} of 1.9 kg yield kg N^{-1}. The other three locations do not show any difference in NUE_{AE} between the -N and NPK treatments.

The absence of relevant yield differences between the treatments -N and NPK due to the high yields of the treatments without N fertilizer is striking as several experimental locations had shown the typical visual symptoms of N deficiencies such as yellow leaves at flowering stage (IFA 1992, CRC 2007) in the -N treatments as compared to the NPK treatments (Figure 5.1).

Figure 5.1 Cotton minus-1 experiment in Yangiaryk, July 2004. The -N treatment shows yellow leaves in comparison to the greener adjacent -K treatment.

Cotton yields differed according to the four picking times. The ANOVA (pick, location, treatment) was highly significant for the interactions location x pick ($p = 0.00$), and location x treatment x pick ($p = 0.00$). This indicates the influence of location-related management differences and the individual picking times (see Figure 5.2). The interactions location x treatment ($p = 0.23$) and treatment x pick ($p = 0.25$) were not significant.

The share of the total yield generally followed the order of pick 1 > pick 2, pick 3 > pick 4 for all treatments, i.e., the later the pick, the less cotton was harvested. Overall, the -N treatments yielded less cotton at all picks than the other three treatments (Figure 5.2). The difference was less pronounced for pick 1 and 2, and significant for the other two picks (Appendix 15.10). At pick 3 and 4, the average yields of the NPK treatment were significantly higher than for the -N treatment.

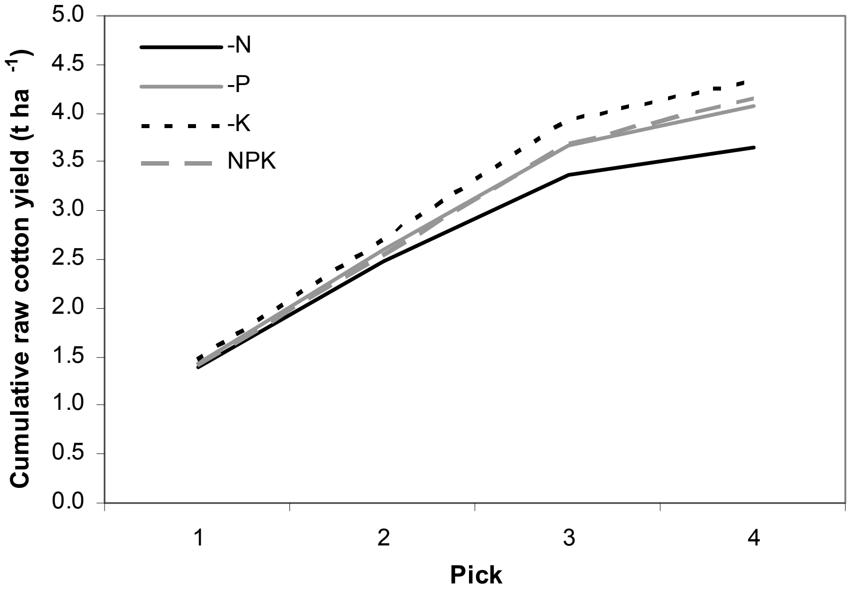

Figure 5.2 Cumulative raw cotton yield (t ha^{-1}) of the four picks of the minus-1 treatments in 2004.

5.1.2 Cotton response experiments

The average total raw cotton yield of the response experiments was 3.5 t ha^{-1}, and ranged from 3.2 t ha^{-1} (N-0) to 3.7 t ha^{-1} (N-160 and N-200). The ANOVA model for the different N rates and locations as well as the interactions, therefore, was not significant ($p = 0.29$). Generally, average cotton yields for the response-LL site were relatively higher than those of the response-ML site (Figure 5.3).

Evaluating the cotton response to N fertilizer, the NUE_{AE} was highest for N-80 with 4.7 kg yield increase for each kg N applied (Table 5.2). All other N rates had a lower efficiency, although the differences were not statistically significant due to high standard deviations (model significance $p = 0.44$). Also, no significant interactions were detected. The treatments N-0 and N-200 of the response experiment are similar to the -N and NPK treatments of the minus-1 experiments with respect to the N rate applied and cotton yields of the respective treatments were similar. The yield difference (0 vs. 200 kg ha^{-1}) ranged between 0.5 and 0.6 t ha^{-1}, and the NUE_{AE} of the treatments NPK and N-200 was 2.6 and 2.2 kg yield kg N^{-1}, respectively.

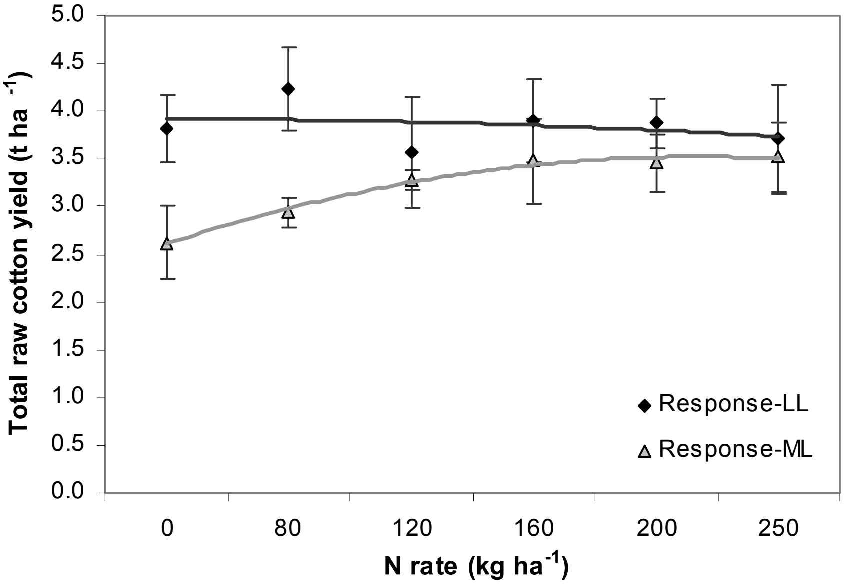

Figure 5.3 Average total raw cotton yield (t ha^{-1}) of the response experiments per treatment for six N rates (kg ha^{-1}) and two locations in Khorezm in 2004. Error bars represent 1 SE of the mean.

Table 5.2 Agronomic N-use efficiency (NUE$_{AE}$, kg yield kg N^{-1}) according to N rates and location (n = 4). SE indicates the standard error of the mean.

N rate	**NUE$_{AE}$**			
	Response-LL		Response-HL	
	Mean	SE	**Mean**	SE
kg ha^{-1}	kg yield kg N^{-1}			
80	5.3	2.4	4.1	2.9
120	-2.0	2.5	5.4	3.9
160	0.5	1.1	5.4	5.0
200	0.3	2.0	4.2	2.3
250	-0.4	1.5	3.6	0.1

Distinguishing yields of the individual picks, the ANOVA indicated that the factors location (p = 0.00), pick (p = 0.00) and location x pick (p = 0.00) had a significant influence on the yield. The significant interaction reflects the effect of management at the different locations on the picking time. On the other hand, the N rate had no significant effect on the yield at either location (p = 0.76). Also, the interactions location x N rate (p = 0.53) and N rate x pick (p = 0.74) and location x N rate x pick (p = 0.99) were not significant. Cotton yields of all picks were significantly higher for the response-LL than for the response-ML site. This tendency coincided with the total yields (Figure 5.3). The yields significantly decreased in the order pick 2 > pick 1> pick 3, pick 4 (Figure 5.4).

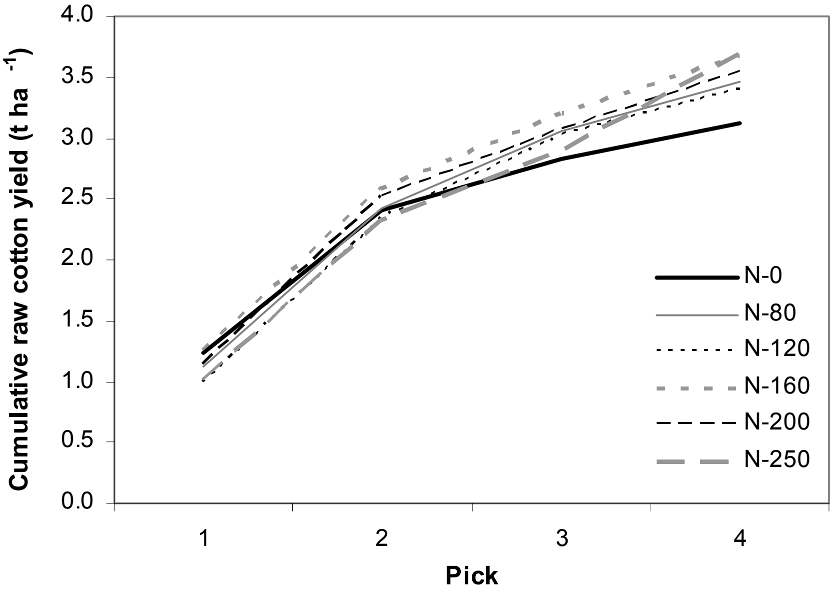

Figure 5.4 Cumulative raw cotton yield (t ha^{-1}) of the response experiments for four picks for the respective N rates (kg ha^{-1}) in 2004.

5.1.3 Cotton ^{15}N Experiment

Irrigation

The total irrigation water applied to the ^{15}N experiment was on average 275 mm (detailed irrigation events and amounts for the ^{15}N cotton experiment are given in Appendix 15.11). For some devices such as the RBC flume, measurements were frequently not possible due to cracks in the dried soil. According to calculations from treatment T12-R1, where measurements could be taken continuously with the quadratic weir, the total water applied to the experimental field was 285 mm.

Yield, harvest index and agronomic nitrogen-use efficiency

The total raw cotton yield was on average 4.4 t ha^{-1}. Yields in the first three plots in replication 1 (T3, T2 and T8), however, were exceptionally low (1.1-1.9 t ha^{-1}) due to rather patchy cotton germination (Figure 5.5). These treatments were excluded from analysis and replaced with the mean of the other replicates. Treatment T12 (160-DUUr) in replication 2 was the only plot where more than 6 t cotton ha^{-1} were harvested

(6.2 t ha^{-1}), while lowest cotton yields were harvested from treatment T14 (160-DUUf) in replication 4 (3.2 t ha^{-1}). As both treatments were located at the outer left side (main wind direction North-South) of the experimental field, there seemed to have been no consistent influence in this direction of the experimental site (wind direction N-S).

Figure 5.5 Field layout and spatial distribution of total raw cotton yields (t ha^{-1}) in Maksud Garden in 2005.

The ANOVA (N rate, fertilizer) was not significant for yield ($p = 0.93$) or NUE_{AE} ($p = 0.93$). Also, the N rate x fertilizer interactions for yield were not significant ($p = 0.88$). For the harvest index, it was significant for the N rates ($p = 0.01$). The interactions were not significant ($p = 0.89$). A slight N-fertilizer response could be observed with yields increasing from 4.3 ± 0.8 t ha^{-1} to 5.0 ± 0.2 t ha^{-1} from treatment N-0 to treatment 120-DUUf (Table 5.3). In comparison to the fertilized treatments, the treatments NPK-0 and N-0 yielded unexpectedly high amounts of cotton of 4.0 and 4.3 t ha^{-1}, respectively, as also observed in the minus-1 and response experiments (see section 5.1.1).

Table 5.3 Average total raw cotton yield (t ha^{-1}), and harvest indices for fertilizer treatments in 2005 ($n = 4$). SE denotes standard error of the mean.

Treatment	**N rate**	**Fertilizer***	**Cotton yield**		**Harvest index**	
			Mean	SE	**Mean**	SE
	kg ha^{-1}		t ha^{-1}			
1	0	NPK-0	**4.0**	0.3	**0.46**	0.04
2	0	N-0	**4.3**	0.4	**0.48**	0.01
3	40	DAP only	**4.2**	0.2	**0.51**	0.01
4	80	DUUr	**4.1**	0.2	**0.46**	0.03
5		UUU	**4.1**	0.5	**0.45**	0.02
6		DUUf	**4.6**	0.3	**0.45**	0.03
7		DAA	**4.3**	0.3	**0.46**	0.03
8	120	DUUr	**4.5**	0.2	**0.44**	0.01
9		UUU	**4.6**	0.4	**0.44**	0.02
10		DUUf	**5.0**	0.1	**0.46**	0.02
11		DAA	**4.6**	0.3	**0.48**	0.02
12	160	DUUr	**4.7**	0.6	**0.43**	0.04
13		UUU	**4.5**	0.3	**0.40**	0.03
14		DUUf	**4.3**	0.5	**0.38**	0.04
15		DAA	**4.3**	0.5	**0.41**	0.02

* *DUUr = 3 splits at the recommended plant growth stages, using DAP, urea, and urea fertilizer*
UUU = 3 splits at the recommended plant growth stages, using urea, urea,and urea fertilizer
DUUf = 3 splits according to farmers' practice, using DAP, urea, and urea fertilizer
DAA = 3 splits at the recommended plant growth stages, using DAP, ammonium nitrate, and ammonium rate

The harvest index decreased with increasing N application amounts in the order N-0 > N-80, N-120 > N-160 (Table 5.3). The harvest indices of treatments DUUr and UUU decreased continuously with increasing N rates, while the harvest index of treatments DUUf and DAA increased at N-120 before decreasing again. At the highest N rate, the harvest index of treatment DUUr was the highest and that of DUUf the lowest.

The harvest index of treatment DAP was highest of all treatments with 0.51 ± 0.02. This indicates a “haying-off” effect (McDonald 1989), i.e., stimulated biomass production in response to initial high soil N content and lack of N and soil at later stages (this treatment received N only at seeding).

Table 5.4 Average total agronomic N-use efficiency ($NUE_{AE,}$ kg yield kg N^{-1}) for fertilizer treatments in 2005 (n = 4). SE denotes standard error of the mean.

Treatment	**N rate**	**Fertilizer**	**NUE_{AE}**	
			Mean	SE
	kg ha^{-1}		kg yield kg N^{-1}	
1	0	NPK-0		
2	0	N-0		
3	40	DAP only	**1.0**	5.7
4	80	DUUr	**0.0**	4.9
5		UUU	**-0.5**	3.9
6		DUUf	**6.1**	2.9
7		DAA	**2.4**	6.6
8	120	DUUr	**2.8**	2.3
9		UUU	**3.9**	3.5
10		DUUf	**6.8**	3.5
11		DAA	**4.0**	1.1
12	160	DUUr	**3.6**	1.6
13		UUU	**2.1**	3.0
14		DUUf	**0.9**	1.8
15		DAA	**1.2**	2.6

The average NUE_{AE} was very low for all treatments and N rates (Table 5.4), ranging from -0.5 kg kg^{-1} (80-UUU) to maximum 6.8 kg kg^{-1} (120-DUUf). However, the standard deviation of the NUE_{AE} was very large, and no significant differences for the main factors or interactions could be detected. Such large deviations for NUE_{AE} values have been also reported elsewhere (e.g., Harmsen and Moraghan 1988)

The yields of pick 1 were always significantly higher than those of pick 2 or pick 3: Between 40-59 % of the total yield was harvested at pick 1, 29-40 % at pick 2 and 11-24 % at pick 3. The full ANOVA showed significant differences only for the picking time (p = 0.00). The interactions (N rate x treatment, treatment x pick, N rate x pick, and N rate x treatment x pick) were not significant (p = 0.97, p = 0.28, p = 0.46, and p = 0.89, respectively).

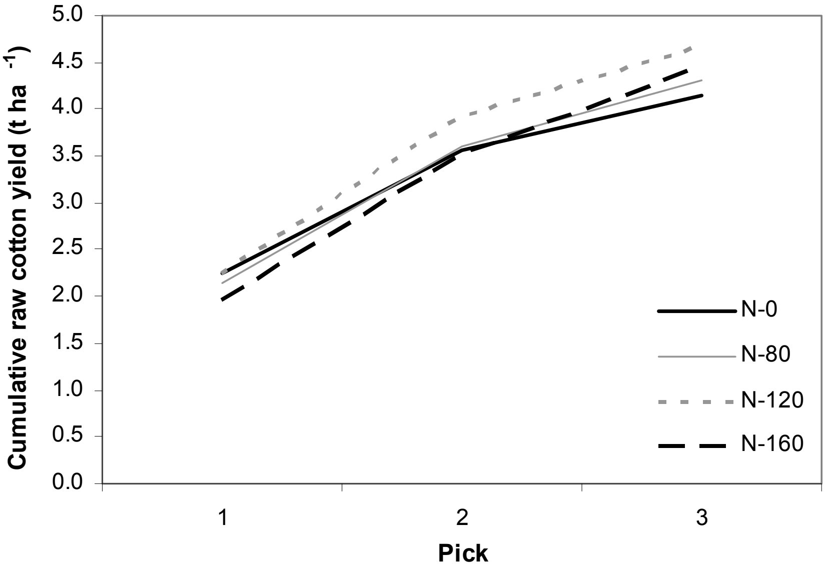

Figure 5.6 Cumulative raw cotton yield (t ha^{-1}) of the ^{15}N cotton experiment for three picks for the respective N rates (kg ha^{-1}) in 2005.

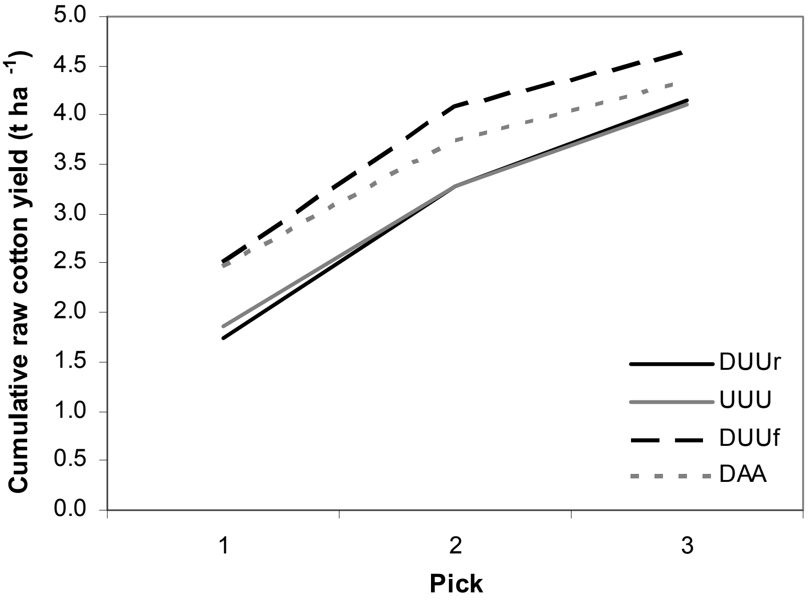

Figure 5.7 Cumulative raw cotton yields for three picks (t ha^{-1}) for fertilizer treatments in 2005 (N rate: 80 kg ha^{-1}).

There was no particular trend in the different treatments, as the yields changed for the different N rates (Figure 5.6). For N-0, the yields were high at pick 1 and lowest at pick 3. For the higher N rates, the trend was the opposite: treatments N-120 and N-160 yielded lowest at pick 1 and highest at pick 3.

The N rates N-80 and N-120 for the treatments DUUf and DAA gave the highest yields for pick 1and lowest for pick 3, whereas for treatments UUU and DUUr the yield dynamics were found to be the other way around (Figure 5.7).

5.1.4 Comparison of cotton experiments (2004-2005)

The data of the minus-1 experiments, the response experiments and the ^{15}N experiments were combined for comparing the yield dynamics and lint quality (see section 9.1) for both years of experimentation.

Overall cotton yield was significantly higher in 2005 than in 2004 (Appendix 15.12). Comparing the yields of the three experiments, a similar yield response to N fertilizer to that of the ^{15}N experiment can be seen for all experiments. Unfertilized plots yielded on average 3.7 t cotton ha^{-1}, whereas the highest fertilized treatments (N-250) produced 3.6 t cotton ha^{-1}. Maximum cotton yields of 4.2 t ha^{-1} were achieved at the fertilizer rate of 128 kg N ha^{-1}.

The official average yields in Khorezm in 2004 and 2005 were reported to be 2.58 and 2.64 t ha^{-1}, respectively (Djumaniyazov 2004). In relation to the official Khorezm-wide yield, the experimental yields were higher for any fertilizer rate, including the control. In relation to official fertilizer recommendations, the harvested cotton from the experimental sites was higher for the rate of 200 kg N ha^{-1}, while for the recommended rate of 250 kg N ha^{-1}, the yields were at the lower end of the predicted yield.

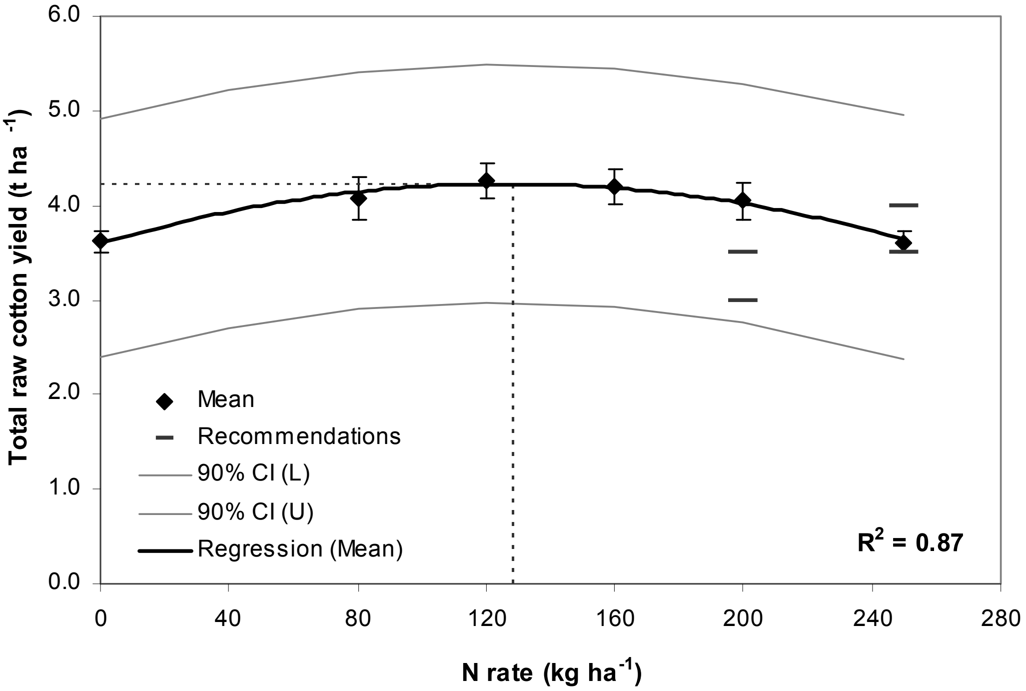

Figure 5.8 Total raw cotton yields (t ha^{-1}) for N rates (kg ha^{-1}) of the minus-1 experiments (2004), the response experiments (2004) and the ^{15}N experiment (2005).
Symbols: Total mean (black) values for N rates. Error bars represent 1 SE of the mean. The short lines represent the expected yield at the officially recommended N rates (Cotton Research Institute 2007)
Lines: Regression line (black) for average yields for the respective N rate. 90%-confidence intervals (grey, U = upper boundary; L = lower boundary). Maximum points are indicated by the dotted line.

5.2 Winter wheat experiments (2005-2006)

5.2.1 Winter wheat minus-1 experiments

The average yield of the minus-1 winter wheat experiments in 2006 was 3.0 t ha^{-1}. Significant differences were found for the main factors location ($p = 0.00$) and treatment ($p = 0.00$), but not for the interactions ($p = 0.41$): Kernel yield in Yangibozor was significantly higher (3.5 ± 0.8 t ha^{-1}) than on the sites in Urgench-LL and Urgench-ML (2.7 ± 0.7 and 2.8 ± 0.6 t ha^{-1}) (Table 5.5).

The minus-N treatment yielded significantly lower values than to all other treatments (2.2 ± 0.7 t ha^{-1}). The yield increase for every kg N applied (NUE_{AE}) was calculated for treatment NPK (N-180) with treatment -N (N-0) as reference. The average NUE_{AE} was 5.2 kg kernels kg N^{-1}. The rather low NUE_{AE}, reflecting the low yield increase between the -N and the NPK treatment[17], is similar to the low yield response in the cotton experiments (section 5.1).

Table 5.5 Average total winter wheat kernel yield (t ha^{-1}) for the minus-1 treatments at three locations in Khorezm (n = 4) in 2005.

Location	**Treatment**	**Mean**	**SE**	***p*<0.1**	**NUE_{AE}**
		kg ha^{-1}			kg kg^{-1}
Urgench-LL	-N	**1.8**	0.3	a	
	-P	**3.0**	0.2	b	
	-K	**3.1**	0.1	b	
	NPK	**3.0**	0.3	b	6.7
Urgench-ML	-N	**2.2**	0.4	a	
	-P	**2.7**	0.2	ab	
	-K	**3.2**	0.3	b	
	NPK	**3.0**	0.1	ab	4.4
Yangibozor	-N	**2.6**	0.3	a	
	-P	**4.1**	0.1	b	
	-K	**4.0**	0.1	b	
	NPK	**3.4**	0.4	ab	4.4
Mean (n = 12)	-N	**2.2**	0.2	a	
	-P	**3.3**	0.2	b	
	-K	**3.4**	0.2	b	
	NPK	**3.1**	0.2	b	5.2

Means with the same letter in the column are not significantly different according to the Tuckey test

5.2.2 Winter wheat response experiments

The calculated average winter wheat kernel yield was 2.9 t ha^{-1}, but the two locations differed significantly ($p = 0.07$): At the site response-LL, the yield was significantly lower (2.7 ± 0.5 t ha^{-1}) than at the response-ML site (3.0 ± 0.3 t ha^{-1}). Only for the treatment N-0, did the response-ML site yield more winter wheat (Figure 5.9). The N amount applied influenced the yield ($p = 0.03$): N rates of 180 and 240 kg ha^{-1} resulted in significantly higher yields (3.0 ± 0.4 t ha^{-1}) than the treatment N-0 (2.3 ± 0.6 t ha^{-1}). However, higher N rates, i.e., N-300, did not increase yields any further. The interactions were not significant ($p = 0.30$).

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[17] The calculations were done for normed yield data (see section 4.5.2). The measured harvested data are given in Appendix 15.14.

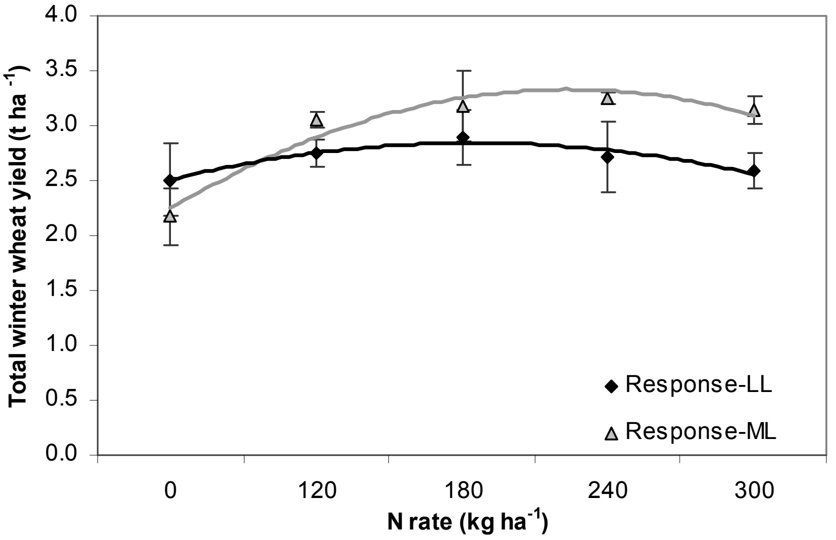

Figure 5.9 Average total winter wheat yield (t ha^{-1}) of the response experiments per treatment for five N rates (kg ha^{-1}) and two locations in Khorezm in 2005. Error bars represent 1 SE.

The average fertilizer-response ratio for the treatment N-180 was relatively low (NUE_{AE}: 2.9 kg kernels kg N^{-1}) compared to that calculated for the NPK treatment of the minus-1 experiments (see above). Highest NUE_{AE} values were found for treatment N-120 (3.4 kg kernels kg N^{-1}) (Table 5.6), although the differences between the treatments were not significant.

Table 5.6 Agronomic N-use efficiency (NUE_{AE}, kg kernels kg N^{-1}) for increasing N rates (kg yield increase per kg N applied) for two locations. SE denotes the standard error of the mean.

N rate	**NUE_{AE}**			
	Response-LL		Response-HL	
	Mean	SE	**Mean**	SE
kg ha^{-1}	kg kernels kg N^{-1}			
120	**3.4**	2.7	**3.3**	1.4
180	**2.8**	1.2	**2.9**	1.6
240	**1.6**	2.2	**2.5**	0.9
300	**0.8**	1.3	**1.6**	0.6

5.2.3 Wheat ^{15}N experiment

Irrigation

Total irrigation water amount applied to the winter wheat ^{15}N experiment was 919 mm (Appendix 15.13), which was more than officially recommended (600 mm). This was mainly due to a second irrigation event in 2005 (19.10.) following a series of warm days in autumn, and to pre-fertilization irrigation at the beginning of March 2006 (01.03.). But the individual irrigation amounts were also always higher than recommended (100 mm). Given that irrigation scheduling based on this schedule prevented any significant plant-water stress in 2005 which underlines the robustness of such management (Forkutsa et al. 2009a).

Yield, harvest index and agronomic nitrogen-use efficiency

The experimental layout and yield distribution is shown in Figure 5.10 (wind direction N-S).

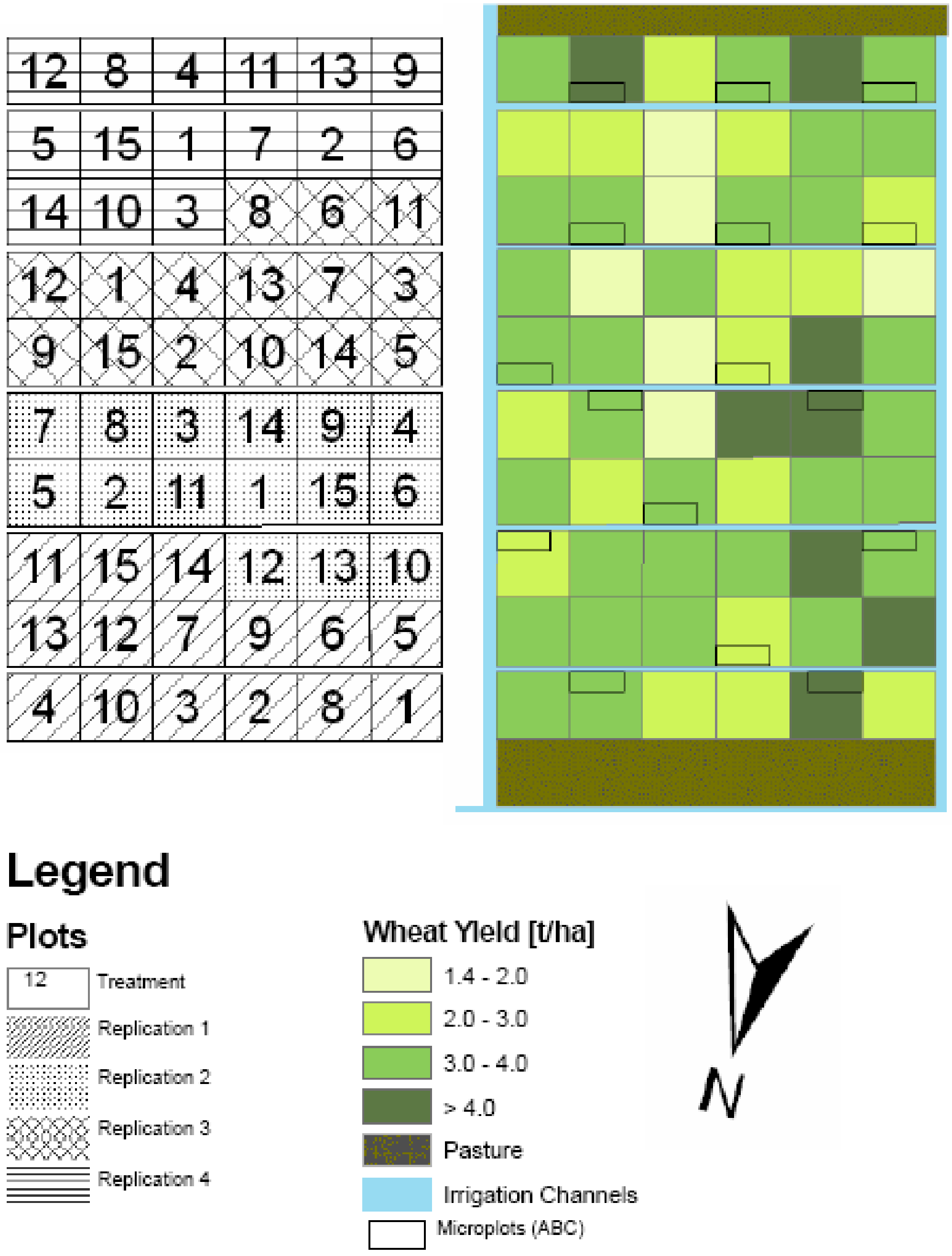

Figure 5.10 Spatial distribution of total winter wheat yield (t ha^{-1}) in 2006.

The average kernel yield was 3.2 ± 0.7 t ha^{-1}. The highest yield (3.8 ± 0.6 t ha^{-1}) was harvested from the treatment with the fertilizer rate N-160.Yields of fertilizer rates 0 and 20 kg N ha^{-1} were significantly lowerby around 1.2 t ha^{-1} than all other N rates (Figure 5.11,Table 5.7). Similarly, the harvest index of N-0 was significantly lower (0.40) than that of the other N rates. The highest harvest index of 0.45 was observed at N rates of 120 and 160 kg ha^{-1}.

Figure 5.11 Wheat ^{15}N experiment in Urgench, April 2006. The lighter colored treatments received 0 or 20 kg N ha^{-1}, while the dark green areas were fertilized with more than 80 kg N ha^{-1}.

The overall ANOVA for yield for the individual fertilizer treatments was significant ($p = 0.03$). However, the yields did not differ significantly amongst the different fertilizer treatments ($p = 0.17$), nor were they different for the N rates 80, 120 and 160 kg ha^{-1} ($p = 0.25$). The interactions were also not significant ($p = 0.64$). In general, treatment DAA gave lowest yields for all N rates, whereas treatment DUUu always yielded highest (Table 5.7).

Table 5.7 Averaged total winter wheat yield (t ha^{-1}), harvest indices and agronomic N-use efficiency (NUE$_{AE}$, kg kernels kg N^{-1}) in 2006 (n = 4). SE denotes standard error of the mean.

Treat	**N rate**	**Fertilizer***	**Wheat yield**			**Harvest index**			**NUE$_{AE}$**	
			Mean	***p*<0.1**	SE	**Mean**	***p*<0.1**	SE	**Mean**	SE
	kg ha^{-1}		t ha^{-1}						kg kernels kg N^{-1}	
1	0	NPK-0	**2.1**	a	0.3	**0.40**	a	0.02		
2	0	N-0	**2.3**	ab	0.4	**0.40**	a	0.03		
3	40	DAP	**2.1**	a	0.1	**0.41**	ab	0.02	**-4.9**	12.9
4	80	DUUr	**3.1**	abc	0.2	**0.43**	ab	0.01	**11.3**	5.1
5		UUU	**3.4**	bc	0.4	**0.43**	ab	0.01	**15.0**	6.3
6		DUUu	**3.6**	bc	0.2	**0.45**	ab	0.01	**17.1**	3.8
7		DAA	**3.0**	abc	0.3	**0.43**	ab	0.02	**10.4**	4.6
8	120	DUUr	**3.8**	c	0.3	**0.45**	ab	0.01	**13.4**	2.8
9		UUU	**3.5**	bc	0.3	**0.45**	ab	0.02	**10.9**	3.4
10		DUUu	**3.3**	abc	0.2	**0.47**	ab	0.02	**8.9**	1.3
11		DAA	**3.0**	abc	0.2	**0.45**	ab	0.02	**6.6**	1.1
12	160	DUUr	**3.5**	bc	0.1	**0.45**	ab	0.01	**8.0**	1.3
13		UUU	**3.8**	c	0.4	**0.44**	ab	0.02	**9.9**	1.2
14		DUUu	**3.9**	c	0.3	**0.48**	b	0.02	**10.4**	3.2
15		DAA	**3.3**	abc	0.2	**0.44**	ab	0.01	**7.0**	2.2

* *DUUr = 3 splits at the recommended plant growth stages, using DAP, urea, and urea fertilizer*
UUU = 3 splits at the recommended plant growth stages, using urea, urea, and urea fertilizer
DUUu = 4 splits, using DAP, urea, urea, and urea fertilizer
DAA = 3 splits at the recommended plant growth stages, using DAP, ammonium nitrate, and ammonium nitrate
Means with the same letter in the column are not significantly different according to the Tuckey test

The harvest indices of the different N rates did not significantly differ (p = 0.20). Furthermore, the treatments had similar harvest indices, yet treatment DUUu had always a higher harvest index for all N rates than the other treatments (Table 5.7). Especially pronounced was this difference for the N rate of 160 kg ha^{-1}, where the harvest index was 0.03 units higher as compared to the other treatments.

The mean NUE$_{AE}$ decreased with increasing N rates (Table 5.7). As in cotton, the spread of NUE$_{AE}$ amongst the treatments was very large with -4.9 to 17.1 kg yield increases per kg N fertilizer for treatments DAP and 80-DUUu, respectively, resulting in an absence of significant differences (p = 0.60). Treatment DAA tended to have the lowest yields, whereas treatment DUUu and UUU always show the highest NUE$_{AE}$.

5.2.4 Comparison of winter wheat experiments (2005-2006)

The data of the minus-1 experiments, the response experiments and the ^{15}N experiments were combined for comparing the yield dynamics and quality for both study years. Data from the rotation experiments conducted in 2003/04 in Urgench district were also added (Appendix 15.14)

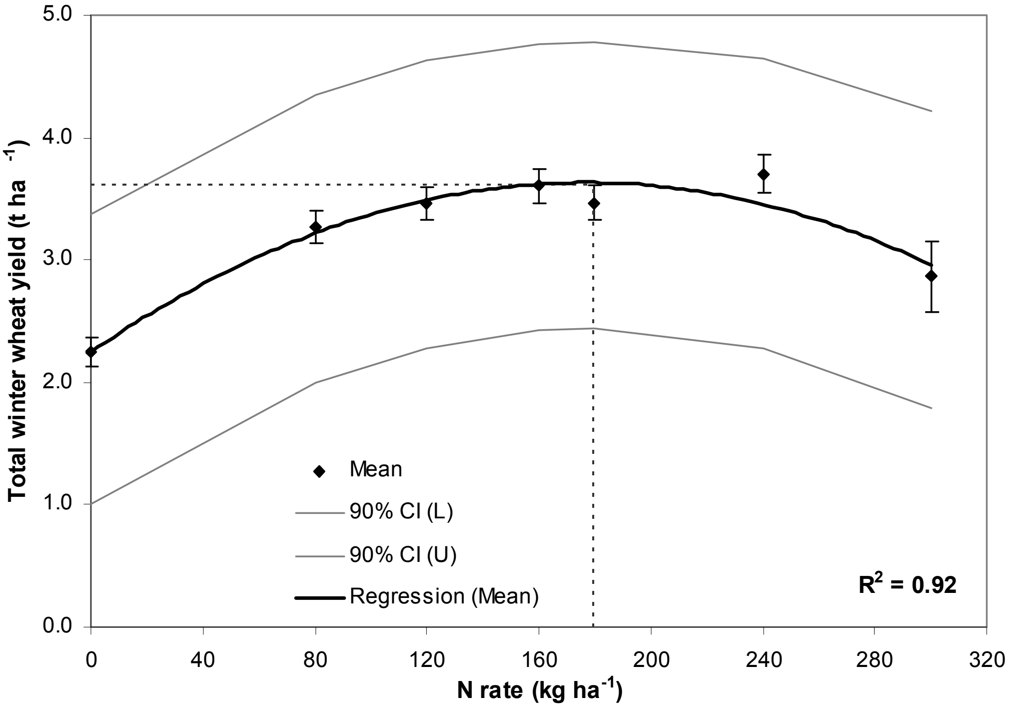

Figure 5.12 Total winter wheat yields (t ha^{-1}) for the respective N rates (kg ha^{-1}) from the rotation experiments (2003/04), the minus-1 experiments (2004/05), the response experiments (2004/05) and the ^{15}N experiment (2005/06).
Symbols: Total mean (black) values for the respective N rate. Error bars represent 1 SE of the mean.
Line: Regression line (black) for average yields for the respective N rate. 90%-Confidence intervals (grey, U = upper boundary; L = lower boundary). Maximum points are indicated by the dotted line.

Combining the total winter wheat yields of the different experiments gave a clear N response (Figure 5.12, Table 9.2). The yield response to N fertilizer follows the quadratic functional form. Highest yields (3.6 t ha^{-1}) were achieved at the N rate 180 kg ha^{-1}. Yields declined for N rates lower or higher than 180 kg ha^{-1}, with significantly lower yields at the rate of N-0 (2.3 t ha^{-1}) and N-300 (2.9 t ha^{-1}).

According to official statistics, in Khorezm 4.2, 4.3 and 4.6 t wheat ha^{-1} was harvested in the years 2004 to 2006 (OblStat 2004, OblStat 2005, OblStat 2006). Uzbekistan-wide, the wheat harvest increased from 3.7 to 4.1 t ha^{-1} from 2004 to 2006 (FAOSTAT 2008). A direct comparison of the research results shown above and the official data, however, is limited, as the presented results were calculated using the same (outlier-corrected) plant density (see section 4.5.2; Appendix 15.14). Looking at the 90 %-confidence intervals of the research data, the official wheat yield data are within the upper interval boundaries of the experiments for the rates 160 to 200 kg N ha^{-1}. The yield predictions with the official fertilizer recommendations of 5 t wheat ha^{-1} for application rates of 180 kg N ha^{-1}, however, are much higher than the research or the official yields.

5.3 Discussion of cotton and wheat yield response to nitrogen fertilizer

Cotton yields of the fertilized treatments in this study were comparable to those observed by other Uzbek researchers (e.g., Sabirov 1974, Khodjizadaeva et al. 1978, Djumaniyazov 2004, Ibragimov 2007). For the N rate of 200 kg ha^{-1}, for example, studies document yields of 4.0 t ha^{-1} (Khodjizadaeva et al. 1978), 4.4 t ha^{-1} (Ibragimov and Rustamova 1988 in Djumaniyazov 2004), 3.8 t ha^{-1} (Sabirov and Rustamova 2002 in Djumaniyazov 2004), and 3.2 t ha^{-1} (Masharipov 2004 in Djumaniyazov 2004). Up-to-date data on winter wheat yield response to N-fertilizer amendments under irrigated conditions, on the other hand, were not available to the author. This is in part due to the fact that winter wheat production in the past was conducted in the rain-fed areas of Uzbekistan (Khakimov 2008, Djumanyiazova forthcoming). In one study, however, Ergamberdiev (2007) reported wheat yields in the Khiva district of Khorezm of 5.5 t ha^{-1} fertilized at the recommended rate of 180 kg N ha^{-1}, which is 1 t higher than the reported wheat yields for Khorezm (OblStat 2004, OblStat 2005, OblStat 2006) and on the national level (FAOSTAT 2008). In this study, the highest wheat yields at this N rate also were 4.0 and 6.0 t ha^{-1} in 2005 and 2006, respectively (Appendix 15.14, Appendix 15.15, thus confirming the findings of Ergamberdiev (2007).

A striking result of the cotton and wheat experiments, however, was the high yield on the unfertilized plots, and the absence of significant yield differences with increasing N-fertilizer rates, even though several experimental locations show the typical visual symptoms of N deficiencies such as light green wheat plants particularly on the control treatments (no N fertilizer) as compared to the fertilized treatments (Figure 5.11). High yields comparable to those in this study on unfertilized plots were also observed by Hasanov (1970) (3.6 t ha^{-1}) in the Bukhara region, and by Khodjizadaeva et al. (1978) (3.0 t ha^{-1}) and Ibragimov and Rustamova (1988 in Djumaniyazov 2004) (3.3 t ha^{-1}) in the Khorezm region. The comparatively low response to N fertilization contrasts with the generally reported response of cotton to N applications worldwide.

A lack of N responses of cotton to N amendments have been documented extensively. Ibragimov and Rustamova (1988) found no differences in yields between N rates of 200, 250 or 300 kg ha^{-1} (Djumaniyazov 2004). In the San Joaquin Valley of California, USA, Fritschi et al. (2003) show significant yield increases for irrigated Pima and Acala cotton grown on a sandy and a clay loam with differences of up to 1136 kg ha^{-1} lint (around 3.1 t raw cotton ha^{-1}). At the same time, the authors found no response to N fertilizers on a sandy loam where the yield difference between minimum and maximum was 186 kg ha^{-1} lint, equal to approximately 0.5 t raw cotton ha^{-1}. Also, Chua et al. (2003) found no significant differences for the Ropesville site between the treatment receiving between 0 and 202 kg N ha^{-1}. At the Lubbok site, yields differed significantly only between the unfertilized and all other fertilized treatments, irrespective of the N rate (Chua et al. 2003).

Winter wheat grown in South Australia also show significantly enhanced vegetative growth for higher N rates, but wheat grain yield was not necessarily increased (McDonald 1992). In fact, only in 3 out of 10 experimental sites responses were significant (McDonald 1992). In the US, rain-fed wheat yields did not respond significantly to N rates above 67 and 90 kg ha^{-1} (Westerman et al. 1994). Lloveras et al. (2001) found responses in Spanish winter wheat only to late applications when the previous N supply was insufficient for maximum yields. However, at the Gimenells site, differences in yield increases were insignificant. The authors argue that this could be caused by various factors including increased lodging of wheat with higher N rates, water stress at grain filling, or high residual soil NO_3-N levels before seeding.

6 SOIL AND GROUNDWATER NITRATE

6.1 Soil-N content of the ^{15}N experiments (cotton and wheat)

Soil characteristics before the start of the ^{15}N experiment with cotton in Maksud Garden were determined for 0-100 cm depth. After the cotton and wheat harvests in November 2005 and June 2006, samples were taken only down to 60 cm depth (Appendix 15.16, Appendix 15.17, and Appendix 15.18) as the main transformations of soil N and SOM were expected to take place in the upper soil layers. Furthermore, these samples were used for ^{15}N analysis, and only limited amounts of ^{15}N fertilizer were expected below this layer.

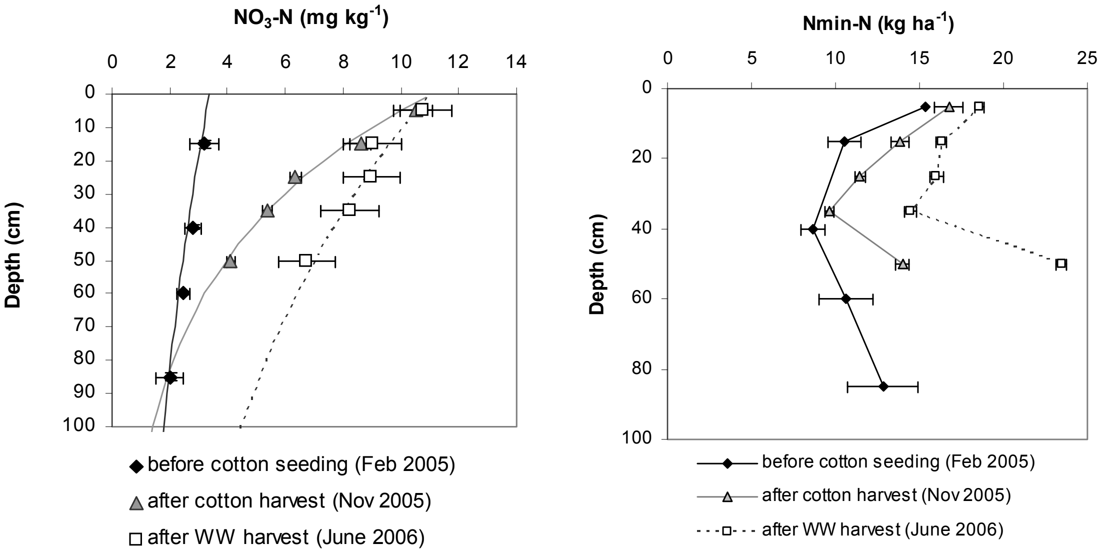

Figure 6.1 Mean NO_3-N content (mg kg^{-1}) and soil mineral N content (Nmin, mg kg^{-1} and kg ha^{-1}) in February 2005 (before cotton seeding), in November 2005 (after cotton harvest), and in June 2006 (after winter wheat harvest). Error bars represent the standard error of the mean.

The initial soil mineral N content (Nmin; sum of NH_4-N and NO_3-N) in the 0-70 cm profile before cotton seeding in 2005 was 9.5 mg kg^{-1}, which, based on bulk density measurements taken after the cotton harvest, equaled 29.8 kg Nmin ha^{-1} (Figure 6.1, Appendix 15.19). After cotton harvest, the Nmin content had increased to around 38.5 mg kg^{-1} in 0-60 cm, which is equivalent to 65.7 kg ha^{-1}. The Nmin content decreased to the depth of around 40 cm and then sharply increased for all sampling times, being especially pronounced for the time after the cotton and winter wheat harvest. No significant differences at $p<0.1$ in Nmin content were found for the fertilizer treatments; only the factor depth was significant (Figure 6.1).

6.2 Groundwater nitrate content in 2007 and 2008

The concentration of nitrate in the irrigation water during cotton and wheat growth was rather low (< 0.5 mg l^{-1}). Groundwater nitrate content was monitored after winter wheat harvest for the summer crops (carrot, cabbage and maize) in 2007 and during the whole winter wheat growth period in 2007/08.

The average nitrate content in the groundwater under the summer crops was 1.8 mg nitrate l^{-1} (Figure 6.2). However, the temporal dynamics of were very much linked to the irrigation and fertilization practices. Almost immediately after fertilization, however, the contamination of the groundwater with nitrate increased to a maximum of 7.8 mg nitrate l^{-1} in the piezometer Pz4. At the beginning of September, the levels had reached levels similar to those prior to fertilization.

The average nitrate content of the groundwater under winter wheat in 2008 was high (23.9 mg nitrate l^{-1}) (Figure 6.3). The minimum nitrate amount in the groundwater of 13.8 mg nitrate l^{-1} on 29.03.08 was measured one week after the last irrigation event (22.03.), while the maximum content of 44.4 mg nitrate l^{-1} on 02.04.08 was found one day after fertilization and irrigation had occurred (01.04.).

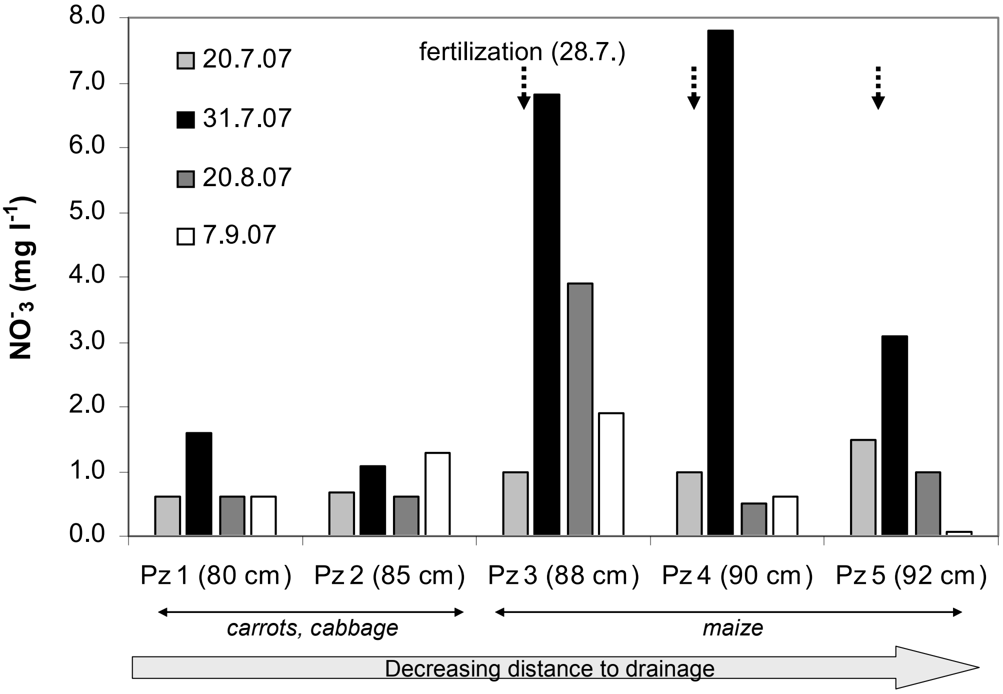

Figure 6.2 Nitrate measurements (mg l^{-1}) in five piezometers (Pz) for four irrigation events in 2007. Average groundwater depth is indicated in brackets. Pz 1 and 2 were installed in carrot and cabbage fields, Pz 3-5 in maize fields.

All measurements in 2008 represent the means of the nitrate test-sticks color step, as photometric measurements were not available. Therefore, individual observation wells showing 75 mg nitrate l^{-1} directly following irrigation could have an actual nitrate content ranging from 50-100 mg nitrate l^{-1}. Still, the overall trend was that nitrate levels in the groundwater increased with every management activity in the field (fertilization, irrigation).

Furthermore, the dynamics of the nitrate content in the water correspond to the changes in groundwater table depth: At times of shallow groundwater (due to irrigation inputs) the nitrate level in the water was also enhanced.

Both nitrate content and water table in general decreased in the direction of the drainage, i.e., from piezometer 1 (Pz1) to piezometer 4 (Pz4). Especially piezometer Pz1 reacted rapidly to fertilization and irrigation events.

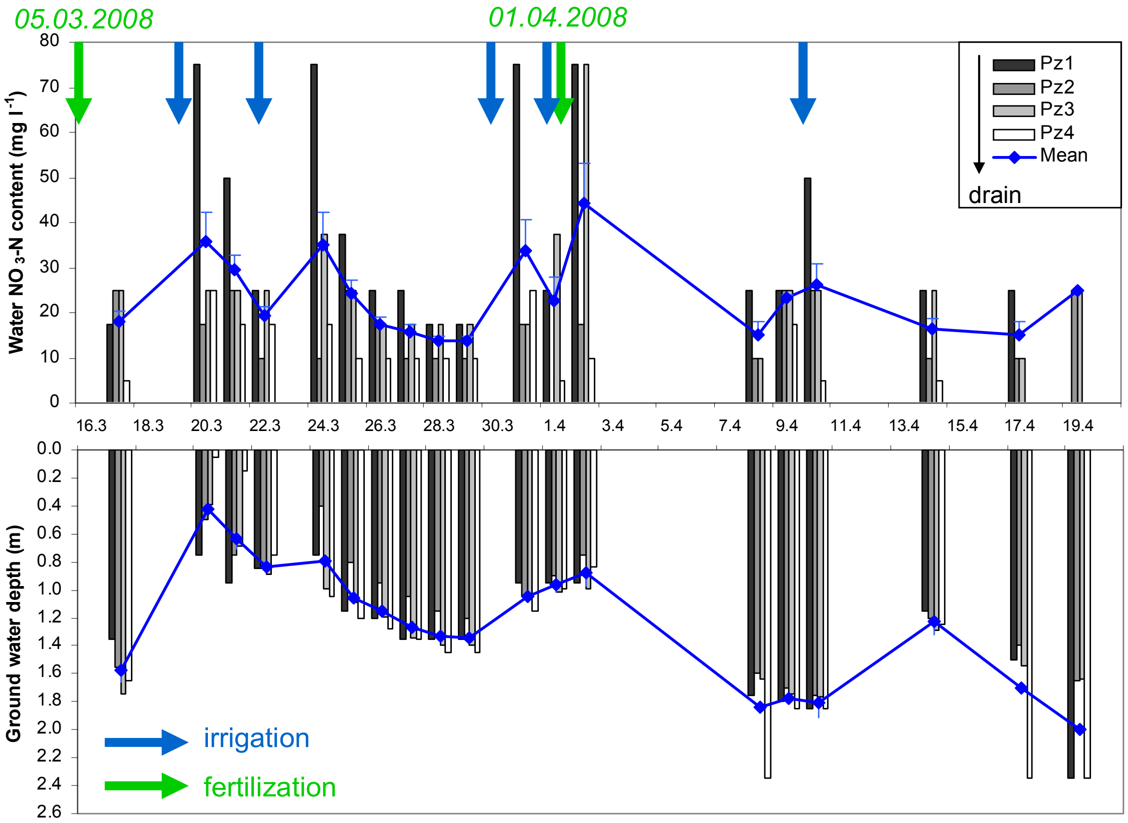

Figure 6.3 Nitrate measurements in groundwater (mg l^{-1}) and groundwater depth (m) in four piezometers (Pz) under winter wheat in 2008. The mean of the four piezometers is indicated as blue line. Fertilization occurred on March 5th and April 1st.

Under the assumption that nitrate is not adsorbed in the soil (Burns 1980), the upward flux of groundwater could be assumed to lead to the nitrate accumulation in the rooting zone. A groundwater contribution of 355 mm (see section 10.2) and an average nitrate concentration in the groundwater of 8 mg l^{-1} would therefore give an approximated upward movement of nitrate of 28 kg nitrate ha^{-1} or 6 kg NO_3-N ha^{-1} (see section 4.4.4). Presuming higher concentrations of 10 mg nitrate l^{-1} and higher (up to 75 mg nitrate l^{-1} as measured directly after irrigation) would consequently enhance also the NO_3-N amounts in the soil. The nitrate input from the irrigation water (280 mm) was with 3 kg nitrate ha^{-1} (at a concentration of 1 mg nitrate l^{-1}) noticeably lower. The calculated upward flux of water using the daily water balance simulations (see section 4.4.4) was 250 mm. With a groundwater flux between 250 and 355 mm and nitrate concentrations of 8-75 mg nitrate l^{-1} the nitrate contribution from the groundwater to the subsoil during the growing season was approximated to be around 23-269 kg nitrate ha^{-1} or 5-61 kg NO_3-N ha^{-1}.

6.3 Discussion - Soil and water nitrogen dynamics

6.3.1 Soil mineral nitrogen content

In the study by Chua et al. (2003), the soil-NO_3-N content after cotton harvest in the 0-60 cm layer was 182 and 159 kg ha^{-1} for treatments receiving 202 kg N ha^{-1}, and 36 and 44 kg NO_3-N ha^{-1} for the non-fertilized treatments. These authors argued that with such soil-N levels, N was not limiting yields. Also, in the North China Plain, wheat yield responses to N were not found when residual N in 0-90 cm depth was on average 212 kg N ha^{-1} (15.7 mg kg^{-1} assuming a bulk density of 1.5 g cm^{-3}) (Cui et al. 2006). Hutmacher et al. (2004) compared cotton yields over 5 years at 8 different locations in the same valley and found significant increases to be dependent on the residual NO_3-N content in the soil: With 70 kg NO_3-N ha^{-1} in 0-60 cm depth (7.8 mg kg^{-1} assuming a bulk density of 1.5 g cm^{-3}), the response to N applications was significant, whereas with an initial NO_3-N content of more than 125 kg ha^{-1} (13.9 mg kg^{-1} assuming a bulk density of 1.5 g cm^{-3}), only 2 out of the 11 sites responded significantly (Hutmacher et al. 2004). In Israel, Halevy and Klater (1970) found significant N response in Acala cotton of around 870 and 1200 kg lint ha^{-1} for application rates of 0 and 120 kg N ha^{-1} at the Kefar Glickson site. At the Bet She'an site, however, no response was observed despite the low NO_3-N content of around 171 kg ha^{-1} (19.0 mg kg^{-1} assuming a bulk density of 1.5 g cm^{-3}) in the top 0-60 cm (Halevy and Klater 1970). The authors argued that NO_3-N levels in the subsoil layer were found to be high enough to supply sufficient mineral N to the cotton plant, so that no response to N could be expected. For the Tashkent soils in Uzbekistan, Rasikov et al. (1980 in Ibragimov 2007) noted that in places where soil NO_3-N was as high as 200-300 kg ha^{-1}, cotton yields of 4.0 t ha^{-1} could be achieved without additional N applications.

The Uzbek classification for available N in the 0-60 cm soil horizon categorizes soil with N contents of < 135 kg ha^{-1} (around 15 mg kg^{-1} assuming a bulk density of 1.5 g cm^{-3}) as very low for cotton if yield levels of 3-4 t raw cotton ha^{-1} are to be achieved (section 2.2.5) (Cotton Research Institute 2007). With an initial NO_3-N content of 26 kg ha^{-1} (2.9 mg kg^{-1}) and 3 kg ha^{-1} NH_4-N (0.33 mg kg^{-1}) in the top 0-

60 cm, the soil of the ^{15}N experiment would, therefore, classify as very low in the Uzbek system, containing considerably less than the thresholds for cotton defined by Hutmacher et al. (2004). For winter wheat, Olson et al. (1976) reported yield responses to N amendments to become insignificant when residual NO_3-N concentrations where higher than 120 kg ha^{-1}. Thus, according to the topsoil NO_3-N content as measured before the implementation of the experiments, a significant cotton and wheat yield response to N amendments would have been expected.

After cotton and wheat harvest, the Nmin content in the soil of the experiments was with 63 and 89 kg Nmin ha^{-1}, which is still below the Uzbek soil fertility class. Riskieva (1989) reported increasing quantities of NO_3-N for samples taken in 0-50 cm depth before cotton seeding and after harvest, ranging between 140 to 234 kg ha^{-1}. The magnitude of Nmin increase in the topsoil layer, however, depended on the time of soil sampling and on the amount of irrigation water applied (Riskieva 1989).

The subsoil (60-150 cm) of the ^{15}N cotton experiment contained 25 kg NO_3-N ha^{-1} before cotton seeding, 21 kg after cotton harvest and 62 kg after wheat harvest (see section 6.1). These concentrations were well below the subsoil concentrations of the responsive Kefar Glickson site (94.5 kg ha^{-1}) in the study of Halevy and Klater (1970). Also, in the soil survey conducted in Karakalpakstan, Riskieva (1989) found the NO_3-N content after cotton harvest to decrease marginally from around 151 to 147 kg ha^{-1} in the 50-150 cm soil horizon. However, the threefold subsoil NO_3-N increase after wheat harvest has also been documented in other studies (e.g., Westerman et al. 1994, Ju et al. 2006, Ju et al. 2007).

6.3.2 Crop water demand and subirrigation

While the ^{15}N winter wheat field was sufficiently supplied with irrigation water, water supplied to the ^{15}N cotton experiment turned out to have been too low to meet the crop water demand. However, the groundwater table under the ^{15}N cotton experiment throughout the growing season was generally shallow (< 1.2 m). Similar levels have also been measured by Zakharov (1957), Khaitbayev (1963), Kadirhodjayev and Rahimov (1972) and Ibragimov et al. (2007a) in previous research experiments with cotton in the Khorezm region. During their cotton experiments, the groundwater level during the vegetation period ranged from around 0.5-1.2 m below the surface. After harvest, the levels decreased to 2.0 m and more (Zakharov 1957, Khaitbayev 1963, Kadirhodjayev and Rahimov 1972, Ibragimov 2004, Ibragimov et al. 2007a).

For regions with particularly shallow groundwater during the vegetation season (see Ibragimov 2004, Forkutsa 2006), a significant amount of crop water is supplied via upward flow of groundwater, which supplement irrigation inputs (Ayars et al. 2006). For loamy soils with a similar groundwater table to that in this study, Ayars et al. (2006) calculated a potential evapotranspiration of around 45 %. Other studies also evidenced a substantial contribution of shallow groundwater tables to satisfy crop water demand (e.g., Chaudhary et al. 1974, Rhoades et al. 1989, Ayars and Hutmacher 1994, Ayars 1996, Ayars et al. 2006). For the Khorezm conditions, Forkutsa (2006) calculated these so-called supplemental irrigations or subirrigations to cotton to be as high as 17 to 89 % of the actual evapotranspiration. The capillary rise of water ranged between 92 and 277 mm depending on the irrigation management (Forkutsa 2006). Forkutsa et al. (2009-a) show that none of the six irrigation events on the ^{15}N cotton field leached water amounts below 80 cm depth. The calculated upward flux of 250 mm from the mass balance equation (section 6.2) is, therefore, in line with these findings, whereas the assumed groundwater contribution, calculated, as actual evapotranspiration minus irrigation amounts, was much higher (355 mm). Furthermore, Conrad (2006) simulated higher actual evapotranspiration amounts over cotton fields in 2005 of 853 mm as compared to the 633 mm in this study. Although his evapotranspiration values were based on a 2-week longer growth period and included crop coefficients and input data based on information of the Central Asian Scientific Irrigation Research Institute (SANIIRI), which may have led to this high value, all results substantiate the plausibility of a large contribution of shallow groundwater to crop evapotranspiration, making even a contribution of 355 mm feasible. Thus, despite the low irrigation amounts applied to cotton during the ^{15}N experiment, the crop water demand was likely met, as the irrigation water amounts were complemented by shallow groundwater.

6.3.3 Supplemental nitrogen fertilization from groundwater

Crops have show enhanced N-utilization, reduced water stress, and stabilized or increased yields when subirrigated via shallow groundwater tables (Drury et al. 1997, Fisher et al. 1999, Patel et al. 2001, Elmi et al. 2002). The accumulated NO_3-N in the groundwater may thus function as supplemental N fertilizer if taken up by the crop (Steenvoorden 1989). During the vegetation period of the ^{15}N cotton experiment, the groundwater table was shallow enough to contribute with approximately 5-61 kg NO_3-N ha^{-1} to crop N uptake. Together with an input of 3 kg N ha^{-1} via the irrigation water, this amount is the equivalent to a single N-fertilizer application. This N supply may contribute to the weak response of cotton to the N amounts applied in this study. The data set collected in this study was not aimed at quantifying the N contribution from groundwater. However, the observations do suggest that the NO_3-N dynamics in the Khorezmian system deserve further study.

7 PLANT-NITROGEN CONTENT, AND UPTAKE

7.1 Cotton plant-nitrogen content, and uptake

The biomass and plant components calculated from the four plant samples of the microplots were compared to the samples taken from the main plots using the fiber: seed ratio of the total cotton harvest and the harvest index. The root biomass was estimated based on modeling results using CropSyst.

Total above-ground biomass on average was 9.3 ± 1.8 t ha^{-1}. The highest contribution to total biomass dry weight came from cotton seeds (28-30 %) followed by leaves (20-22 %) (Figure 7.1). Fiber, stems and squares contributed only with 16-17 % to the total biomass. The computed root dry weight was 25 % of the total plant biomass with 2.6 t ha^{-1} (2634 kg ha^{-1}), and the root biomass in the top 0-20 cm was 893.6 kg ha^{-1}. The plant material that had accumulated on the soil surface was collected but not included in the analysis.

Although no significant differences were found at $p<0.1$ between the treatments for any of the plant parts, treatment UUU on average yielded higher dry weight for leaves and stems than the other treatments. Treatment DUUf on the other hand produced more dry weight of cotton fiber and seed. The treatment DAA tended to have lowest biomass and cotton dry weight.

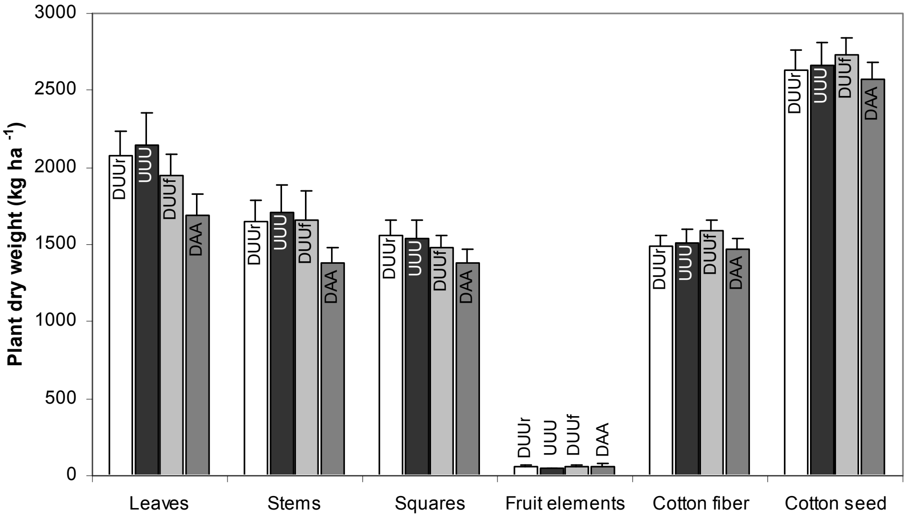

Figure 7.1 Cotton plant components (kg ha^{-1}) as affected by treatment in 2005 (N rate: 120 kg ha^{-1}). Error bars indicate 1 SE.

The N uptake into cotton biomass was calculated including the root biomass of 0-20 cm depth (Table 7.1). On average, the N uptake was 165 ± 32 kg N and 159 ± 31 kg N into the total biomass and above-ground biomass, respectively. The exported amount of N as stem, squares and raw cotton was around 119 ± 21 kg N. Around 50 % of the biomass-N was taken up by the cotton seeds, 23 % by the leaves, while less than 10 % were found in the stems, squares and fiber. Differences between the fertilizer treatments or timing could not be statistically detected although the plants on the treatment DUUr followed by DUUf and UUU on average took up more N in comparison to treatment DAA.

Table 7.1 N uptake (kg ha^{-1}) of cotton plant components as affected by fertilizer treatments (N rate: 120 kg ha^{-1}, n = 12). SE denotes the standard error of the mean.

Plant component	**DUUr***		**UUU**		**DUUf**		**DAA**	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
	--- kg N ha^{-1} ---							
Total biomass**	**174.3**	11.0	**167.9**	11.1	**169.2**	5.5	**149.8**	8.1
Above-ground biomass	**167.6**	10.5	**161.3**	10.7	**162.6**	5.3	**144.2**	7.6
Leaves	**42.6**	3.8	**42.0**	4.2	**38.3**	3.0	**32.5**	3.2
Stems	**13.4**	1.2	**13.9**	1.7	**13.9**	1.2	**11.7**	1.2
Squares	**15.4**	1.4	**14.6**	1.6	**13.2**	1.0	**11.6**	1.3
Fruit elements	**59.2**	8.6	**45.1**	7.4	**56.7**	8.1	**63.9**	11.2
Cotton fiber	**11.1**	1.1	**9.64**	1.6	**10.2**	2.1	**8.3**	0.8
Cotton seed	**83.9**	4.4	**80.6**	5.2	**86.0**	2.2	**78.9**	3.6
Export	**123.8**	6.9	**118.6**	7.5	**123.3**	4.2	**110.5**	5.0

* *DUUr = 3 splits at the recommended plant growth stages, using DAP, urea, and urea fertilizer*
UUU = 3 splits at the recommended plant growth stages, using urea, urea,and urea fertilizer
DUUf = 3 splits according to farmers' practice, using DAP, urea, and urea fertilizer
DAA = 3 splits at the recommended plant growth stages, using DAP, ammonium nitrate, and ammonium nitrate
** *Including root biomass from 0-20 cm depth*

The average N uptake into above-ground cotton biomass of treatments NPK-0 and N-0 was 148 kg ha^{-1}, which was only 10 kg lower than the average N uptake of plants fertilized with 120 kg N ha^{-1} (Table 7.2). The apparent N recovery (NUE_{AR}) in the biomass was extremely low with 8.8 %, as was the yield increase per kg N fertilizer applied (agronomic efficiency; NUE_{AE}).

Table 7.2 Calculated cotton N efficiency (kg *x* kg N^{-1}) for the N rate 120 kg ha^{-1}. NUE_{AR} denotes the apparent N recovery, and NUE_{AE} the agronomic efficiency of the cotton plant.

N rate	Cotton yield	Biomass	N uptake*	NUE_{AR}	NUE_{AE}
kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	%	kg yield kg N^{-1}
0	4148	8923	148.3		
120	4676	9454	158.9	8.8	4.4

* *above-ground biomass*

7.2 Discussion of cotton N uptake

Although in general, higher N amendments result in higher plant-N uptake by cotton, the documented uptake rates for cotton and wheat vary greatly across studies. The N uptake for an unfertilized treatment in the study of Chua et al. (2003) in the US, for example, was 68 kg ha^{-1} but increased to 94 kg N ha^{-1} when fertilized with 134 kg N ha^{-1}. At an N-application rate of 202 kg ha^{-1}, the N uptake was 104 kg ha^{-1}. In Australia, Rochester et al. (1997) reported even a higher plant-N yield of 193 kg N ha^{-1} for the fertilizer rate N-150, and 208 kg N ha^{-1} for N-200. In this study, the observed N assimilation of the cotton plants of around 160 kg N ha^{-1} for the N-application rate of 120 kg ha^{-1} were closer to the Australian cotton than to that in the US.

As in the study of Rochester et al. (1997), the cotton plants in the ^{15}N experiments took up around 120 kg more N than was supplied by the fertilizers. The difference between the N-fertilizer rate and plant-N uptake has usually been attributed to the contribution of the residual soil Nmin content and of N that has mineralized during the growth period (e.g., Jansson and Persson 1982, El Gharous et al. 1990, Rochester et al. 1993, Stevens et al. 2005). In this study, however, the sum of the initial Nmin content (approximately 30 kg ha^{-1}) and the mineralized soil-N (30 kg ha^{-1} according to simulations) was too low to explain the increased N uptake by cotton. Only when the supplemental N contributions from the groundwater and irrigation water, estimated to be around 5-61 kg ha^{-1} (section 6.3.3) are included in the overall balance, does the calculated external N supply match plant-N uptake better.

Although the mineralizable N pool has to be quantified more accurately to complete the N balance (section 10.3), it can already be concluded that irrespective of supplemental N sources such as irrigation and groundwater, fertilizer rates below 200 kg N ha^{-1} would lead to slow mining of the soil-N resources by the cotton plants. Such rates thus are not to be recommended. The recommended fertilizer rates of 200 and 250 kg N ha^{-1} for cotton in the study region (Cotton Research Institute 2007) (section 2.2.5) can, therefore, be confirmed as appropriate for the Khorezmian cotton production conditions.

7.3 Winter wheat plant-nitrogen content and uptake

The total above-ground biomass of wheat was 10.5 ± 1.6 t ha^{-1} in the microplots, but only 6.9 ± 1.4 t ha^{-1} in the main plots. The stems and kernels equally contributed to the plant dry weight with on average 40 and 41 %, respectively. The remaining 19 % of the weight came from the chaff. The total simulated root biomass was 2.9 t ha^{-1} (2901 kg ha^{-1}), and the root dry weight in the top 0-10 cm was computed to be around 320 kg ha^{-1}.

Wheat kernel dry weight of treatment DUUu was significantly higher than that of treatment DAA (p = 0.05 Figure 7.2). For all other plant parts, no significant differences at $p<0.1$ according to treatment or fertilizer timing were detected.

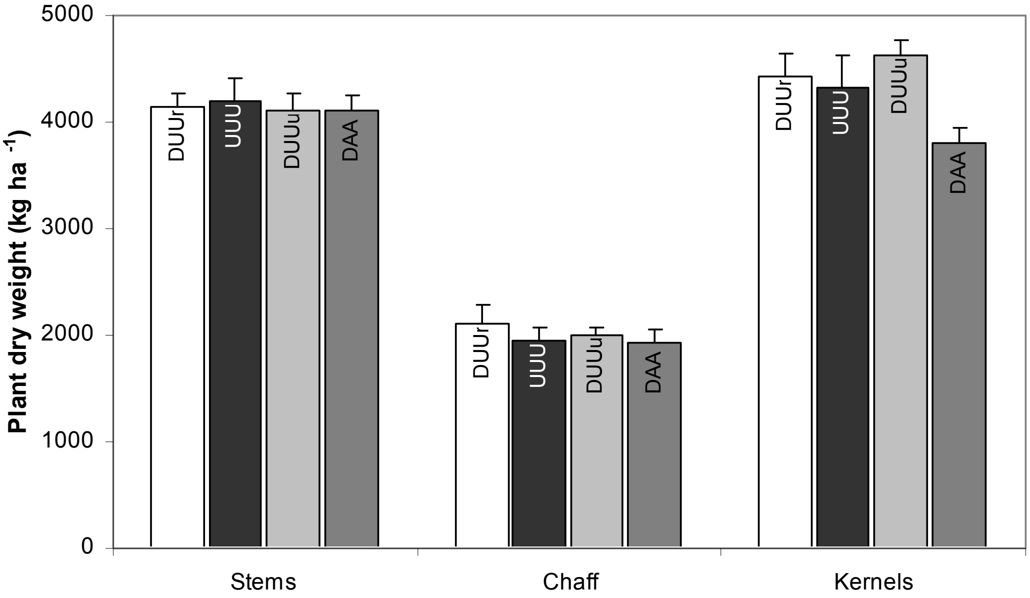

Figure 7.2 Winter wheat plant components (kg ha^{-1}) as affected by treatment in 2006.

The N uptake into the different components of the plant was calculated also including dry weight of roots from 0-10 cm depth (Table 7.3). The average N uptake into total plant biomass was 99.3 ± 18.4 kg ha^{-1}. The highest N uptake was found in the wheat kernels (72 % of total N uptake), while only 10 % of the N uptake was found in the stems and 16 % in the chaff.

The ANOVA (fertilizer, time) of N uptake was significant for the total biomass (p = 0.03) and the kernels (p = 0.00) with respect to the fertilizer treatments. Neither the fertilizer timing nor the interactions were significant at $p<0.1$. For both biomass and kernels, the uptake for the fertilizer treatment DUUu were significantly higher than for treatment DAA (Table 7.3). Kernels of treatment DUUu took up more N (83.0 ± 9.5 kg ha^{-1}) than treatments DUUr and UUU (70.1 ± 15.2 and 71.3 ± 15.4 kg ha^{-1}), and the N uptake from treatment DAA was lowest (59.5 ± 8.1 kg N ha^{-1}) in comparison to all other treatments ($p<0.1$).

Table 7.3 N uptake (kg ha^{-1}) of winter wheat plant components as affected by fertilizer treatments (N rate 120 kg ha^{-1}). SE denotes the standard error of the mean (n = 12).

Treat	**Total biomass****			**Above-ground**			**Kernels**			**Stems**		**Chaff**	
	Mean	SE	$p<0.1$	**Mean**	SE	$p<0.1$	**Mean**	SE	$p<0.1$	**Mean**	SE	**Mean**	SE
	--- kg ha^{-1} ---												
DUUr*	**97**	7	ab	**96**	7	ab	**70**	4	bc	**10**	1	**16**	2
UUU	**98**	5	ab	**97**	5	ab	**71**	4	b	**11**	0	**15**	1
DUUu	**112**	3	a	**110**	3	a	**83**	2	a	**11**	0	**16**	1
DAA	**86**	3	b	**85**	3	b	**60**	2	c	**10**	0	**15**	1

* *DUUr = 3 splits at the recommended plant growth stages, using DAP, urea, and urea fertilizer*
UUU = 3 splits at the recommended plant growth stages, using urea, urea, and urea fertilizer
DUUu = 4 splits, using DAP, urea, urea,and urea fertilizer
DAA = 3 splits at the recommended plant growth stages, using DAP, ammonium nitrate, and ammonium nitrate
** *Including root biomass from 0-10 cm*
Means with the same letter in the column are not significantly different according to the Tuckey test

The average N uptake into the above-ground biomass of treatments NPK-0 and N-0 was 50 kg ha^{-1} (Table 7.4). Almost double this amount (95 kg ha^{-1}) was taken up by plants fertilized with 120 kg N ha^{-1}. The apparent N recovery (NUE_{AR}) was 36.9 %, and the agronomic efficiency (NUE_{AE}) was 10 kg yield increase per kg N fertilizer applied.

Table 7.4 Calculated winter wheat N efficiencies (kg kg N^{-1}) for the N rate of 120 kg N ha^{-1}. NUE_{AR} denotes the apparent N recovery; and NUE_{AE} agronomic efficiency of the wheat plant.

N rate	**Wheat yield**	**Biomass**	**N uptake***	**NUE_{AR}**	**NUE_{AE}**
kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	%	kg yield kg N^{-1}
0	2191	5358	50.2		
120	3387	7164	94.5	36.9	10.0

* *above-ground biomass*

7.4 Discussion - Wheat N uptake

The N uptake of the winter wheat plants was not higher than the N fertilizer applied (N-120). Even the best performing treatment DUUu, which received an additional N application at the heading stage, still took up less N (111 kg ha^{-1}). The plant-N yield was nevertheless in the range reported in other studies. Bronson et al. (1991), for example, found total plant N to increase from 90 kg ha^{-1} to 118 kg ha^{-1} when N rates were doubled from 67 to 134 kg ha^{-1}. At higher N rates (150 kg N ha^{-1}), the values increased to 127 kg ha^{-1} (Smith and Whitfield 1990) and 159 kg ha^{-1} (Wuest and Cassman 1992a). As found in other studies (e.g., Wuest and Cassman 1992a, Fischer et al. 1993), total N uptake increased linearly from before seeding to the heading stage. Increased plant N simultaneously increased the protein content of the kernels (sections 8.3.3 and 9.3), which confirms findings by others (e.g., Ottman et al. 2000, Lloveras et al. 2001, Woolfolk et al. 2002, Farrer et al. 2006).

8 ^{15}N RECOVERY

8.1 Total ^{15}N recovery under cotton cultivation

The recovery of the fertilizer, applied at different growth stages, is provided in Table Table 8.1. The average recovery of ^{15}N fertilizer applied before seeding in plant biomass and soil was 89 ± 1 %. The average recovered ^{15}N amount of that applied at the 2-4 leaves stage was about 20 % lower (64 ± 9 %) but later applications (at budding and flowering) were in the 80-90 % range again (Figure 8.1, Table 8.1). As a result, the overall ^{15}N recovery averaged over all treatments and weigted for the different amounts applied with the different splits was 82± 3. However, differences in tital recovery among treatments for the total ^{15}N recovery were not significant ($p = 0.39$).

In the plant (Table 8.1), the ^{15}N derived from fertilizer significantly increased for N applied before seeding (20 ± 12 %) to that applied at flowering (50 ± 26 %). The N applied at 2-4 leaves and budding did not significantly differ from that applied before seeding (20 ± 9 and 33 ± 10 %, respectively). In the soil, the ^{15}N recovery was significantly less, the later the N was supplied, decreasing from 70 ± 18 to 31 ± 9 %.

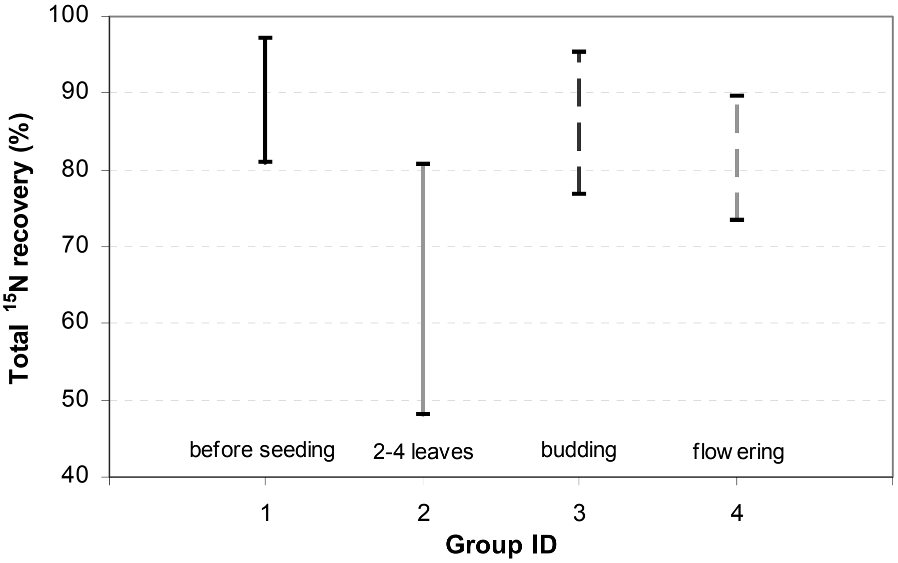

Figure 8.1 Confidence intervals of total ^{15}N content (%) in cotton biomass and soil (0-60cm) for the respective timing of fertilizer application in 2005. Group IDs were defined for visualization purpose only.

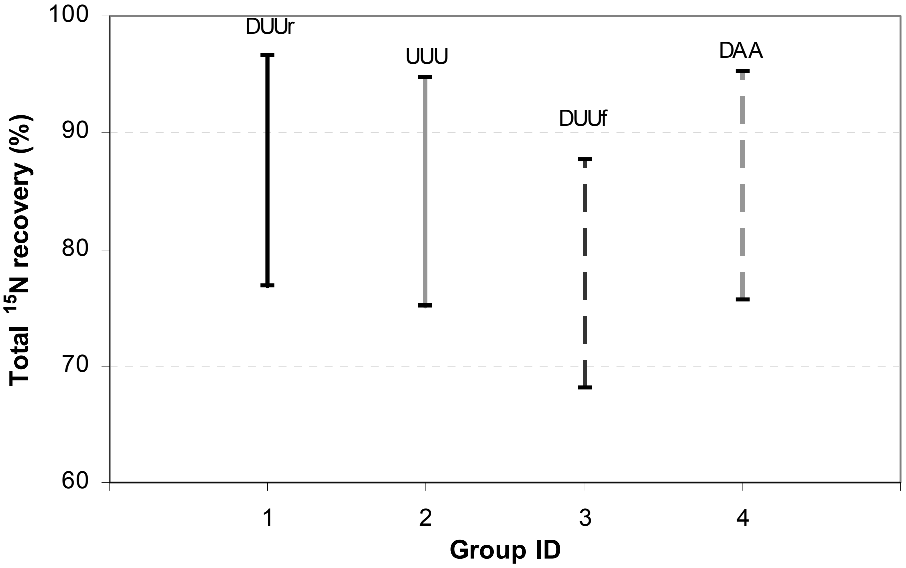

Figure 8.2 Confidence intervals of total ^{15}N content (%) in cotton biomass and soil (0-60cm) for the four fertilizer treatments in 2005. Group IDs were defined for visualization purpose only.

Table 8.1 ^{15}N-fertilizer recovery (%, for 120 kg N ha^{-1}) in total cotton biomass and soil (0-60 cm) as a function of N application time (2005). SE denotes the standard error of the mean.

N application time	Biomass*	SE	*p*<0.1	Soil	SE	*p*<0.1	Total	SE
	%			%			%	
Before seeding	**19.9**	2.9	a	**69.5**	4.6	a	**89.4**	4.5
2-4 leaves	**19.6**	4.7	a	**44.7**	8.0	b	**64.4**	9.0
Budding	**32.9**	2.9	a	**53.1**	4.9	b	**86.0**	4.6
Flowering	**50.2**	6.6	b	**31.0**	2.2	c	**81.2**	5.7
Average	**34.6**	3.2		**47.7**	3.1		**82.3**	2.9

* *including roots (0-20 cm); means with the same letter in the column are not significantly different according to the Tuckey test; the recovery rates were weighted according to the fertilizer quantity applied at the respective time*

8.1.1 ^{15}N recovery in cotton biomass

The ANOVA test for the overall ^{15}N recovery in the plant components shows significant differences for the different fertilizer application times (p = 0.00) but not for fertilizer type, with the recovery significantly increasing from application before seeding to flowering (see Figure 8.1).

Table 8.2 Absolute and relative ^{15}N recovery (kg ha^{-1} and %) in cotton biomass of the four fertilizer treatments as affected by timing of the microplots (n = 4). SE denotes the standard error of the mean.

Timing	**Fertilizer***	**N applied**	**Plant ^{15}N recovery**				
			Mean	SE	**Mean**	SE	$p<0.1$
		kg ha^{-1}	kg ha^{-1}		% of ^{15}N applied		
before seeding	DUUr	30	**6.1**	1.5	**20.5**	6.8	-
	UUU	30	**5.9**	0.3	**19.6**	3.4	-
	DUUf	24	**4.6**	2.1	**19.1**	7.9	-
	DAA	30	**6.1**	1.6	**20.2**	7.1	-
budding	DUUr	42	**12.9**	1.8	**30.6**	5.1	ab
budding	UUU	42	**10.3**	1.1	**24.6**	1.5	ab
2-4 leaves	DUUf	60	**11.8**	2.9	**19.6**	4.7	a
budding	DAA	42	**18.3**	1.3	**43.5**	2.2	b
flowering	DUUr	48	**29.0**	7.8	**60.4**	17.7	-
	UUU	48	**19.7**	6.9	**41.0**	16.4	-
	DUUf	36	**22.5**	4.4	**62.4**	11.2	-
	DAA	48	**19.2**	2.6	**40.0**	3.4	-

* *DUUr = 3 splits at the recommended plant growth stages using DAP, urea, and urea fertilizer*
UUU = 3 splits at the recommended plant growth stages, using urea, urea, and urea fertilizer
DUUf = 3 splits according to farmers' practice, using DAP, urea, and urea fertilizer
DAA = 3 splits at the recommended plant growth stages, using DAP, ammonium nitrate, and ammonium nitrate
Means with the same letter in the column are not significantly different according to the Tuckey test; "-"= model not significant, no significant differences; the recovery rates were weighted according to the fertilizer quantity applied at the respective time

The ^{15}N recovery rates, however, differed significantly for the second fertilization: For treatment DAA the highest amounts of ^{15}N were recovered (44 ± 4 %; fertilized at the budding stage). Lower amounts of ^{15}N were found for treatment DUUf (20 ± 9 %; fertilized at the 2-4 leaves stage), although statistically not significant at $p<0.1$. Also, for the last fertilizer application at flowering, plants in treatment DUUr and DUUf contained relatively more ^{15}N (60 ± 35 and 62 ± 22 %) than in treatments UUU and DAA (41 ± 33 and 40 ± 7 %), although again these differences were not significant at $p<0.1$.

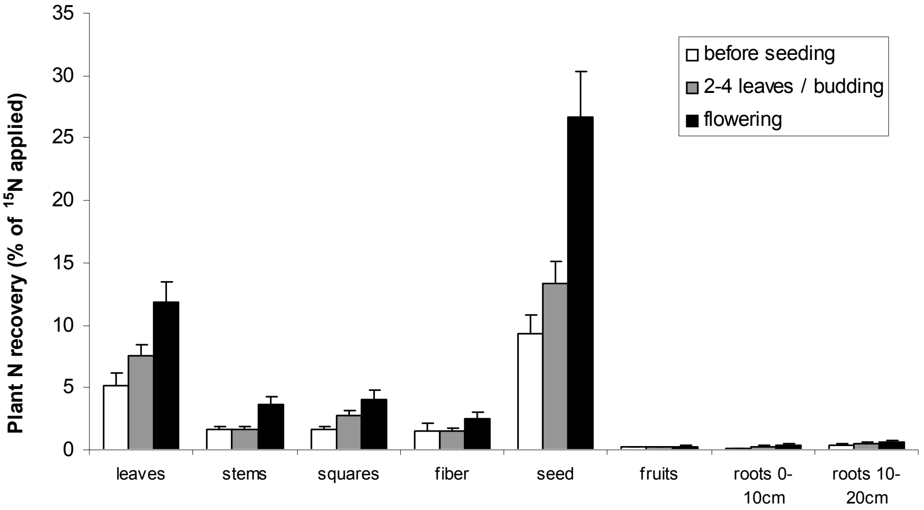

Figure 8.3 Average ^{15}N-fertilizer recovery (% of ^{15}N applied) in cotton plant components for three times of N applications in 2005 (total N rate: 120 kg ha^{-1}). Error bars show 1 SE.

In the cotton biomass, most fertilizer-derived N was found in the seed and in the leaves with 49 and 25 %, respectively, of the total ^{15}N applied (Figure 8.3,Appendix 15.20). The recovery of ^{15}N in the plant components was significantly influenced by the fertilizer timing of the fertilizer application. The highest ^{15}N recovery rates were observed when N was applied at flowering in the cotton seeds with 27 ± 15 %, whereas 12 ± 6 % were recovered in the leaves.

8.1.2 ^{15}N recovery in soil under cotton

The largest percentage of ^{15}N applied before seeding was recovered in the soil with 70 ± 18 % (Table 8.3). The total recovery of soil ^{15}N was significantly different for the different fertilizer application times ($p = 0.00$), but not for the types of N ($p = 0.33$) or interactions ($p = 0.11$). The recovery rates in the soil decreased from before seeding to flowering. The relative ^{15}N recovery was not significantly different for the 2-4 leaves vs. budding stage. However, the treatments UUU and DUUr show the highest ^{15}N recovery rates at budding (59 ± 16 %). At the flowering stage, the ^{15}N recovery rate in UUU (43 ± 8 %) differed significantly from those of the other treatments (mean 27 %).

Table 8.3 Absolute and relative soil profile ^{15}N recovery (kg ha^{-1} and %) as affected by treatment and timing in cotton (n = 4). SE denotes the standard error of the mean.

Timing	**Fertilizer***	**^{15}N applied**	**Soil ^{15}N recovery (0-60 cm)**				
			Mean	SE	**Mean**	SE	p<0.1
		kg ha^{-1}	kg ha^{-1}		% of ^{15}N applied		
before seeding	DUUr	30	**18.4**	0.6	**61.3**	2.0	-
	UUU	30	**20.6**	2.1	**68.5**	7.0	-
	DUUf	24	**15.4**	0.7	**64.3**	2.7	-
	DAA	30	**24.9**	4.9	**83.0**	16.2	-
budding	DUUr	42	**24.7**	2.0	**58.8**	4.8	-
budding	UUU	42	**24.6**	4.5	**58.5**	10.8	-
2-4 leaves	DUUf	60	**26.8**	4.8	**44.7**	8.0	-
budding	DAA	42	**17.6**	3.3	**42.0**	8.0	-
flowering	DUUr	48	**13.7**	0.9	**28.5**	1.9	a
	UUU	48	**20.5**	1.8	**42.7**	3.8	b
	DUUf	36	**8.5**	0.8	**23.5**	2.2	a
	DAA	48	**13.2**	0.6	**27.5**	1.2	a

* *DUUr = 3 splits at the recommended plant growth stages, using DAP, urea, and urea fertilizer*
UUU = 3 splits at the recommended plant growth stages, using urea, urea,and urea fertilizer
DUUf = 3 splits according to farmers' practice, using DAP, urea, and urea fertilizer
DAA = 3 splits at the recommended plant growth stages, using DAP, ammonium nitrate, and ammonium nitrate
Means with the same letter in the column are not significantly different according to the Tuckey test; "-"= model not significant, no significant differences; the recovery rates were weighted according to the fertilizer quantity applied at the respective time

Overall, around 57 ± 20 % of the total soil-^{15}N was recovered in the top 0-20 cm where ^{15}N fertilizer was applied before seeding, whereas only 40-43 ± 7 % was found when applied at 2-4 leaves/budding, and 23 ± 10 % at flowering (Figure 8.4). No significant differences were detected for the recovery rates with respect to fertilizer treatment (p = 0.18) and for the three-way interactions (depth x treatment x time, p = 0.21). For the factors treatment, time, and depth, and the interactions the ANOVA was significant (p<0.02). At flowering, only treatment UUU shows significantly higher values than all other treatments with a ^{15}N recovery rate of 25 ± 7 % in 0-10 cm depth.

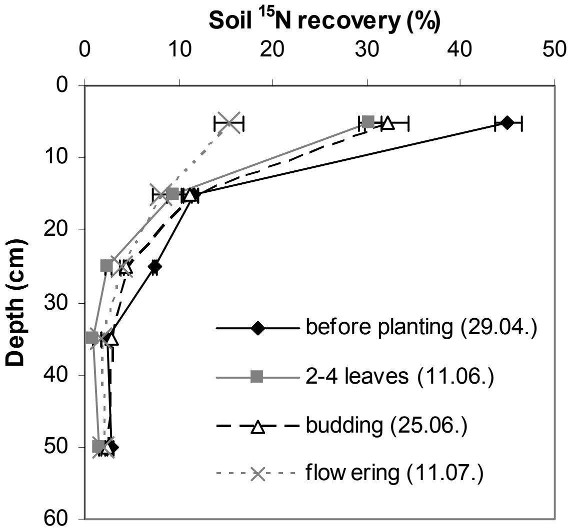

Figure 8.4 Relative recovery (% of ^{15}N applied) in the soil profile as affected by fertilizer timing of the cotton microplots in 2005. Error bars represent 1 SE.

The total plant N uptake of around 160 kg ha^{-1} was on average 45 kg higher than the total amount of N fertilizer applied (120 kg) (Figure 8.5, section 7.1). Around 30 kg of soil mineral N was available before seeding (section 6). Together with the N fertilizer, this would have covered total N uptake by the plants. However, the fertilizer-derived N in the plant was on average 42 kg only. Apparently, the fertilizer was not the only N source, as the initial soil mineral N and fertilizer amounted to only 78 kg. At the same time, the mineral N content in the soil after harvest was more than twice as high as at the beginning of the study (66 kg).

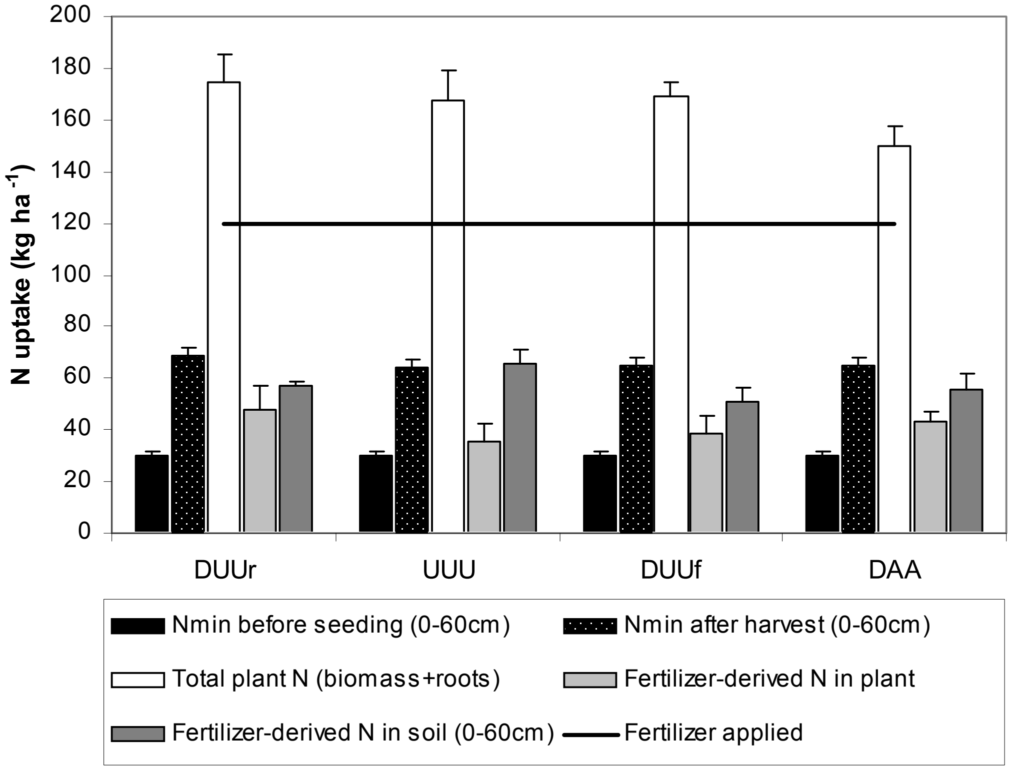

Figure 8.5 Relationship between soil-derived (non-labeled) mineral N (before seeding, 0-60 cm depth), uptake of total N in cotton plant, fertilizer-derived (^{15}N) N in plant, and fertilizer-derived N in soil following application of 120 kg N ha^{-1} for four N-fertilizer treatments. Error bars represent the standard error of the mean.

8.2 Total ^{15}N recovery under winter wheat cultivation

Total recovery of ^{15}N derived from fertilizer in winter wheat biomass and soil was on average 83 ± 20 %. The ANOVA (fertilizer, time) shows significant differences for the factor time ($p = 0.00$). The fertilizer treatments ($p = 0.11$) and the interactions were statistically not different ($p = 0.24$). Total ^{15}N recovery increased with later application in the order before seeding < tillering, booting < heading, i.e., N applied before seeding was recovered at around 67 ± 14 % of ^{15}N, whereas that applied at the heading stage was nearly fully recovered (Figure 8.6,Table 8.4).

The post hoc test for the type or method of application shows no significant difference between treatment means, although ^{15}N recoveries from treatment DAA were relatively higher than, for example, from treatment UUU (Figure 8.7).

The average plant recovery of ^{15}N fertilizer was 36 ± 19 %, and the average soil recovery was 47 ± 14 %. However, the recovered amount of ^{15}N in the biomass was significantly lower for N applied before seeding (11 ± 2 %) and increased steadily with later application until heading (52 ± 18 %). Soil ^{15}N recovery rates were similar for all application times (50-55 ± 11 %) except the booting application (38 ± 11 %). While for the application before seeding, the ^{15}N recovery rate in the biomass was 20 % of the soil recovery rate, at the heading stage, the same amount of ^{15}N was recovered in the biomass and soil.

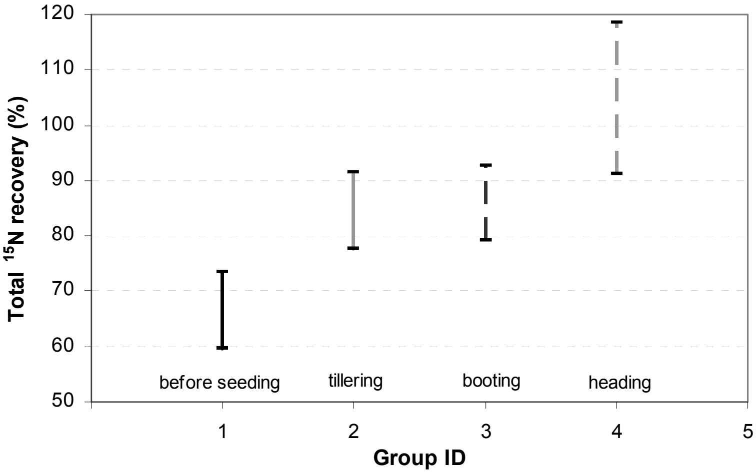

Figure 8.6 Confidence intervals of the total ^{15}N content (%) in winter wheat biomass and soil (0-60 cm) for different N application times in 2005/06. Group IDs were defined for visualization purposes only.

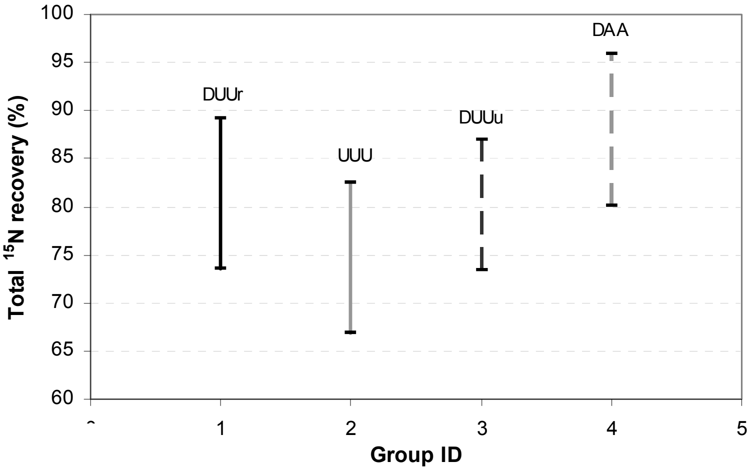

Figure 8.7 Confidence intervals of the total ^{15}N content (%) in winter wheat biomass and soil (0-60 cm) for four fertilizer treatments (type and method of application) in 2005/06. Group IDs were defined for presentation purposes only.

Table 8.4 ^{15}N-fertilizer recovery (% of 120 kg ha^{-1} N applied) in total winter wheat biomass and soil (0-60 cm) for the respective N application time in 2006. SE denotes the standard error of the mean.

N application time	**Biomass***	SE	*p*<0.1	**Soil**	SE	*p*<0.1	**Total**	SE	*p*<0.1
	%			%			%		
Before seeding	**11.3**	0.6	a	**55.2**	3.8	a	**66.5**	3.5	a
Tillering	**34.3**	2.1	b	**50.0**	2.6	b	**84.2**	4.1	ab
Booting	**49.1**	3.8	c	**37.8**	2.6	b	**86.9**	5.4	bc
Heading	**51.7**	8.9	c	**53.2**	4.4	b	**104.9**	5.3	c
Average	**36.1**	2.6		**46.6**	1.9		**82.7**	2.8	

* *including roots (0-10 cm); means with the same letter in the column are not significantly different according to the Tuckey test; "-"= model not significant, no significant differences; the recovery rates were weighted according to the fertilizer quantity applied at the respective time*

8.2.1 ^{15}N recovery in winter wheat biomass

The recovery rates of ^{15}N in the biomass (time, fertilizer) were significant only for the fertilizer time (p = 0.00). The differences caused by fertilizer type (p = 0.48) and interactions (p = 0.81) were not significant. The ^{15}N recovery rates increased with later application in the season for all treatments. However, the amount recovered in treatment DAA increased more sharply until the booting stage (59 ± 12 % of ^{15}N applied) than in the other treatments (44-46 ± 14 % of ^{15}N applied).

The highest amount of ^{15}N was found in the kernels (Figure 8.8, Appendix 15.21) with significant differences only for the fertilizer timing (p = 0.00). The interactions were not significant (p = 0.84). The ^{15}N in the kernels increased significantly in the order of N application before seeding (7 ± 2 %) < tillering (24 ± 2 %) < booting (35 ± 3 %), heading (42 ± 16 %).

The ^{15}N recovery in the stems and chaff was significant for time of application (p = 0.00). In addition, recovery in the stems was also significant for the fertilizer types (p = 0.00) as were the interactions (p = 0.07). The recovery rate in stems and chaff was highest when applied at tillering and the booting stage (4 ± 1 and 5 ± 1 %), and significantly so. The trend was: before seeding < heading < tillering, booting.

Table 8.5 Absolute and relative ^{15}N recovery (kg ha^{-1}) in winter wheat biomass of the microplots as affected by treatment and timing of fertilizer application (n = 4). SE denotes the standard error of the mean.

Time of application	Fertilizer*	N applied	Plant ^{15}N recovery			
			Mean	SE	**Mean**	SE
		kg ha^{-1}	kg ha^{-1}		% of ^{15}N applied	
before seeding	DUUr	24	**2.5**	0.3	**10.5**	1.4
	UUU	24	**2.6**	0.1	**10.9**	0.5
	DUUu	24	**3.3**	0.2	**13.6**	0.7
	DAA	24	**2.5**	0.3	**10.3**	1.4
tillering	DUUr	48	**16.9**	1.5	**35.1**	3.2
	UUU	48	**13.9**	2.6	**28.9**	5.3
	DUUu	36	**12.6**	0.9	**35.1**	2.5
	DAA	48	**18.4**	2.6	**38.4**	5.5
booting	DUUr	48	**22.3**	3.8	**46.4**	7.9
	UUU	48	**22.0**	1.1	**45.8**	2.2
	DUUu	36	**15.7**	4.4	**44.4**	11.5
	DAA	48	**28.2**	3.0	**58.7**	6.2
heading	DUUu	24	**12.4**	2.1	**51.7**	8.9

* *DUUr = 3 splits at the recommended plant growth stages, using DAP, urea, and urea fertilizer*
UUU = 3 splits at the recommended plant growth stages, using urea, urea, and urea fertilizer
DUUu = 4 splits, using DAP, urea, urea,and urea fertilizer
DAA = 3 splits at the recommended plant growth stages, using DAP, ammonium nitrate, and ammonium nitrate; the recovery rates were weighted according to the fertilizer quantity applied at the respective time

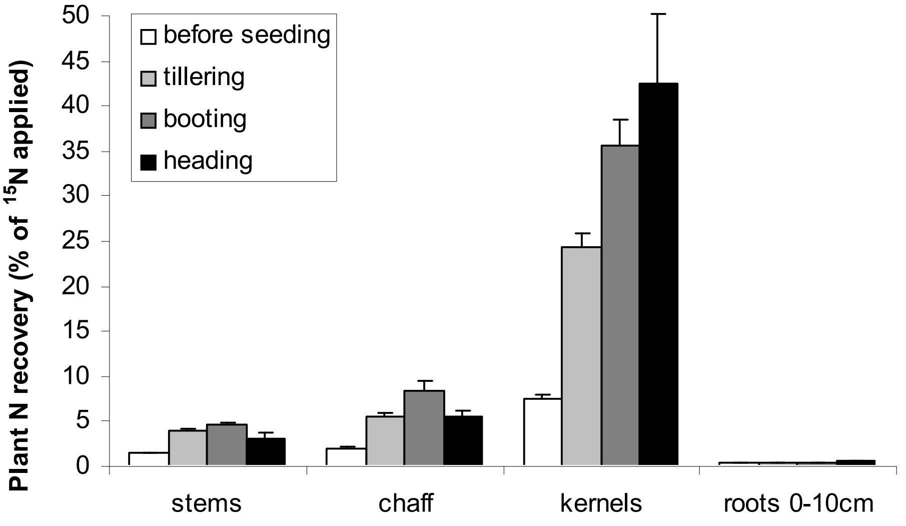

Figure 8.8 Average N-fertilizer recovery (% of ^{15}N applied) in winter wheat plant components at different fertilizer application times in 2006.

8.2.2 ^{15}N recovery in soil under winter wheat

The average ^{15}N amount recovered in the soil in 0-60 cm depth was 47 ± 14 % of the total ^{15}N applied with significant differences for fertilizer types (p = 0.05) and time of the fertilizer application (p = 0.00) as well as for the interactions (p = 0.03).

The ^{15}N recovery rate in the soil decreased from the first fertilizer application (before seeding, 55 ± 15 %) to the booting-stage application (38 ± 11 %), and increased again for the last fertilizer application time (heading; treatment DUUu) to 53 ± 9 %. The percentage of ^{15}N applied was found at the booting stage was significantly lower than at all other fertilizer application times (Table 8.6). Only for treatment DUUu was the decrease not as linear, but of the N applied at the tillering, comparably more ^{15}N was recovered than for the N applied before seeding.

Table 8.6 Average soil N recovery (kg ha^{-1} and %) in profile (0-60cm) as affected by treatment and fertilizer application time in winter wheat (n = 4). SE denotes the standard error of the mean, respectively.

Time of application	**Fertilizer***	**N applied**	**Soil ^{15}N recovery (0-60cm)**				
			Mean	SE	**Mean**	SE	p<0.1
		kg ha^{-1}	kg ha^{-1}		% of ^{15}N applied		
before seeding	DUUr	24	**13.6**	2.7	**56.5**	11.1	-
	UUU	24	**15.1**	0.6	**63.0**	2.5	-
	DUUu	24	**9.9**	1.0	**41.4**	4.1	-
	DAA	24	**14.4**	1.6	**59.8**	6.7	-
tillering	DUUr	48	**24.2**	2.7	**50.4**	5.6	ab
	UUU	48	**18.2**	1.7	**37.9**	3.6	a
	DUUu	36	**19.6**	0.7	**54.5**	1.8	b
	DAA	48	**27.8**	1.8	**57.9**	3.7	b
booting	DUUr	48	**21.7**	2.3	**45.3**	4.7	a
	UUU	48	**18.0**	0.9	**37.5**	1.9	ab
	DUUu	36	**9.7**	1.8	**26.9**	4.9	b
	DAA	48	**18.7**	2.7	**38.9**	5.6	ab
heading	DUUu	24	**12.8**	1.1	**53.2**	4.4	-

* *DUUr = 3 splits at the recommended plant growth stages, using DAP, urea,and urea fertilizer*
UUU = 3 splits at the recommended plant growth stages, urea, urea, and urea fertilizer
DUUu = 4 splits, using DAP, urea, urea, urea fertilizer
DAA = 3 splits at the recommended plant growth stages, using DAP, ammonium nitrate, and ammonium nitrate
Means with the same letter in the column are not significantly different according to the Tuckey test; "-"= model not significant, no significant differences; the recovery rates were weighted according to the fertilizer quantity applied at the respective time

The ANOVA for the recovery of soil ^{15}N was highly significant for all factors (depth, fertilizer, time) and all interactions ($p<0.03$). The ^{15}N fertilizer content in the soil decreased exponentially with depth (Figure 8.9), and was significantly higher in the top 0-10 cm (25 ± 11 % of ^{15}N applied) than in the rest of the soil profile (around 6 %) irrespective of fertilizer application time or treatment. However, the ^{15}N recovery in the soil profile differed depending on soil layer. The ^{15}N recovery amounts in the soil differed also according to the fertilizer application times. Generally, in the 0-10 cm layer, the significantly lowest recovery of ^{15}N was for N applied at the heading stage (16 ± 0.5 %). Below this layer, however, the value was highest for fertilizer applied at the heading stage (e.g., 12 ± 6 % in 10-20 cm depth). This corresponds with relative values for the treatment DUUu which, in the top 0-10 cm depth, were significantly lower than for the other treatments before seeding and at the booting stage. At tillering, the significantly lowest value was found for 0-10 cm in treatment UUU.

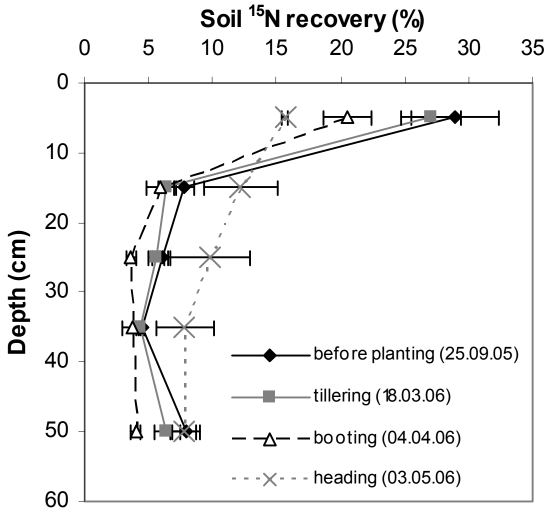

Figure 8.9 Relative recovery (% of ^{15}N applied) in the soil profile of the winter wheat microplots as affected by fertilizer timing in 2006. Error bars represent 1 SE.

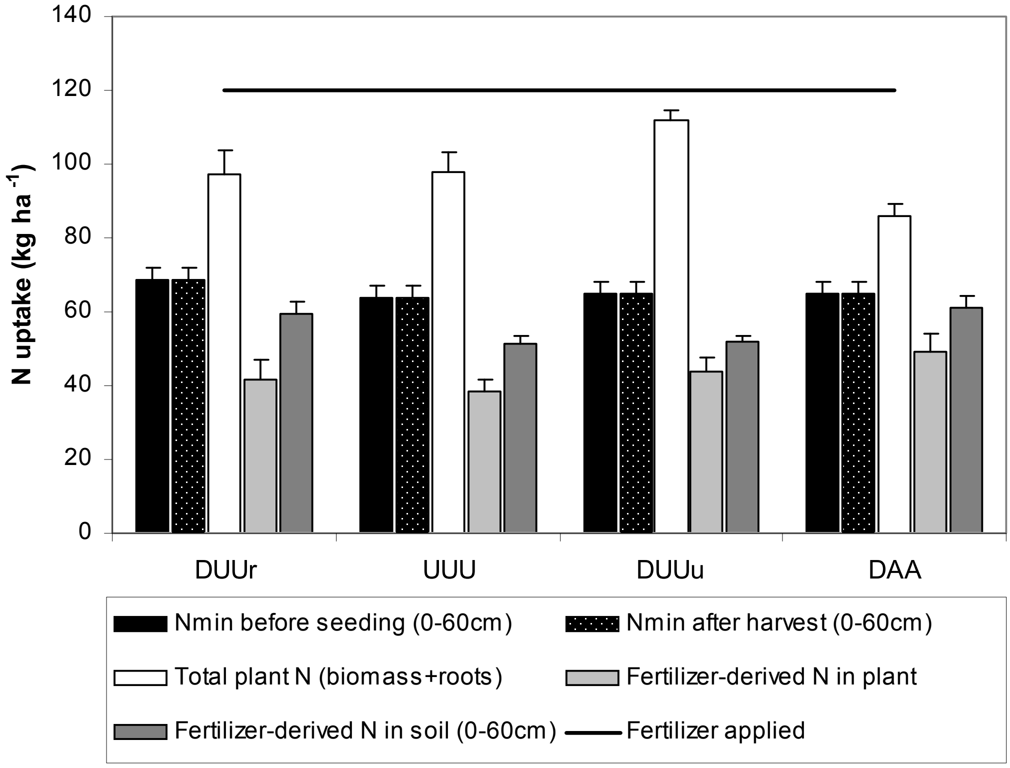

Figure 8.10 Relationship between soil-derived (non-labeled) mineral N (before seeding, 0-60 cm depth), uptake of total N into biomass, fertilizer-derived (^{15}N) N in the boimass, and fertilizer-derived N in the soil following application of 120 kg N ha^{-1} for four N-fertilizer treatments for winter wheat. Error bars represent the standard error of the mean.

In relation to the total N uptake of around 99 kg ha^{-1}, the applied N fertilizer amount of 120 kg ha^{-1} was sufficient (Figure 8.10), and even covered the significantly highest N uptake in treatment DUUu (112 kg ha^{-1}). The soil mineral N content was stable at around 65 kg ha^{-1} from before seeding to after harvest, and was not significantly different for any of the treatments at $p<0.1$. Total fertilizer-derived N in biomass and soil also do not show any effect related to the fertilizer treatment. The ^{15}N recovery in the soil was lower (56 kg ha^{-1}) than the mineral N content after harvest. As the ^{15}N derived from the plant (43 kg ha^{-1}) together with the initial soil mineral N content was still lower than the total plant-N uptake, the remaining N must have come from other sources.

8.3 Discussion of nitrogen-fertilizer efficiency in cotton and wheat

8.3.1 Plant-derived nitrogen

The ^{15}N found in the cotton plants (35 %) is comparable to previous recovery studies from Uzbekistan. From fields receiving 120 kg N ha^{-1}, Ibragimov (2007) recovered 32 % ^{15}N. Results are further in line with those of American and Australian studies, which reported less than 35 % recovery of the ^{15}N fertilizer (Constable and Rochester 1988, Freney et al. 1993, Rochester et al. 1993, Rochester et al. 1997, Silvertooth et al. 2001a). The wheat plant ^{15}N recovery in this study of around 36 % is also in the range of other studies in irrigated regions (e.g., Smith et al. 1989, Smith and Whitfield 1990, Hamid and Ahmad 1993, Carefoot and Janzen 1997, Mahmood et al. 1998), although higher rates of wheat plant-derived N of 38-58 % have also been reported (e.g., Bronson et al. 1991, Wuest and Cassman 1992a, Fischer et al. 1993, Ortiz-Monasterio et al. 1994, Ottman and Pope 2000). There is no difference in the recovery values for the different cotton and wheat plant components as compared to other studies (e.g., Smith and Whitfield 1990, Fritschi et al. 2004a).

Fritschi et al. (2004a) measured no differences in ^{15}N-fertilizer recovery in cotton, i.e., the rates ranged between 43 and 49 % irrespective of the N rate applied. Also, Norton and Silvertooth (2007) observed no clear trend in ^{15}N recovery rates when increasing N rates from 168 to 336 kg ha^{-1}. In 1997, they reported even decreasing recovery rates from 35 to 26 % for higher N applications, whereas in 1999, the recovery increased from 32 % to 35 % (Norton and Silvertooth 2007). In this study, ^{15}N recovery rates were calculated as the agronomic N-use efficiency for the respective N-fertilizer treatment (NUE_{AE}) (see section 4.8). In comparison to previous results from fertilizer research conducted in the same study region Khorezm, the reported average NUE_{AE} values of 4.4 kg cotton yield increase per kg N applied (N-120) were much higher than the estimated 1.9 kg N kg^{-1} (N-160) in this study. The maximal NUE_{AE} in 1972 was 8.0 kg N kg^{-1} (N-250) but only 4.3 kg N kg^{-1} in 1973 (Sabirov 1974). The N use efficiencies calculated by Khodjizadaeva et al. (1978) and Rustamova (1988 in Djumaniyazov 2004) were 5.1 kg N kg^{-1} for similar yield response experiments (N-200, N-250). For winter wheat, no results were available for Uzbekistan. The present results, however, show that NUE_{AE} values did not significantly change when increasing N applications from 0/20 to 160 kg ha^{-1}. Also, in similar studies conducted in Khorezm, increasing N rates to 300 kg ha^{-1} did not influence the amount of recovered N in cotton (Djumaniyazov 2004). Similar to cotton, the NUE$_{AE}$ values for winter wheat in this study are not significantly affected by the N-fertilizer amounts, i.e., 10.0 kg kg^{-1} and 8.8 kg kg^{-1} for N-120 and N-160, which confirms findings by Fischer (1993). For both crops, however, the results from the difference method (NUE$_{AE}$) vary extremely between positive and negative values, greatly exceeding the efficiencies derived from the ^{15}N method. This confirms findings by Olson and Swallow (1984), who noted that the values derived from the difference method fluctuated even in the negative range in some years and replications. Therefore, the dilution technique usually is preferred as the more consistent method (Rao et al. 1992) despite its limitations as previously discussed (section 2.3.4).

Comparing the N-fertilizer recovery rates for the rate of 120 kg N ha^{-1} calculated from the isotope dilution method (^{15}N) with the apparent N recovery rates (NUE$_{AR}$) computed using the difference method, the values diverge widely for cotton and wheat. Whereas the discrepancy between the two values for cotton was remarkable (9 % NUE$_{AR}$ vs. 35 % ^{15}N), the winter wheat values from both methods only slightly differed (37 % NUE$_{AR}$ vs. 36 % ^{15}N). These findings contradict those of Fritschi et al. (2004a), who found NUE$_{AR}$ values for irrigated cotton in the US to be comparable to efficiencies derived from the ^{15}N technique. A method comparison conducted by Norton and Silvertooth (2007) in turn revealed no differences for the first year 1997; however, in 1999, the ^{15}N method produced 10-30 % lower N-recovery values than the difference method. In contrast to both values, Rochester et al. (1993) reported significantly higher NUE$_{AR}$ values (48 %) than ^{15}N-derived cotton recoveries (28 %) in Australia.

Differences between the two methods usually indicate added N interactions (section 2.3.4) (Jenkinson et al. 1985, Harmsen and Moraghan 1988, Rao et al. 1992), which may lead to an underestimation of ^{15}N-fertilizer recovery (Olson and Swallow 1984, Krupnik et al. 2004). In this study, however, the diverging recovery rates in the cotton experiment can be attributed to the calculation procedure of the apparent N-recovery rate NUE$_{AR}$. This method is based on the assumption that plant-N uptake substantially/significantly differs between the fertilized and the unfertilized (control) treatments. As in this study plant-N uptake for the unfertilized treatments was very high (section 7), and in fact did not significantly differ from the fertilized treatment. The method thus underestimated the N recovery. The ^{15}N-soil recovery rates give rise to the assumption that immobilization processes strongly influenced the recovery rates (section 8.3.2 and section 2.3.4).

8.3.2 Soil-derived nitrogen

The ^{15}N recovery rates in the soil of around 48 and 47 % in the ^{15}N cotton and wheat experiments, respectively, were between 14 and 30 % higher than those found in other studies and regions (section 2.3.4) (e.g., Bronson et al. 1991, Freney et al. 1993, Mahmood et al. 2001, Fritschi et al. 2004a, Ibragimov 2007). Only Smith et al. (1989) recovered relatively higher rates of 43 % in Australian soil under wheat.

High soil-^{15}N recovery rates indicate that considerable N-fertilizer immobilization and/or pool substitution must have taken place (Jenkinson et al. 1985, Harmsen 2003b) (section 2.3.4). According to Ibragimov (2007), in a Tashkent soil receiving 120 kg N ha^{-1}, 39 % of the N fertilizer was immobilized in the organic fraction. In comparison, the immobilization rates simulated from CropSyst were only 24 %. The lower estimation, however, is likely due to the limitations of the model (section 10.3), as the high observed ^{15}N-recovery rates point towards higher immobilization levels than those computed with the model.

When immobilized, the ^{15}N fertilizer may be protected against leaching or denitrification. In this study, more than 25 % of the N fertilizers applied are recovered in the top 20 cm of the soil. Evidently, the high irrigation amounts in the winter wheat experiment had not caused movement of ^{15}N to lower depths. The fertilizer timing did not affect the depth of ^{15}N movement into the soil either. This confirms findings by others, where despite the high variation in N recovery in the soils, in most cropping systems, the highest amount of soil-^{15}N was recovered from the top 60 cm (e.g., Harmsen and Moraghan 1988, Smith et al. 1989, Ju et al. 2006). Thus, ^{15}N leaching can be considered of minor importance in this study. However, it can not be excluded that following the high irrigation application rates commonly applied by farmers in the region, substantial amounts of soil-N are regularly leached into deeper soil horizons, including some of the N that was released due to pool substitution. Ottman and Pope (2000) assumed that the NO_3-N leached to the groundwater must not necessarily come from the (^{15})N fertilizer, but could also be from re-mineralized soil organic N.

The low soil-^{15}N recovery rates below 50 cm suggest that some fertilizer losses evidently may have occurred from the topsoil layer. Chua et al. (2003) suggested that the 25-50 % of N fertilizer not accounted for may have been subject to denitrification as the main loss pathway. Denitrification research from flood-irrigated cotton fields conducted by Mahmood et al. (2000, 2008) in the Central Punjab region of Pakistan, or by Scheer et al. (2008a, 2008b) in the Khorezm region of Uzbekistan support this estimate. Applying nitrification inhibitors proved successful in increasing the soil recovery rates from 27 to 37 % using 3-methyl pyrazole (Rochester et al. 1996), and the plant recovery rates from 57 to more than 70 % by using acetylenic compounds (Freney et al. 1993). Also, changes in N-fertilizer placement practices, i.e., deep placed urea in the study by Rochester et al. (1993), reduced gaseous losses while enhancing plant-derived ^{15}N to up to 56 %.

The ^{15}N fertilizer unaccounted for could also be attributed to real losses caused by uneven N-fertilizer distribution in the field, uptake by weeds, and pest competition (Byerlee and Siddiq 1994). Furthermore, fertilizer-N could also be lost in the form of NH_3 through the plant, e.g., during cotton flowering and fruiting (Chua et al. 2003). Especially NH_4-N-based fertilizers applied to the soil surface, which are rapidly hydrolyzed to NH_3, may be lost via volatilization from unsaturated warm soils (Sadeghi et al. 1988, Sadeghi et al. 1989). Such volatilization losses, calculated as the difference between surface-applied and deep-placed urea treatments, were estimated to be up to 55 % (Rochester et al. 1993).

8.3.3 Effect of fertilizer timing

While the increasing plant-^{15}N recovery rates over time monitored in this study are related to increasing crop-N demand and N uptake (Olson and Kurtz 1982, Sieling and Beims 2007), the high initial soil-^{15}N recovery rates show poor utilization of fertilizer-N of the young plants, giving the opportunity for the applied N to be immobilized (Jenkinson et al. 1985) (sections 8.3.2 and 2.3.4). Rochester et al. (1993) found the initially applied ^{15}N-urea rapidly immobilized and only re-mineralized later, whereas during the vegetation period, pool substitution occurred only once the Nmin pool was empty (Jenkinson et al. 1985).

It is recommended to apply N fertilizer at the 2-4 leaves stage (treatment DUUf) (Ibragimov 2008, personal communications) in case fertilizer was not applied before seeding. The N fertilizer should then be incorporated into the soil. However, during extremely hot summers such as in 2005, cotton fields already had to be irrigated at the 2-4-leaves stage. This creates conditions for denitrification (Scheer et al. 2008b). At this stage cotton plants are still small, N uptake is low, and consequently plant-N recovery is low (Olson and Kurtz 1982). The low ^{15}N recovery rates for N applied at the 2-4 leaves stage, where 60 kg ^{15}N fertilizer were applied but only 20 % (12 kg) recovered in the plant, corresponds to measurements of Ibragimov (2007) who found recovery rates of <10 kg ha^{-1}. The ^{15}N fertilizer remaining in the soil is susceptible to losses. Soil-^{15}N recovery rates of the N applied at the 2-4 leaves stage were around 14 % lower than the N fertilizer applied at the budding stage (treatments DUUr and UUU). The farmers' fertilizer management (DUUf), i.e., applications at the 2-4 leaves stage, always yielded highest cotton yields but lowest uptake and plant- and soil-^{15}N recovery rates in comparison to the recommended N-fertilizer timing, i.e., at budding stage. The additional N application at the heading stage (treatment DUUu) yielded highest total ^{15}N recovery rates in the winter wheat. Smith and Whitfield (1990) attributed the high recovery rates at anthesis to the fact that the soil mineral N content was so low, that any additional N would be rapidly taken up by the plant. Most importantly, the high plant-^{15}N recovery levels prove that fertilizer N contributes to the observed high plant-N uptake and increased protein content suggesting that kernel quality levels can be improved by split applications of fertilizer-N at the heading stage without negative economics effects.

8.3.4 Effect of fertilizer types

The different N-fertilizer types behaved similarly in terms of plant-N recovery by cotton. Nevertheless, plant-N recovery was significantly higher for treatments receiving ammonium-nitrate fertilizer (DAA) instead of urea during the budding stage, which suggests an uptake preference of NO_3-N over NH_4-N during this growth stage. Uptake preference of cotton for NO_3-N over NH_4-N, especially during dry-matter production, has been reported previously (CRC 2007). Sabirov (1974) and Belousov (1975) in turn found no preferences of NO_3-N or NH_4-N usage for cotton, whereas Khajiyev and

Bairov (1992) and Elbordiny et al. (2003) found higher cotton yields and recovery rates after urea than after nitrate-containing fertilizer application.

For winter wheat, the total ^{15}N-recovery and plant-^{15}N recovery were higher for the DAA treatment than for the other treatments. Plant-N recovery rates for this nitrate-containing treatment were especially high during the tillering and booting stage in comparison to the other times of application (Table 8.5). These findings are in line with those of Olson and Kurtz (1982), who found NO_3-N uptake rates to be higher later in the season. Also, Recous et al. (1988) reported higher NO_3-N recovery rates throughout the season as compared to labeled ammonium-containing fertilizers.

9 CROP QUALITY

9.1 Cotton fiber and seed quality

Fiber and seed quality of cotton obtained from the response and ^{15}N experiments were analyzed. Out of all quality parameters, the three main fiber quality determinants such as length, strength, and micronaire, and the cotton thousand-seed weight (TSW) are presented (Table 9.1).

Table 9.1 Average raw cotton fiber length (mm), strength (g tex^{-1}), micronaire and 1000-seed-weight (TSW, g). SE represents the standard error of the mean.

Year	Pick	Length			Strength			Micronaire			TSW		
		Mean	SE	$p<0.1$	**Mean**	SE	$p<0.1$	**Mean**	SE	$p<0.1$	**Mean**	SE	$p<0.1$
		mm			g tex^{-1}						g		
2004	1	**31.0**	0.3	a	**24.4**	0.1	a	**4.25**	0.02	a	**113.8**	0.9	a
	2	**31.6**	0.3	a	**24.2**	0.0	b	**4.12**	0.02	b	**109.9**	1.1	b
	3	**30.9**	0.3	a	**24.2**	0.0	b	**3.81**	0.03	c	**102.0**	0.9	c
2005	1	**31.6**	0.4	a	**26.3**	0.1	a	**4.36**	0.03	a	**115.1**	1.3	a
	2	**31.0**	0.4	a	**26.1**	0.1	a	**4.32**	0.03	a	**114.5**	1.5	a
	3	**30.5**	0.7	a	**25.3**	0.1	b	**4.07**	0.03	b	**113.0**	1.8	a
	4	**30.4**	0.5	a	**24.4**	0.1	c	**3.58**	0.05	c	**100.5**	1.5	b
Mean		**31.0**	0.2		**25.0**	0.1		**4.08**	0.02		**109.9**	0.6	

Means with the same letter in the column are not significantly different according to the Tuckey test

On average, the fiber length was 31.0 ± 2.3 mm, within the range of the officially reported length for this variety of around 28.6 mm (SIFAT 2005, Ustyugin and Gulyayev 2005). Statistical analysis (year, pick, N rate) shows that only the interactions of pick x N rate are significant (p = 0.05). At lower N rates (0 to 80 kg ha^{-1}), the fiber of the first pick was longer than that of later picks. The fiber length at higher N rates, on the other hand, was longer at the later picks.

In comparison to the officially reported strength of 30.1 g tex^{-1} (SIFAT 2005, Ustyugin and Gulyayev 2005), the fiber strength determined in this study was notably lower (25.0 ± 0.9 g tex^{-1}). The fiber strength (stelometer) was significantly different for the factors year (p = 0.00) and picking time (p = 0.00), and for the interactions with the picking time (pick x year: p = 0.06; pick x N rate: p = 0.00). The fiber harvested in 2004 was significantly weaker (24.3 ± 0.3 g tex^{-1}) than that of 2005 (25.5 ± 0.6 g tex^{-1}). The strength also significantly decreased from pick 1 to the last for both years. It was also lowest for the N rates 200 and 250 kg ha^{-1} for any picking time.

Similar to fiber strength, the micronaire was significantly lower for the cotton harvested in 2004 than for that in 2005 (4.06 ± 0.13 vs. 4.08 ± 0.20), and decreased with every pick (Table 9.1). The fiber micronaire (year, pick, N rate) was significantly affected by the factors year (p = 0.00) and pick (p = 0.00) and for the interaction pick x N rate (p = 0.00). The fiber maturity (ripeness) and linear density (fineness) followed the same tendency as presented for micronaire. N fertilizer rates did not affect the micronaire. A positive relationship between fiber fineness and micronaire was observed for both years and all picks (Figure 9.1). The R^2 for both years was high with 0.95 and 0.97, respectively. In comparison to the official Uzbek reports of micronaire values of 4.62 (SIFAT 2005, Ustyugin and Gulyayev 2005), the overall micronaire from the experiments was notably lower with 4.08 ± 0.31.

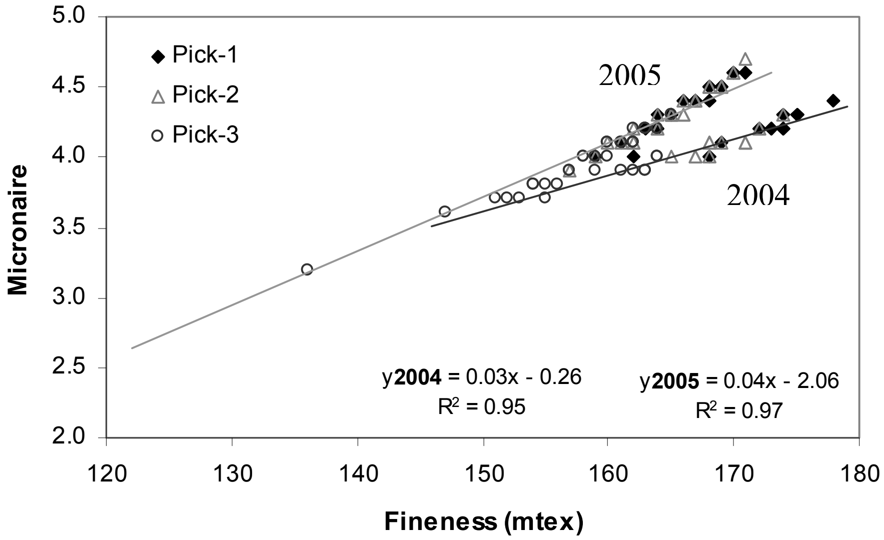

Figure 9.1 Relationship between cotton fiber micronaire and fineness (mtex) of the cotton variety *Khorezm-127* and picking time (response and ^{15}N experiments).

Cotton 1000-seed weight was on average 109.9 ± 9.1 g and increased with increasing N-application (Figure 9.2). All main factors (pick, year, N rate) were significant. Also, the interaction year x pick (p = 0.07) was significant. The remaining interactions year x N rate (p = 0.10), pick x N rate (p = 0.17) and pick x N rate x year (p = 0.87) were not significant. In 2004, the weight of the seeds was significantly lower (108.5 ± 5.3 g) than in 2005 (110.8 ± 8.3 g). The weight also decreased with picking time in both years, although more pronouncedly in 2004 (Table 9.1). The heaviest seeds were found for the N rate of 160 kg ha^{-1} and the lightest for the rate N-0. The weight of all other N rates ranked between those two.

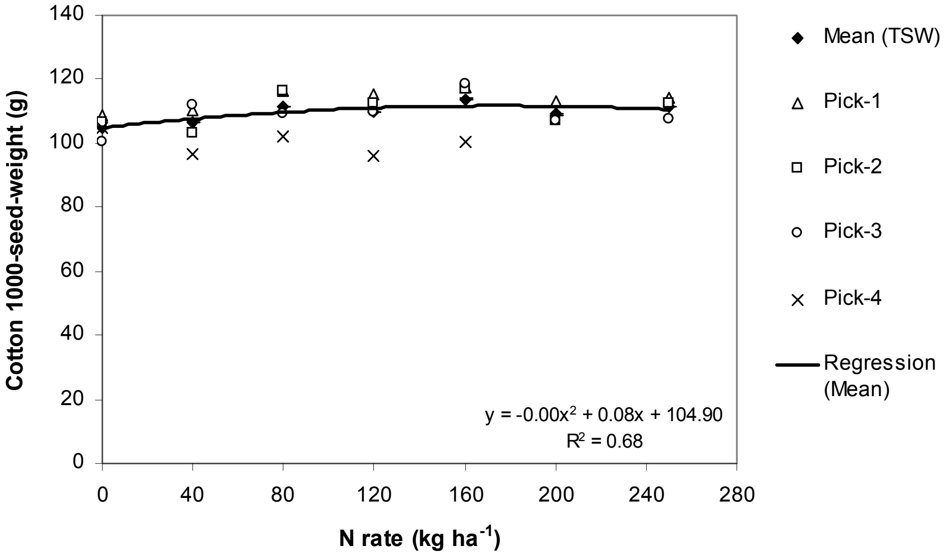

Figure 9.2 Cotton 1000-seed weight (g) of the cotton variety *Khorezm-127* according to N fertilizer rate (kg ha^{-1}) and picking time (response and ^{15}N experiments).

9.2 Discussion of cotton quality

The results of this study confirm findings of Constable et al. (1992) and Blaise et al. (2005) that cotton fiber quality remains unaffected by N rates in contrast to the seed to fiber ratio, which significantly increases with N applications (Blaise et al. 2005). Also, in the study of Girma et al. (2007), the micronaire did not change with N amendments. Length and strength, however, were found to have a positive linear relationship (Bradow and Davidonis 2000, Fritschi et al. 2003, Girma et al. 2007). However, no effect of N application on strength was reported in an earlier study by Boman and Westerman (1994).

Cotton seed weight showed a slight response to increasing N rates. As the delinted seed consists of around 60 % crude protein and crude fat (DLG 1997), any increase in N would be expected to be reflected in the seed weight (Khaitbayev 1963).

Cotton boll quality decreased from the first pickings to the last, which can be attributed to decreasing fiber maturity (Chaudhry and Guitchonouts 2003). With decreasing light duration and temperature especially the micronaire decreases (Bradow et al. 1997, Jones and Wells 1998). Micronaire and fiber fineness were also significantly affected by the year. Former findings show that cotton bulk micronaire and length are indeed sensitive to planting date, and that irrigation practices, especially timing, and other environmental factors affect the carbon assimilation in the cotton plant (Bradow et al. 1997, Johnson et al. 2002). The difference in cotton quality between the study years 2004, 2005 and 2006 confirmed the above. According to the Uzbek breeding classification (Ibragimov et al. 2008), the length, strength and micronaire characteristics of the cotton variety *Khorezm-127* qualify the cotton as lowest grade.

9.3 Wheat kernel quality

For the statistical quality analysis, data were taken from the above-mentioned experiments (minus-1, response and ^{15}N experiment) and from the rotation experiments conducted in 2003/04 in Urgench district (Appendix 15.22).

Table 9.2 Average winter wheat yield (Mg ha^{-1}), protein and gluten content (%) and 1000-kernel weight (TKW, g) for 2004-2006. SE denotes standard error of the mean.

N rate	**Wheat yield**			**Protein content**			**Gluten content**			**TKW**		
	Mean	SE	*p*<0.1	**Mean**	SE	*p*<0.1	**Mean**	SE	*p*<0.1	**Mean**	SE	*p*<0.1
kg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}		%	%		%	%		g	g	
0	**2312**	182	a	**10.4**	0.5	abc	**22.4**	1.3	a	**33.3**	0.5	a
24	**2093**	137	a	**8.9**	0.9	a	**21.7**	2.5	a	**35.3**	0.6	bc
80	**3269**	133	bc	**9.8**	0.3	ab	**21.0**	0.8	a	**37.2**	0.3	cd
120	**3572**	139	c	**11.0**	0.2	bc	**20.7**	1.0	a	**36.7**	0.4	bc
160	**3603**	139	c	**11.1**	0.3	bc	**23.5**	1.1	a	**39.0**	0.4	d
180	**3927**	274	c	**12.3**	0.3	c	**23.0**	1.3	a	**35.5**	0.4	bc
240	**3980**	344	c	**14.1**	0.5	d	**24.0**	1.3	a	**36.3**	0.9	bc
300	**2598**	461	ab	**15.2**	1.3	d	**25.0**	5.0	a	**34.9**	1.0	ab

Means with the same letter in the column are not significantly different according to the Tuckey test

The protein content was significantly higher in 2004 (13.1 ± 1.5 %) and 2005 (12.4 ± 1.7 %) than in 2006 (10.2 ±1.3 %) (Figure 9.3). Also, the N rates made a difference at $p<0.1$ (Table 9.2): Kernels with N rates of 240 and 300 kg ha^{-1} had significantly higher protein content (14.1 ± 1.4 and 15.2 ± 1.8 %) than those from the lower N rates. The critical protein value of 11.5 % was used to create the Cate-Nelson diagram (Figure 9.4), as it corresponded to the maximum yield of the entire data set. At

70 % of the maximum yield, the horizontal line divided the data set into three groups. Below the critical value, the data were especially scattered in the upper left quadrant

The fertilizer treatments also significantly influenced the protein content of the kernels. Wheat from treatment DUUu had a significantly higher protein content (10.3 ± 0.8 %) than that from the other treatments (Figure 9.5).

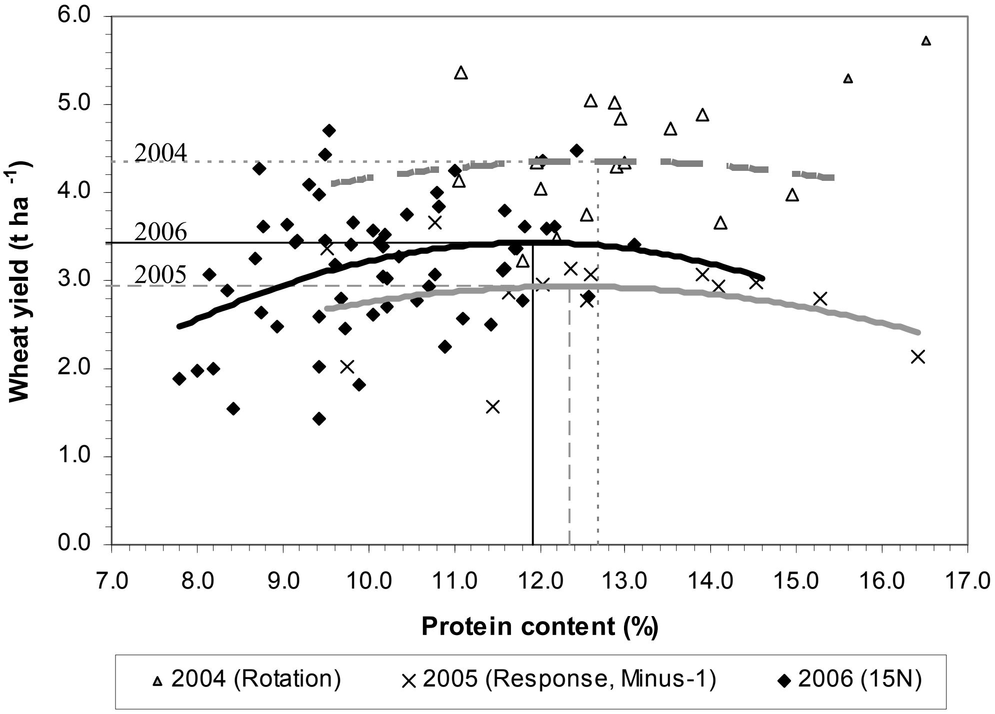

Figure 9.3 Relationship of mean protein content (%) and mean wheat kernel yield (kg ha^{-1}) of the rotation experiment (2003/04), the minus-1 experiments and response experiments (2004/05), and the ^{15}N experiment (2005/06) (*Symbols*).
Line: Regression line (black) for the average N rates.

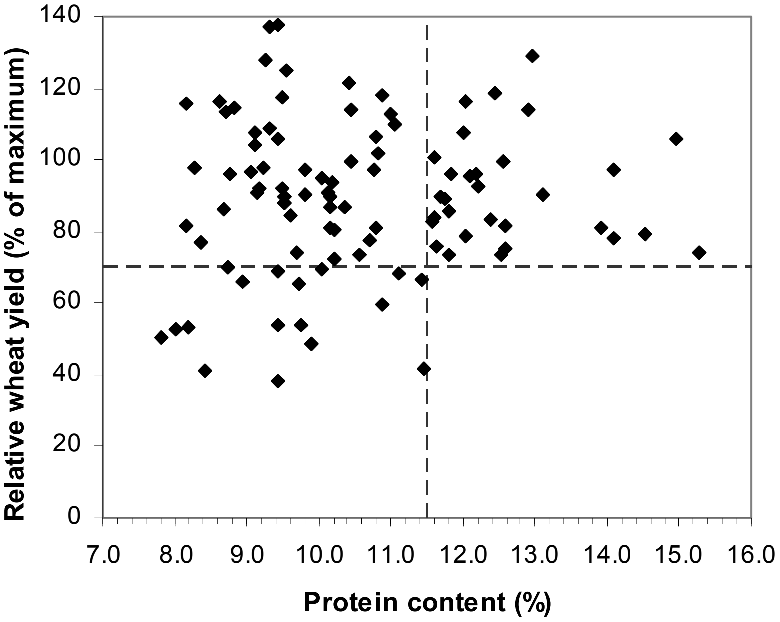

Figure 9.4 Cate-Nelson diagram to locate the critical protein content after Cate and Nelson (1971)

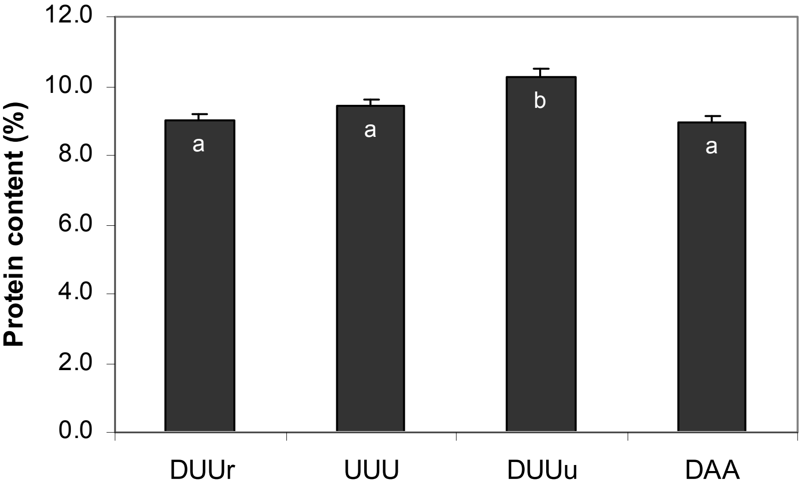

Figure 9.5 Average protein content (%) of wheat of the ^{15}N experiment (N rate of 120 kg ha^{-1}). Error bars represent 1 SE. Same letters are not significantly different at $p<0.05$.

The regional wheat quality reported by the state mills was class 3, i.e. class 3 is equivalent to unsatisfactory soft wheat of a gluten quality value of 105-120. All wheat from the experiments, except four cases, was in better classes (1 and 2). Comparing the data with the German protein classification for baking quality (Raiffeisen 2008), the protein class low (10.5 %) was met when 120 kg N ha^{-1} was applied. At the application rate of more than 180 kg N ha^{-1}, the kernels reached the protein class medium (12.5 %). All wheat kernels receiving less than 120 kg ha^{-1} of N fertilizer were below the minimum requirements.

Kernel gluten content was on average 22.1 ± 4.3 %. Gluten content changed significantly for the year to year and the interactions year x N rate were significant as well. The factor N rate alone was not significant. The gluten content was significantly lower in 2004 (20.7 ± 5.7 %) than in 2005 (23.7 ± 3.0 %). Significant differences for the fertilizer management treatments were found only between the DAA and DUUr: DAA kernels yielded the highest gluten content of 23.9 ± 3.9 %, and DUUr kernels the lowest (19.9 ± 3.5 %).

The kernels of all N rates were above the threshold level of 20.0 % gluten content according to the international classification (Raiffeisen 2008). However, the medium class (23.5 %) was reached only for wheat fertilized with 160-180 kg N ha^{-1}. Higher N application rates did not bring the kernels to the highest gluten class.

The 1000-kernel weight (TKW) of the Khorezmian wheat was generally higher than the 5-year average of 33 g in US wheat for soft red wheat (SRW) (Gwirtz et al. 2007) (Figure 9.6). The weight, however, differed according to the harvest year: kernels were significantly lighter in 2005 (34.1 ± 2.5 g) than in 2004 and 2006 (37.4 ± 2.1 g). The TKW followed the trend of the yield; the response to the N rate can be described by a quadratic function. The TKW was significantly higher for N-160 (38.9 ± 1.6 g) than for the other N rates. The lowest TKW was found for N-0 (33.3 ± 2.6 g).

The fertilizer management also had a significant effect on TKW (data from the ^{15}N experiment). The kernels of treatment DUUu were 2 g heavier (39.3 ± 1.9 g) than those of the other fertilizer combinations (on average 37.5 g). Treatment 160-DUUu had the heaviest kernels (42.9 g).

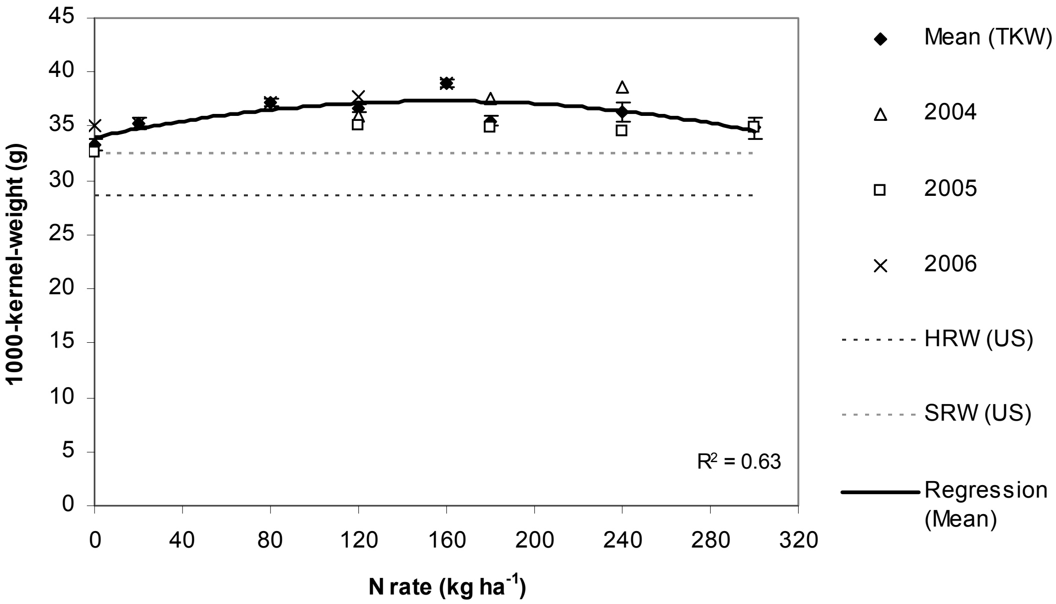

Figure 9.6 1000-kernel weight of winter wheat (g) for the respective N rates (kg ha^{-1}) of the rotation experiment (2003/04), minus-1 experiments and response experiments (2004/05), and ^{15}N experiment (2005/06).
Symbols: Mean (black) and median (white) values for the respective N rate. Error bars represent 1 SE of the mean.
Line: Regression line for average yields for the respective N rate. The dotted lines indicate the 5-year average of US wheat for hard red wheat (HRW) and soft red wheat (SRW) (Gwirtz et al. 2007).

9.4 Discussion of wheat quality

Similar to the yield increase, the protein content in the wheat kernels also increased with higher N rates. However, the increase was more linear for kernel protein than for yield, which followed a quadratic function. Although the curves of the regression were rather flat, a quadratic relationship between yield and protein content could be discerned. Maximum yield of the variety *Kupava R2* therefore did not correspond to the highest protein content, but decreased again for maximum protein content as a result of higher N amendments. The highest protein level of 15.2 % was achieved by applying 300 kg N ha^{-1}. At this N rate, however, yields decreased from the maximum of 3.6 to approximately 2.7 t ha^{-1}. The protein content at the highest yield level (N rate of 181 kg ha^{-1}) in return was only around 12.2 %, just reaching the medium protein level (Raiffeisen 2008). A similar relationship was previously reported (Johnson et al. 1973), where the potential for protein and yield increase for the wheat variety *Lancer* was quadratic as opposed to the variety *Comanche* that had a more linear potential. Also, Selles and Zentner (2001) attributed the negative correlation between kernel protein and yield to water stress rather than N availability for the crop. Many researchers, therefore, stress the need to breed wheat varieties with high quality and yield potential so that the farmers have a higher guarantee of high yields at acceptable quality levels (e.g., Johnson et al. 1973, Cox et al. 1985, Calderini et al. 1995, Ortiz-Monasterio et al. 1997, Fowler 2003).

Several post-harvest criteria for N-deficiency assessment via protein-yield relationships have been developed and discussed (Terman 1979, Goos et al. 1982, Glenn et al. 1985, Fowler et al. 1990, Engel et al. 1999, Fowler 2003). Graphical methods such as the Cate-Nelson-Split (Black 1993) by Cate and Nelson (1971) and statistical methods using an interaction chi-square (Keisling and Mullinix 1979) or the corrected sum of squares (Cate and Nelson 1971) have been applied to identify critical protein concentrations as a predictor for sufficient N fertilization for high wheat yields. According to Fowler (2003), however, these critical concentrations strongly depend on location and genotype. Values for soft wheat varieties were lower, ranging from 8.8 % (Glenn et al. 1985) to 12.0 % (Goos et al. 1982), whereas for hard wheat varieties higher protein concentrations of 12.8 % (Selles and Zentner 2001) to around 13 % (Fowler and Brydon 1989) indicated the boundary of N sufficiency and -insufficiency.

In this study, the Cate-Nelson method was also applied to the protein and yield data using the protein value of 11.5 % as the critical level (see Figure 9.4). However, below this value the data were extremely scattered in the vertical direction making it difficult to conclude that N nutrition was limiting for wheat quality and yield. Goos et al. (1982) noted that in the absence of a linear relationship between yield and protein level, the latter is of limited use for post-harvest assessment of N need. This is due to the fact that for flat yield response curves as in this study, large steps in kernel protein concentrations implied only small changes in yield, which made meaningful quantitative predictions of N rates more difficult (Fowler 2003).

Gluten did not significantly change with increasing N rates but differed between the years. Significant year and location effects on yield, protein and gluten levels have also been observed by others (e.g., Fowler et al. 1989, Lloveras et al. 2001, Alaru et al. 2003, Farrer et al. 2006). Generally, these effects were considered of equal, if not of more importance than the influence of the wheat genotypes (Miezan et al.

1977, Terman 1979, Fowler et al. 1990, Fowler 2003). Especially planting dates, seasonal temperatures, irrigation timing and related water stress during spring up to anthesis are known to influence the tiller density, N accumulation, seed size and wheat quality (Fowler et al. 1990, Farrer et al. 2006).

The 1000-kernel weight show a similar (slight) response to N rates as wheat yields. This agrees with findings by Alaru et al. (2003). However, Frederick et al. (2001) found 1000-kernel weight to be only slightly correlated with overall yield. They attributed this to the selection performance of breeders, who select for higher kernel number per square meter rather than for heavier kernels. Also, Eck (1988) and Badaruddin et al. (1999) found insignificant differences in seed weight among N treatments. The 1000-kernel weight was more affected by warm dry weather conditions and water stress during grain filling (Eck 1988, Frederick et al. 2001). Water-stress induced premature ripening had the effect of decreasing seed numbers and kernel weights, thus reducing yields (Eck 1988).

Overall, officially recommended N-fertilizer rates of 150-180 kg N ha^{-1} (MAWR 2000) were found to be acceptable for wheat production. However, the protein and gluten data show that Khorezmian winter wheat can meet the criteria only of a satisfactory to good wheat filler and flour thickener of low to medium quality (Oliver 1988, Abugalieva et al. 2003b, Raiffeisen 2008). There is thus much room for improvement, in particular by increasing N use efficiencies through more judicious application strategies (sections 8.3.3 and 8.3.4). The present results show that those treatments receiving an additional N rate at the heading stage yielded highest protein content in the kernels of the local variety. Late applications of N thus should be included as an option to increase N concentrations in the wheat kernels to improve their quality. Indeed, supplemental fertilization at this development stage is a common management strategy to raise protein levels in specific environments (e.g., Fowler and Brydon 1989, Ottman et al. 2000, Woolfolk et al. 2002, IFA 2006).

As long as Khorezmian farmers are not adequately paid according to protein yield (see section 2.1.2), it is unlikely that under present conditions they will apply higher N rates at extra cost to produce maximum protein. Without reimbursement for the additional costs for protein production, farmers only produce maximum yields at lowest costs. However, in view of the currently worldwide escalating food prices, the shortage in wheat production and the necessity for Uzbekistan to import better quality flour to mix with the domestically produced wheat in order to upgrade the baking quality (Rudenko 2008). Any progress in wheat production and kernel quality would alleviate the present bottlenecks.

10 CROPSYST – MODELING

10.1 Model parameterizationand calibration

The model CropSyst was parameterized using data from the observed ^{15}N raw cotton yield in 2005 and from the response experiments in 2004 (Appendix 15.24). Soil properties such as texture, and total and available N content (0-1 m) were determined in February 2005 (Appendix 15.16, Appendix 15.17, Appendix 15.18, as in section 6). Soil hydraulic properties were derived using an inverse modeling procedure, in which soil moisture and pressure head dynamics observed in 2005 in the same field were used for optimization (Forkutsa et al. 2009a). Soil pH and CEC were set as observed values. For initiating state variables, results of soil samples taken at the ^{15}N experiment in February 2005 were used (Appendix 15.16). The soil textural analysis in November 2005 identified this soil as a loam with 43-50 % sand and 14-18 % clay with an average topsoil (0-30 cm) bulk density of 1.51 g cm^{-3} (Appendix 15.16). In the soil profile, two bulk density peaks were observed at 30-40 cm (1.64 g cm^{-3}) and 115 cm depth (1.71 g cm^{-3}). Water content at the onset of the simulation run (January 1, 2005) was assumed to be at field capacity or at or close to saturation, if in the range of groundwater (soil layer 3-5).

The optimum growing temperature for cotton was calibrated to 25°C. The base and cutoff temperature was set to 8°C and 20°C, respectively. Given the high vapor pressure deficit prevailing in Khorezm, the above-ground biomass transpiration coefficient and the unstressed light to above-ground biomass conversion (radiation use efficiency) had to be adjusted above values observed for temperate regions. With a transpiration coefficient of 8.1 kPa kg m^{-3}, simulated above-ground biomass production and yield under fully fertilized conditions matched observations (Sommer et al. 2008b). The radiation-use efficiency was adjusted to 2.0 g MJ^{-1}. Maximum expected leaf area index at the end of the vegetative growth (LAI) and the leaf area per unit of leaf biomass (specific leaf area, SLA) were measured at 3 m^{2} m^{-2} and 13 m^{2} kg^{-1}, respectively. According to the phenological observations (Appendix 15.4), the senescence of the new green leaf area index (leaf duration) of the plant was reached after 950 growing-degree days (GDD). Moreover, based on observations, the crop stages emergence, flowering, beginning of grain filling, end of vegetative growth (peak

LAI), and physiological maturity were adjusted to 110, 1165, 1180, 1200 and 1630 GDD, respectively. Cotton rooting depth was at its maximum with 90 cm after a thermal time of 1040 GDD following observations made by Forkutsa (2006). The model assumes that at 0-5 cm depth there are no roots. This fitted well the conditions in Khorezm, where high salinity levels may occur in the soil layers close to the surface (Forkutsa et al. 2009b).

The evapotranspiration crop coefficient at full canopy of 1.1 and the soil solution osmotic potential for 50 % yield reduction of -623.4 kPa was derived from FAO standards (Abrol et al. 1988, Allen et al. 1998). The extinction coefficient for solar radiation was calibrated to 0.9 following results of Ko et al. (2005). Observed irrigation dates and amounts served as input data. Three leaching events took place in early spring 2005. Dates and quantities applied were not recorded and, hence, they were estimated based on studies by Awan and Tischbein (personal communications).

The harvest indices derived from the ^{15}N experiment were complemented with those from the response experiment for the higher N rates (200 and 250 kg N ha^{-1}). The average N concentration in leaves, stems and squares at maturity of 0.012 kg N kg dry matter^{-1} determined for treatments T8-T11 (N rate of 120 kg ha^{-1}) was used as chaff and stubble concentration. The average root N concentration on these treatments was analyzed to be 0.007 kg N kg dry matter^{-1}.

Table 10.1 Soil hydraulic properties according to Campbell

Layer	Depth	Air entry potential	Campbell b	Saturated water content	Saturated hydraulic conductivity
	cm	J kg^{-1}		cm cm^{-1}	cm d^{-1}
1	0-5	-3.67	6.164	0.453	126
2	5-30	-3.67	6.164	0.453	126
3	30-50	-1.65	5.560	0.453	126
4	50-100	-2.15	4.800	0.453	112
5	100-200	-2.15	4.800	0.453	112

Table 10.2 Soil profile data (water content, nitrate, ammonium, soil organic matter and salinity) for five horizons for model initialization.

Layer	Depth	Water content	NO_3-N	NH_4-N	SOM	Salinity
	cm	m^3 m^{-3}	mg kg^{-1}	mg kg^{-1}	%	dS m^{-1}
1	0-5	0.262*	2.6	0.25	0.94	7.0
2	5-30	0.262*	11.7	1.24	0.94	7.0
3	30-50	0.260*	8.1	0.97	0.80	5.0
4	50-100	0.305**	16.1	2.37	0.66	3.0
5	100-200	0.395**	19.9	4.46	0.35	2.2

* *field capacity*

** *influenced by groundwater and, hence, close to saturation*

Table 10.3 Observed leaching and irrigation events and amounts (mm) used for simulations.

Day of year	Date	Water application (mm)	Event
74	15.03.05	70*	leaching
91	01.04.05	70*	leaching
105	15.04.05	70*	leaching
146	26.05.05	41	irrigation
147	27.05.05	18	irrigation
177	25.06.05	59	irrigation
197	12.07.05	62	irrigation
209	28.07.05	28	irrigation
210	29.07.05	20	irrigation
227	15.08.05	27	irrigation
228	16.08.05	25	irrigation
Total		**280**	

* *estimates*

Table 10.4 Model settings and parameterization according to Sommer et al. (2008b), own observations and calibration (in bold); C = calibrated parameters (literature source in parenthesis, if applicable), D = model default, O = observed data

Parameter	**Value**	**Source**
Life cycle and land use	Annual row crop	
Photosynthetic pathway	C3	
Harvested biomass	Seed (= raw cotton)	
Aboveground biomass-transpiration coefficient [kg m^{-2} kPa m^{-1}]	8.1	C
Radiation-use efficiency (= light to aboveground biomass conversion) [g MJ^{-1}]	2.0	C
Optimum mean daily temperature for growth	25	C
Initial green leaf area index [m^{2} m^{-2}]	0.011	D
Maximum LAI	3	O
Fraction of maximum LAI at physiological maturity	0.55	O
Specific leaf area [m^{2} kg^{-1}]	13.0	O
Leaf/stem partition coefficient	2.6	C
Leaf duration [°C day]	950	O
Extinction coefficient for solar radiation	0.9	C (Ko et al. 2005)
ET crop coefficient at full canopy	1.1	C (Allen et al. 1998)
Soil solution osmotic potential for 50% yield reduction [kPa]	-623.4	C (Abrol et al. 1988)
Salinity tolerance exponent (Van-Genuchten)	4	C
Accumulated growing degree-days from		
- seeding to emergence [◦C day]	110	O
- seeding to peak LAI (end of vegetative growth) [◦C day]	1200	O
- seeding to flowering [◦C day]	1165	O
- seeding to beginning grain filling [◦C day]	1180	C
- seeding to maturity [◦C day]	1630	C
maximum rooting depth [◦C day]	1040	C
Maximum rooting depth [m]	0.9	O
Curvature of root density distribution	0.5	C
Maximum water uptake [mm day^{-1}]	14	C
Base temperature [°C]	8	C
Cutoff temperature [°C]	20	C
Stubble area covered to mass ratio [m^{2} kg^{-1}]	4	C
Surface residue area covered to mass ratio (flattened) [m^{2} kg^{-1}]	15	C
Sensitivity to water and N stress		
- during flowering	0.7	C
- during grain filling	0.5	C
Unstressed harvest index (see Table 5.3)	T1-T15	**O**
Harvest index for T16-19 (Scenario 200 kg N ha^{-1})2)	0.401	**O**
Harvest index for T16-19 (Scenario 250 kg N ha^{-1})2)	0.298	**O**
Maximum N concentration in chaff and stubble [kg N kg DM^{-1}]	0.012	**O**
Standard root N concentration [kg N kg DM^{-1}]	0.007	**O**
Maximum uptake during rapid linear growth [kg ha^{-1} day^{-1}]	5.00	**C - D**
N demand adjustment	0.70	**C**
Residual N not available for uptake [ppm]	1.00	**C - D**
Soil N concentration at which N uptake starts decreasing [ppm]	5.00	**C - D**
Plant available water at which N uptake starts decreasing	0.5	**C - D**
Mineralization rate adjustment	0.17	**C**
Nitrification rate adjustment	2.00	**C**
Denitrification rate adjustment	2.00	**C**
Maximum transformation depth	0.5	**C - D**

2) *Harvest index was derived from the response experiment*

The yield response to N fertilizer was further calibrated for the treatments by adjusting the crop N demand constant and the mineralization, nitrification and denitrification rate constant of the single soil organic matter (SOM) pool model. Without detailed information about the SOM pool, its components and decomposition dynamics, the mineralization rates could only be approximated. It was assumed that SOM would not decrease substantially during one vegetation period, which seems valid for soils in arid regions that have been under some type of cultivation for several decades. This was achieved with a mineralization rate of 0.17 that resulted in a decrease in SOM of less than 0.01 % in one year. The nitrification and denitrification rates were increased from 0.8 and 0.2 to 2.0, which is the upper model default range, in order to simulate gaseous losses close to findings of Scheer et al. (2008b).

The average plant N uptake measured for the N rate of 120 kg ha^{-1} (T8-T11) was used as reference for the predicted N uptake. To meet the observed N uptake, the maximum uptake rate during linear growth was set to 5 kg ha^{-1} day^{-1}, which is on the one hand equal to the model default value and secondly similar to findings of Boquet and Breitenbeck (2000). The crop N demand constant was decreased from 1.0 to 0.7.

10.1.1 Observed vs. predicted cotton yield

In comparison to measured raw cotton yields, a yield response to lower N rates was simulated. The yield for the rate of 0 kg N ha^{-1} was calculated as 1.1 t ha^{-1}, while the observed yield was 4.1 t ha^{-1}. For the other N rates, the model predicted the observed yield well (Figure 10.1).

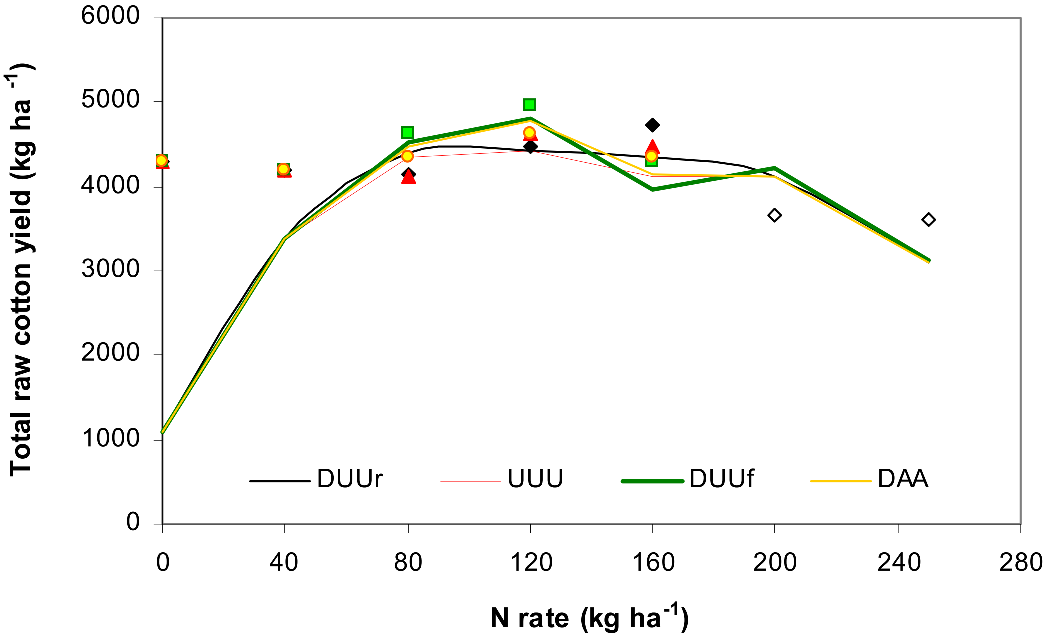

Figure 10.1 Observed (symbols) and predicted (lines) raw cotton yield (kg ha^{-1}) of the ^{15}N experiment according to N rates (kg ha^{-1}) in 2005.

Using the measured harvest indices for the different treatments and the different N rates, the model best predicted the yield changes in treatments DUUf and DAA. The observed yields in treatment DUUr with 160 kg N ha^{-1} on the other hand were higher (0.4 t ha^{-1}) than the predicted. This changed when a higher harvest index than the observed average of 0.425 ± 0.08 was used, i.e., the mean of N-120 (harvest index = 0.455 ± 0.04). The sensitivity of the model to different harvest indices could not be eliminated as yields are simulated based on the harvest index. The harvest index is reduced only in response to different stresses such as water, salinity, temperature or N supply, none of which seem to have occurred for the model. The effect that cotton plants develop more green biomass (see section) and less cotton bolls as response to higher N rates cannot (yet) be simulated in CropSyst, and requires the manual adjustment of the harvest indices.

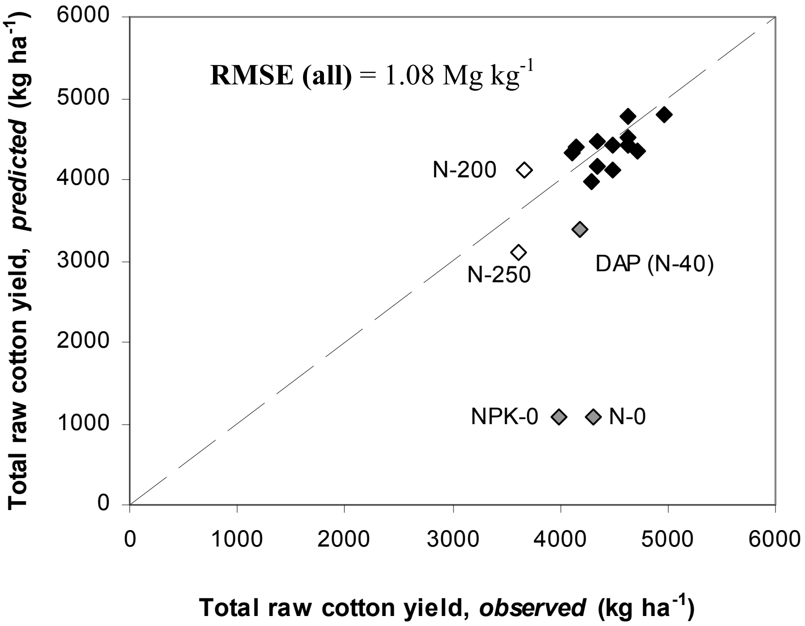

Figure 10.2 Observed and predicted raw cotton yield (kg ha^{-1}) of the ^{15}N experiment in 2005.

The RMSE for the complete observed and predicted yields of all treatments was 1.08 Mg kg^{-1}. The model prediction was insufficient especially for the low-N treatments NPK-0 and N-0 (Figure 10.2). Some deviation was observed for treatments N-200 and N-250 from the response experiment in 2004. The RMSE for T3 through T15, i.e., excluding treatments NPK-0 and N-0, was four times lower with 0.3 Mg kg^{-1}. The weak prediction of the low N fertilizer rates must be attributed partly to the fact that the current version of the model does not capture groundwater N (section 10.2.2 and 10.3).

10.2 Simulations

10.2.1 Water balance

For the period of cotton growth, the FAO-56 potential evapotranspiration was 714 mm (Table 10.5). Simulated actual evapotranspiration fluctuated around 633 mm. The amount of water actually transpired by cotton was 230 mm lower. Potential and actual evapotranspiration (Figure 10.3) diverged particularly in the first month after seeding (May), and during mid June, due to low water availability in the soil and subsequent water stress until the first irrigation event. Treatment DUUf (farmers' practice) always shows higher actual evapotranspiration than the other treatments.

Table 10.5 Simulated potential and actual evapotranspiration (mm) and soil water drainage amount for increasing N fertilizer rates (kg ha^{-1}) for two fertilizer treatments (DUUr and DUUf) for the cropping season 2005.

Treatment	**N rate**	**Fertilizer**	**Average groundwater depth (season)**	**Seasonal precipitation**	**Total irrigation**	**Seasonal potential evapotranspiration**	**Seasonal actual evapotranspiration**
	kg ha^{-1}	-	m	mm			
1	0	NPK-0	1.3	27	280	714	587
16	250	DUUr					640
18		DUUf					641

* *DUUr = 3 splits at the recommended plant growth stages, using DAP, urea, and urea fertilizer*
DUUf = 3 splits according to farmers' practice, using DAP, urea, and urea fertilizer

Furthermore, the actual evapotranspiration (and crop transpiration) during the vegetation season estimated by the model was higher than the total irrigation water applied (Table 10.5). The difference between the simulated evapotranspiration and the irrigated water amount ranged from 283 mm for non-fertilized treatments to 335 mm for treatments receiving 250 kg N ha^{-1}.

The high evaporative demand and comparatively low irrigation amounts are according to Forkutsa (2006) responsible for a strong upward flow of groundwater (capillary rise); this was confirmed by the simulations (Figure 10.4).

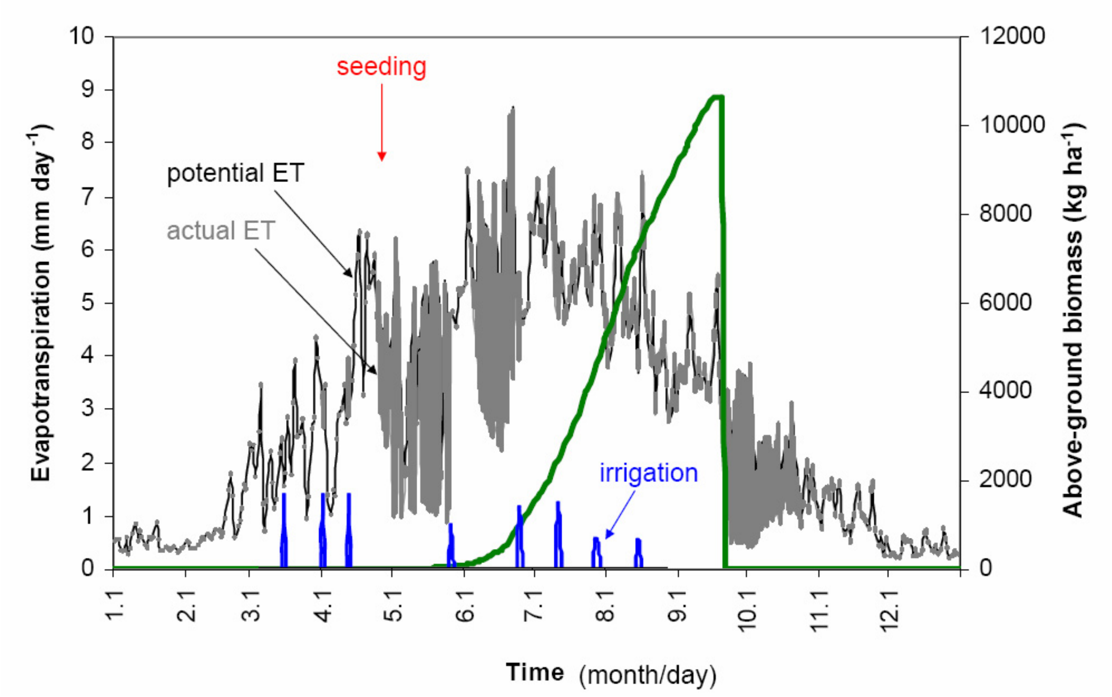

Figure 10.3 Simulated actual and potential evapotranspiration (mm day^{-1}), above-ground biomass (green line, kg ha^{-1}) and irrigation (blue line) for treatment 120-DUUf in 2005.

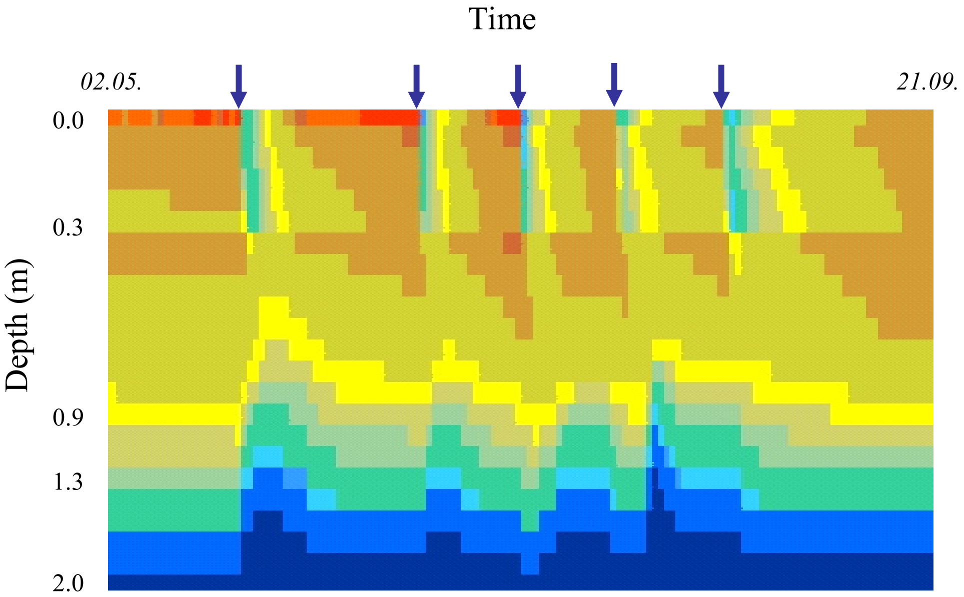

Figure 10.4 Simulated water content in 0-2 m depth during cotton vegetation period for treatment 120-DUUf in 2005.
Blue colors indicate high water content (0.43-0.45 $m^3\ m^{-3}$), red colors low (0.14-0.19 $m^3\ m^{-3}$), and yellow colors intermediate water content (0.30-0.34 $m^3\ m^{-3}$).
Blue arrows indicate irrigation times.

10.2.2 Nitrogen dynamics for different nitrogen-fertilizer amounts and treatments

The RMSE for the observed vs. predicted N uptake was 9.2 kg ha^{-1}. The simulated N uptake into biomass increased with higher N fertilizer amounts to a maximum of 212 kg N ha^{-1} for a fertilizer rate of 250 kg N ha^{-1} in the DUUf treatment (Table 10.6). For all treatments up to the N fertilizer rate of 160 kg ha^{-1}, the uptake into the plant biomass was higher than the fertilizer amount applied. Only for N rates of 200 and 250 kg ha^{-1} was the N uptake covered by the applied fertilizer (Figure 10.5). This coincides with findings by Rochester et al. (1997) who found high-yielding cotton to take up around 200 kg N ha^{-1}.

The simulated N uptake for plants in treatment DAA was the same as in the treatments DUUr and UUU, although in the experiment the N uptake rates were always lower for treatment DAA than for the other treatments.

Table 10.6 Simulated raw cotton yield (kg ha^{-1}), plant N uptake into biomass (kg ha^{-1}) and N losses (kg ha^{-1}) for increasing N fertilizer rates (kg ha^{-1}) and different fertilizer treatments.

Treatment	**N rate**	**Fertilizer**	**Total raw cotton yield**	**N uptake (biomass)**	**Total mineralization**	**Immobilization**	**Total gaseous losses**	**Total volatilization**	**Total N leaching**
	kg ha^{-1}	**-**	Mg ha^{-1}	kg ha^{-1}					
1	0	NPK-0	**1.08**	49	30	29	2	0	10
2	0	N-0	**1.08**	49	30	29	2	0	10
3	40	DAP	**3.39**	85	30	29	4	1	12
4	80	DUUr	**4.40**	122	30	29	6	1	12
5		UUU	**4.34**	122	30	29	6	1	12
6		DUUf	**4.52**	121	30	29	6	1	12
7		DAA	**4.47**	122	30	29	6	1	12
8	120	DUUr	**4.42**	**158**	30	29	10	1	12
9		UUU	**4.41**	**158**	30	29	10	1	12
10		DUUf	**4.81**	**157**	30	29	10	1	12
11		DAA	**4.78**	**158**	30	29	9	1	12
12	160	DUUr	**4.36**	193	30	29	14	2	12
13		UUU	**4.12**	193	30	29	14	2	12
14		DUUf	**3.97**	192	30	29	15	2	12
15		DAA	**4.16**	194	30	29	13	1	12
20	200	DUUr	**4.13**	209	30	32	20	2	12
21		UUU	**4.13**	209	30	32	20	2	12
22		DUUf	**4.22**	214	30	31	21	2	12
23		DAA	**4.13**	209	30	32	19	2	12
16	250	DUUr	**3.11**	211	30	33	28	3	12
17		UUU	**3.11**	211	30	33	28	3	12
18		DUUf	**3.14**	214	30	33	29	3	12
19		DAA	**3.11**	211	30	33	27	2	12

* *DUUr = 3 splits at the recommended plant growth stages, using DAP, urea, and urea fertilizer*
UUU = 3 splits at the recommended plant growth stages, using urea, urea, and urea fertilizer
DUUf = 3 splits according to farmers' practice, using DAP, urea, and urea fertilizer
DAA = 3 splits at the recommended plant growth stages, using DAP, ammonium nitrate, and ammonium nitrate

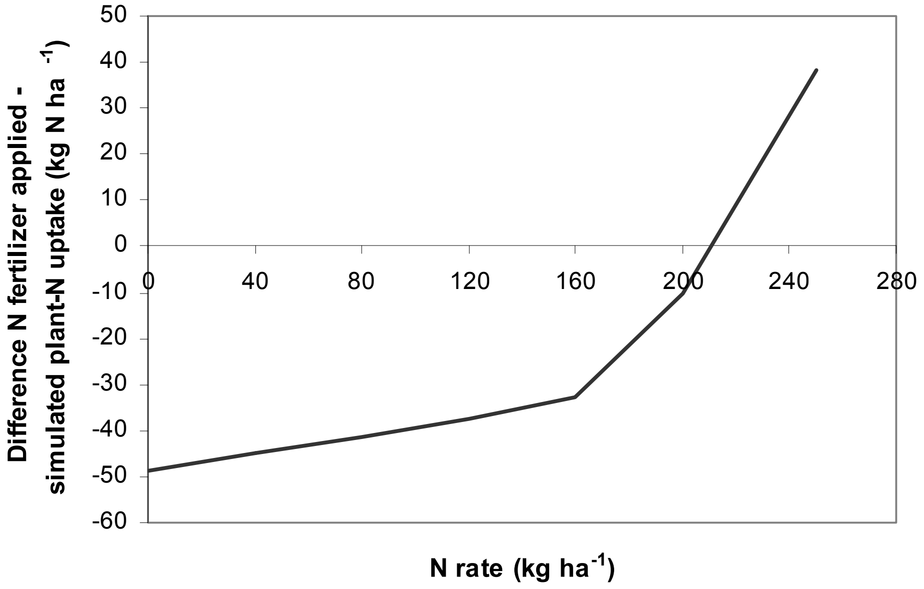

Figure 10.5 Difference between actual rate of N fertilizer applied and simulated average N uptake by cotton biomass (kg N ha^{-1}).

Predicted N leaching losses from below the rooting zone (90 cm) were low (10-12 kg ha^{-1}). This is in line with the generally low irrigation amount and a dominating upward movement of water flow during the vegetation period (Figure 10.4). However, as the quantification of actual water volumes draining below the rooting zone was not in the scope of this study, a follow-up study should be conducted to confirm these data in the field.

The average computed N losses via denitrification and volatilization (total gaseous losses) for all fertilizer rates was 9 ± 1 % of the N amount applied. With increasing N amounts, the absolute denitrified N increased from 7 to 11 % (Table 10.6). The denitrification losses during the vegetation period followed the pattern of fertilization and irrigation events (Figure 10.6). Losses were highest where N application was followed by irrigation, i.e., at the 2-4 leaves (DUUf), budding (DUUr) and flowering (DUUr and DUUf) stage. This was due to the fact that higher soil moisture regimes directly after fertilization boosted the release of N_xO_x. Although not fertilized at the budding stage, treatment DUUf still showed substantial denitrification losses. Overall, the simulated gaseous losses of all fertilizer treatments did not significantly differ, nor were they in the magnitude as measured by Scheer et al. (2008) (section 2.3.1).

Increasing the mineralization rate in the model for the treatment where no N fertilizer was applied from 0.170 to 0.614 without changing any other parameter markedly improved the yield prediction for this treatment (observed 4.1 t ha^{-1}, simulated$_{new}$ 4.0 t ha^{-1}), as the total mineralized N during the vegetation season increased from 30 to 69 kg N ha^{-1} and the N uptake increased from 49 to 102 kg ha^{-1}. At the same time, however, the SOM decreased during the simulated period from 0.94 to 0.90 % in the 0-10 cm horizon, and such sever decreases of SOM of intensively cropped fields with high inputs and biomass production during one year are unlikely.

If fertilization was omitted (N[PK]-0), simulated soil NO_3-N and NH_4-N continuously decreased during the vegetation period (Figure 10.7). For the other treatments, the dynamics were analogous to the respective fertilization scheme but decreased after the last fertilization to the same level as treatment NPK-0. In comparison to the observed NO_3-N content in the soil profile down to 2 m (80 kg ha^{-1}) (section 6), however, the simulated content (around 30 kg ha^{-1}) was rather low.

Simulated NH_4-N content in the soil (0-2 m) were closer to the observed: Except for the fertilizer inputs, the simulated NH_4-N content decreased slightly during the vegetation period by around 1 kg ha^{-1}. The final observed amount and the simulated amounts differed by only 2 kg (7 kg NH_4-N ha^{-1} vs. 5 kg NH_4-N ha^{-1}).

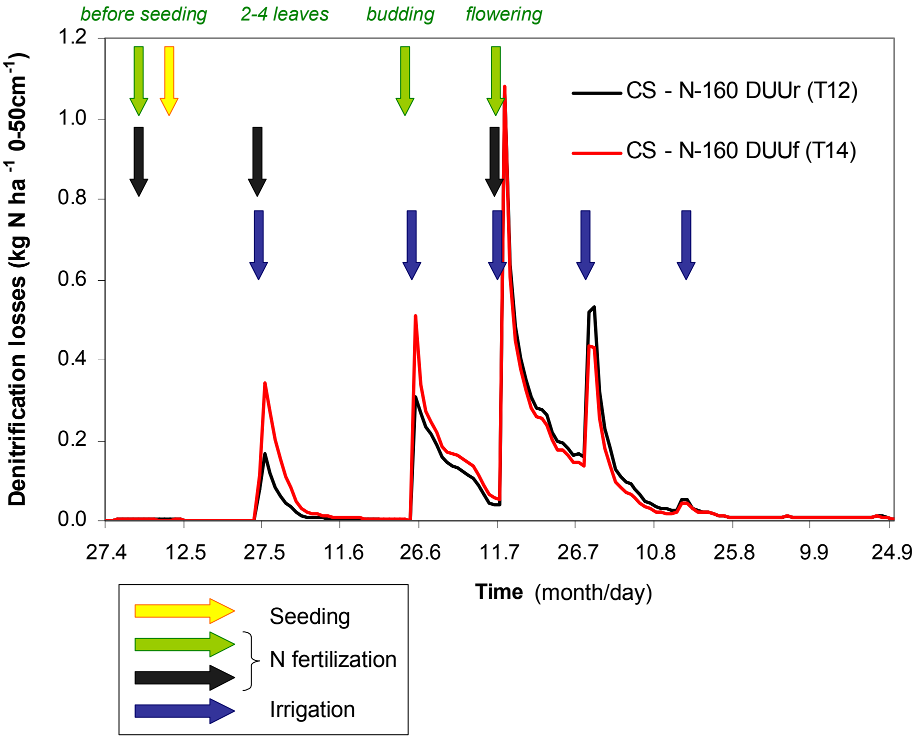

Figure 10.6 Simulated denitrification losses (kg N ha^{-1}) during the veg etation period for two treatments DUUr (T12) and DUUf (T14) (N rate: 160 kg ha^{-1}).

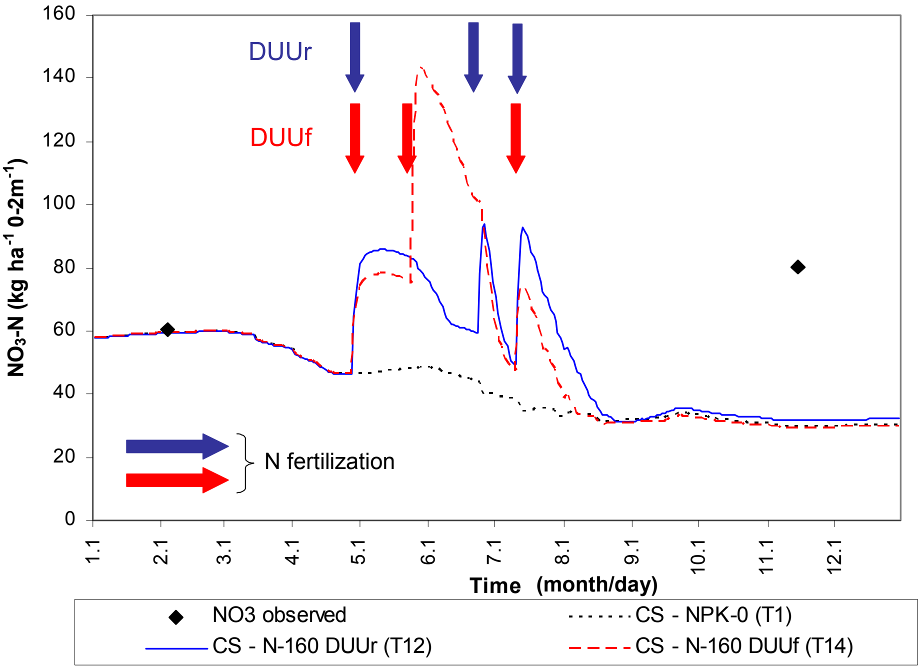

Figure 10.7 Observed and predicted soil NO_3-N dynamics (kg ha^{-1}) for the top 0-2 m for 2005 for three treatments (NPK-0; 160-DUUr and 160-DUUf).

10.2.3 Increasing yields while reducing nitrogen losses

Simulations revealed that crop production in treatment DUUf was not N-limited when more than 80 kg N ha^{-1} was applied. Hence, when maintaining the total amount of N-fertilizer (120 or 250 kg N ha^{-1}), changing the timing (or total number of split applications) did not improve yields. Furthermore, N losses in this treatment were only reduced by a change in irrigation regime (Table 4.18, Table 10.7).

For all four automatic irrigation regime scenarios, the N uptake into plants was similar to the base simulation treatment DUUf, and did not exceed the N fertilizer application rate (Table 10.7). Six automatic irrigation events of 40 mm every two weeks starting 24 days after sowing and ending 94 days after sowing (auto-10.1 and auto-18.1) produced similar yields (4.8 and 3.1 t ha^{-1}), gaseous losses (10 and 32 kg N ha^{-1}) and leaching losses (11 kg N ha^{-1}) as compared to the base simulations for treatment DUUf (see section 4.9.1). Irrigating already 14 days after seeding (auto-10.3 and auto-18.3) reduced water stress (Figure 10.9) and decreased N-leaching losses slightly more to 8 kg ha^{-1} irrespective of N quantities applied.

Table 10.7 Simulated N dynamics for treatment DUUf for observed and simulated (automatically every 14 days) irrigation events.

Treatment	**N rate**	**Fertilizer***	**Total irrigation amount**	**Actual ET**	**Total raw cotton yield****	**N uptake (biomass)**	**Total gaseous losses**	**Total N leaching**	**Total volatilization**	**Total mineralization**	**Immobilization**
	kg ha^{-1}	-	mm	mm	Mg ha^{-1}	kg ha^{-1}					
10	120	DUUf	280	640	**4.81**	157	**10**	**12**	1	30	29
auto-10.1			240	640	**4.83**	158	**10**	**11**	1	30	29
auto-10.2			180	640	**4.82**	158	**10**	**9**	1	30	29
auto-10.3			180	640	**4.83**	152	**10**	**8**	1	29	29
auto-10.4			150	640	**4.80**	159	**9**	**9**	1	29	29
18	250	DUUf	280	641	**3.14**	214	**29**	**12**	3	30	33
auto-18.1			240	640	**3.14**	214	**32**	**11**	3	30	33
auto-18.2			180	640	**3.13**	214	**30**	**9**	3	30	32
auto-18.3			180	640	**3.14**	214	**29**	**8**	3	30	31
auto-18.4			150	640	**3.12**	213	**29**	**9**	3	29	32

* *DUUf = 3 splits, farmers' practice, using DAP, urea, and urea fertilizer*

** *simulated yields for actual harvest indices*

The total actual evapotranspiration was the same at the end of the cropping season for all of the base treatments 10 and 18 and for the simulations with 640 mm. However, the irrigation regime of scenario auto-18.1, auto-18.2 and auto-18.3 increased the actual evapotranspiration in June as compared to the base scenario T18 (Figure 10.8, Figure 10.9). Also, scenario auto-18.4 consisted of one irrigation event less (the first observed irrigation was excluded) than the base simulation, which decreased the actual evapotranspiration in May, cotton growth was not affected (Figure 10.10, Table 10.7). This in line with common irrigation scheduling literature reporting that cotton is less sensitive to water stress at the early growth stage (Roth et al. 2004).

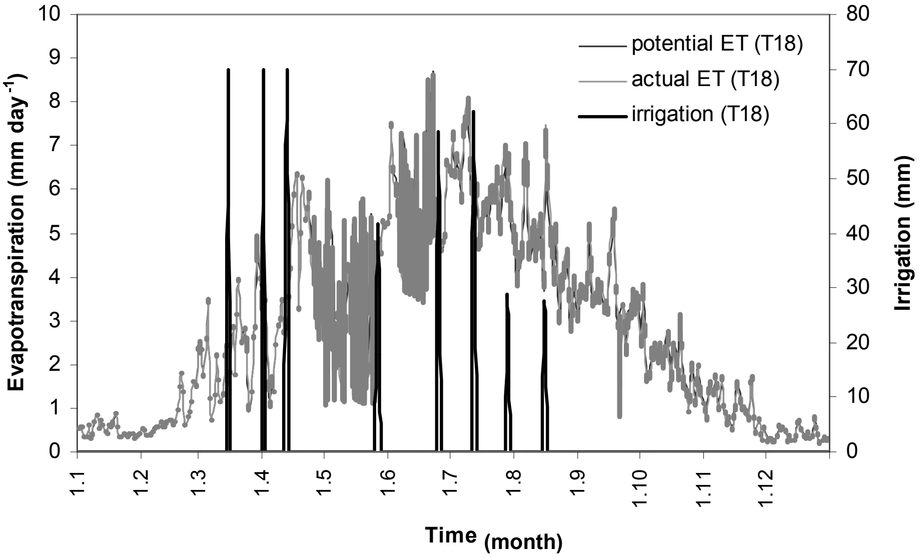

Figure 10.8 Potential and actual evapotranspiration (mm day^{-1}) and applied irrigation amounts (total of 280 mm) and frequency (mm) in 2005 for treatment 250-DUUf (T18).

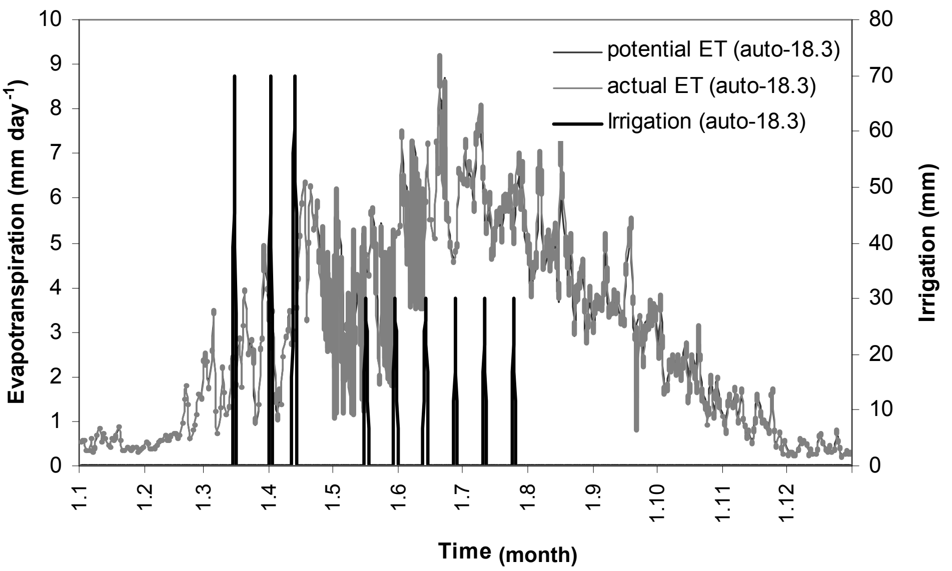

Figure 10.9 Potential and actual evapotranspiration (mm day^{-1}) and simulated irrigation amounts (total of 180 mm) and frequency (mm) in 2005 for treatment 250-DUUf (auto-18.3).

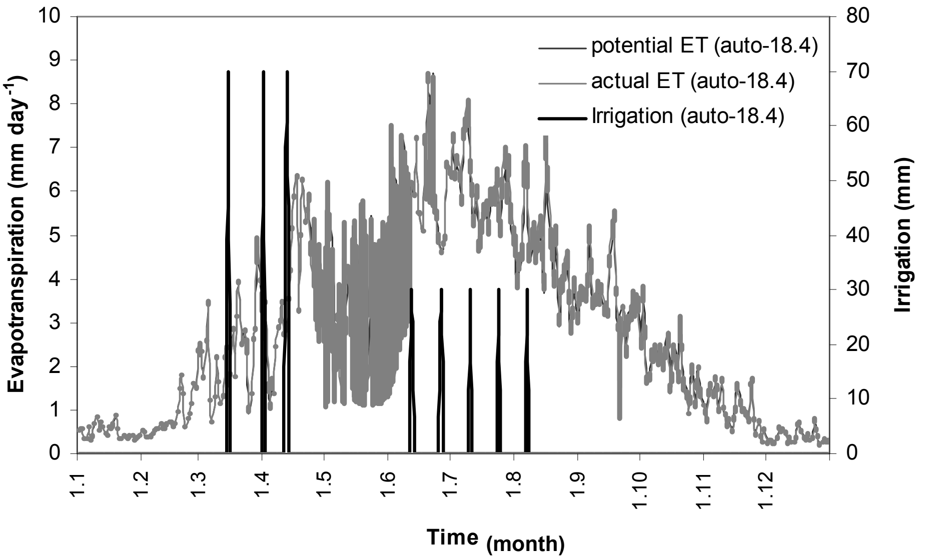

Figure 10.10 Potential and actual evapotranspiration (mm day^{-1}) and simulated irrigation amounts (total of 150 mm) and frequency (mm) in 2005 for treatment 250-DUUf (auto-18.4).

10.3 Discussion of crop model application and limitations

The cotton generic routine for the CropSyst model was developed and verified using independent field data from the study area of the ^{15}N experiments. The model was successfully parameterized. Validating the performance using the data from the ^{15}N experiments, CropSyst was able to reproduce the yields with high accuracy, except for those of the non-fertilized and low-fertilized treatments. This discrepancy is due to the lower N amounts available for uptake as the modeled crop growth for these treatments was influenced only by the initial soil N and SOM content, the mineralized N during the vegetation season, and the little amount of N fertilizer applied. Results in section 6.3 allow the assumption that N contributions from irrigation and groundwater influence the N balance and enhance N uptake. However, no NO_3-N routine for irrigation and groundwater had been incorporated into the model yet that would allow simulations of the N contribution via (sub-surface) water supply. Increasing the mineralization rate released an additional 39 kg N, which proved sufficient N for uptake to match the observed yields for the non-fertilized treatments. This simulated amount roughly corresponds to the estimations of a groundwater and irrigation water contribution of 5-61 kg N ha^{-1} (section 6.3.3). However, a higher mineralization rate resulted in a substantial reduction of SOM during one year, which is unlikely to occur in intensively cropped fields.

Therefore, the mineralization and nitrification rates were adjusted conservatively, as neither rates had been measured in arid environments. Thus, the computed dynamics of soil NO_3-N and NH_4-N content have to be interpreted with care, as mineralization, nitrification and denitrification processes substantially alter the soil N status. More detailed within-season measurements (Maas 1993), as was done for instance by Forkutsa et al. (2009b) for the salinity dynamics, and further calibration is necessary to improve the accuracy of the estimated parameters and confirm the simulations.

The magnitude of denitrification losses predicted by Scheer et al. (2008c) for the ^{15}N experimental field could not be reproduced. Even the treatments receiving higher irrigation water and N-fertilizer amounts that matched the measurement conditions of Scheer et al. (2008b, 2008c) did not produce comparable N_2O emissions.

On the other hand, the ability of the model to handle denitrification processes is confined to simplified computations (C. Stockle, personal communications), and supplemental N input from the groundwater could not be accounted for at the time of the simulations. Therefore, the output can be only taken as a rough estimation of emission development under certain management systems or soil conditions, and the rates of gaseous losses need to be further verified with the help of more specialized models such as ecosys (Grant 1995). It should be noted, however, that a precondition for successful and reliable simulation of gaseous losses of N is the precise description of the different soil organic matter pools and the mineral N dynamics. This is in progress (Forkutsa, forthcoming Ph.D. thesis).

It has to be noted that CropSyst is not a specific cotton growth model such as GOSSYM, COTONS, Cotton2K, OZCOT, or other cotton-only models. These models undoubtedly allow much more detailed simulations with respect to water and N stress on plant phenology and development once the detailed data has been collected, i.e., allocation of N to plant organs, new node and boll production, and aging of leaves (Marani 2004). Also, the indefinite end of cotton yield formation, i.e., cotton bolls open over a 3-month period, can be handled by these models, which allow calculating fiber harvest for several picking times (Marani 2004). CropSyst in turn calculates yield based on the harvest index and accumulated biomass at the termination of crop growth. Therefore, the yield predictions derived from CropSyst would actually be equal to one single pick and thus less precise than specific cotton models under conditions of multiple (manual) cotton picks like in Uzbekistan. However, in view of the fact that more than 60-70 % of raw cotton is harvested at pick 1, and the observed N uptake and the corresponding yields were reproduced satisfactorily, the model served the basic purpose.

Recognizing the above-mentioned limitation, the results on the whole show that the presently developed and calibrated model can accurately estimate cotton growth response to N amendments, despite the uncertainty in the seasonal N dynamics and other factors influencing growth such as supplemental N fertilization. Simulation results indicate changes in crop growth and yield and the soil-N balance for different management practices. Potential losses and the scope for improvement of fertilizer management were identified.

11 FINANCIAL ASSESSMENT

11.1 Cotton

The results of the partial budget analysis comprise the total costs that vary (TCV), the net benefit and the rate of return for the ^{15}N cotton experiment of 2005. The ANOVA for the TCV was significant only for the N rate ($p = 0.00$) and the rate of return ($p = 0.08$), but not for the net benefit ($p = 0.95$). The interactions (N rate x fertilizer) were not significant (TCV: $p = 0.88$; rate of return: $p = 0.87$; net benefit: $p = 0.83$).

Table 11.1 Cost analyses of the fertilizer treatments for cotton. SE is the calculated standard error.

Treat	**N rate**	**Fertilizer**	**Total costs that vary**		**Net benefit**		**Rate of return**	
			Mean	SE	**Mean**	SE	**Mean**	SE
	kg ha^{-1}		--- soum ha^{-1}					
1	0	NPK-0	**155,366**	12,190	**1,016,091**	69,535	**6.6**	0.1
2	0	N-0	**307,863**	15,956	**970,364**	104,704	**3.1**	0.2
3	40	DAP	**335,070**	8,666	**901,142**	64,130	**2.7**	0.1
4	80	DUUr	**341,015**	9,535	**864,072**	63,992	**2.5**	0.1
5		UUU	**332,034**	17,982	**862,611**	127,095	**2.6**	0.2
6		DUUf	**357,370**	10,425	**1,017,629**	73,791	**2.8**	0.1
7		DAA	**346,853**	11,943	**936,806**	89,176	**2.7**	0.2
8	120	DUUr	**368,937**	5,823	**953,518**	47,480	**2.6**	0.1
9		UUU	**367,397**	13,864	**977,458**	100,948	**2.6**	0.2
10		DUUf	**386,302**	5,043	**1,069,332**	29,756	**2.8**	0.0
11		DAA	**372,657**	9,574	**998,579**	68,423	**2.7**	0.1
12	160	DUUr	**400,762**	22,402	**991,421**	159,943	**2.4**	0.3
13		UUU	**377,894**	9,801	**926,710**	88,479	**2.4**	0.2
14		DUUf	**381,755**	18,122	**881,522**	120,162	**2.3**	0.2
15		DAA	**384,789**	18,364	**885,854**	128,183	**2.3**	0.2

* *DUUr = 3 splits at the recommended plant growth stages, using DAP, urea, and urea fertilizer*
UUU = 3 splits at the recommended plant growth stages, using urea, urea,and urea fertilizer
DUUf = 3 splits according to farmers' practice, using DAP, urea, and urea fertilizer
DAA = 3 splits at the recommended plant growth stages, using DAP, ammonium nitrate, and ammonium nitrate

The TCV ranged from a minimum of 155,366 (NPK-0) to maximal 375,142 UZS ha^{-1} (160-DUUf) (Table 11.1). The TCV increased with increasing N application, and followed the treatment order: treatment NPK-0 < N-0, DAP < DUUr, UUU, DUUf, DAA. The treatment of the N rate of 0 kg ha^{-1} had significantly lower TCV than any of the other treatments. Amongst the fertilizer treatments, the UUU treatment was the cheapest for any N rate, whereas the DUUf treatment was always the most expensive for N-80 and N-120. Only for N-160 was treatment DUUr more expensive.

The net benefit ranged from 862,611 UZS ha^{-1} (80-UUU) to 1,069,332 UZS ha^{-1} (120-DUUf), but differences were not statistically significant. The net benefit also does not show any particular differences for any of the N rates (Table 11.1). For the respective picking times, the raw cotton benefit paid at the cotton ginneries differed. Around 86 % of the total cotton benefit was obtained from the first and second pick (Table 11.2). Even for lower output prices for the second pick (data not shown), the return from the raw cotton alone would have been more than 70 % of the total cotton benefit. The third pick, on the other hand, brought only 14 % of the total cotton benefit. A fourth pick, therefore, is often not beneficial.

Table 11.2 Proportion of cotton benefit (%) for the respective picking times in relation to total cotton benefit.

Treat	**N rate**	**Fertilizer**	**First pick**		**Second pick**		**Third pick**		**Total**	
			% of total yield	% of cotton benefit	% of total yield	% of cotton benefit	% of total yield	% of cotton benefit	Yield	Cotton benefit
	kg ha^{-1}		sub-class 1-1*		sub-class 1-2		sub-class 3-1		t ha^{-1}	soum ha^{-1}
1	0	NPK-0	47	**49**	36	**36**	17	**15**	4.0	1141173
2	0	N-0	61	**63**	27	**28**	11	**9**	4.3	1248736
3	40	DAP	59	**60**	29	**29**	13	**11**	4.2	1211446
4	80	DUUr	42	**44**	37	**38**	21	**18**	4.1	1175915
5		UUU	45	**48**	34	**35**	20	**17**	4.1	1167697
6		DUUf	54	**56**	34	**34**	12	**10**	4.6	1341832
7		DAA	57	**59**	30	**30**	14	**11**	4.3	1253689
8	120	DUUr	49	**51**	36	**37**	15	**13**	4.5	1288293
9		UUU	40	**42**	40	**41**	20	**17**	4.6	1311255
10		DUUf	48	**50**	36	**36**	16	**14**	5.0	1423687
11		DAA	56	**58**	33	**33**	11	**9**	4.6	1341525
12	160	DUUr	48	**50**	35	**36**	17	**14**	4.7	1348971
13		UUU	41	**43**	35	**36**	24	**20**	4.5	1265345
14		DUUf	42	**44**	35	**37**	23	**19**	4.3	1212212
15		DAA	46	**48**	34	**35**	20	**17**	4.3	1234967
Average			49	**51**	34	**35**	17	**14**	4.4	**1264450**

* *output prices for sub-class 1-1: 299080 soum* t^{-1}*; sub-class 1-2: 291320 soum* t^{-1}*; sub-class 3-1: 239360 soum* t^{-1} *(see section 4.8.5)*

The rate of return, i.e., the net benefit divided by the TCV, shows significant differences for N rates and fertilizer treatments, but not for the interactions. The rate of return for the N rate N-0 was significantly higher than all other N rates (Table 11.1).

The fertilizer treatment NPK-0 was significantly higher than the N-0, which was significantly higher than all other treatments. No difference was found between the fertilizer treatments.

Although treatment UUU was cheapest (TCV), the net benefit was still too small to achieve a high rate of return, only for N-160 was it amongst the highest. Although treatment DUUf mostly had the highest net benefit, the TCV was too high to achieve a high rate of return. However, this treatment still performed best for N-80 and N-120.

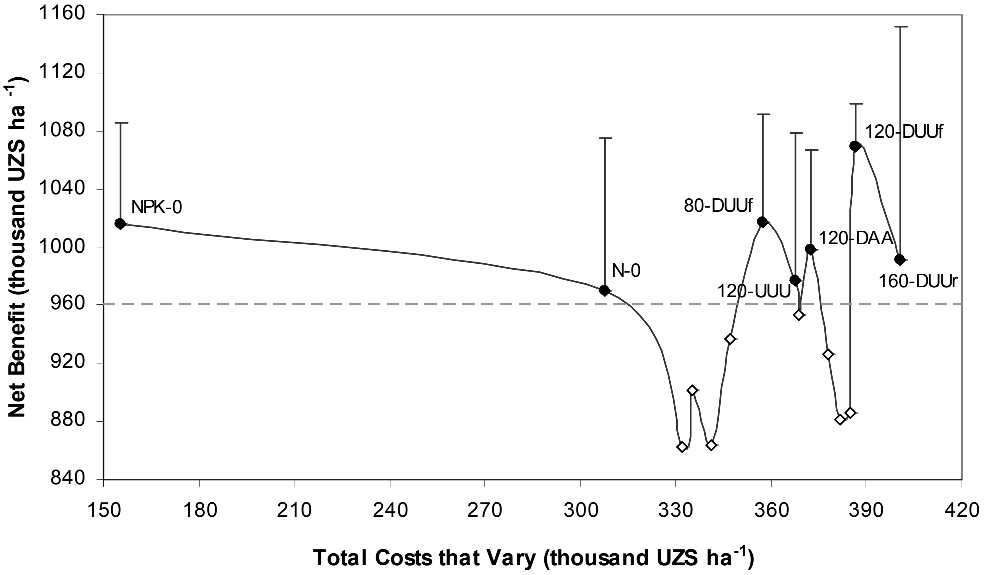

Figure 11.1 Relationship between total cost that vary (Uzbek soum, UZS) and net benefit for cotton (Uzbek soum, UZS) for the different fertilizer treatments in 2005. Error bars represent 1 SE. Black symbols (and labels): dominating treatments (mean + SE).

The dominance analysis shows that 3 treatments dominated over all other treatments (Figure 11.1, Table 11.3): NPK-0, 80-DUUf and 120-DUUf. Out of these, treatment 120-DUUf had the highest net benefit but also the highest costs, whereas NPK-0 was lowest, as the fertilizer costs were zero. When the standard error is included in the selection criterion, the treatments N-0, 120-UUU, 120-DAA and 160-DUUr show a better net benefit in relation to TCV than the other treatments.

Table 11.3 Remaining fertilizer treatments after dominance analysis in ascending order of total costs that vary; SE represents the standard error of the mean.

Treat	**N rate**	**Fertilizer**	**Total cost that vary**	**Net benefit**	**Net benefit + SE**
	kg ha^{-1}		soum ha^{-1}		
1	0	NPK-0	155366	**1016091**	
2	0	N-0	307863	970364	1075068
6	80	DUUf	357370	**1017629**	
9	120	UUU	367397	977458	1078405
11	120	DAA	372657	998579	1067001
10	120	DUUf	386302	**1069332**	
12	160	DUUr	400762	991421	1151364

The marginal rate of return (data not shown) for increasing the fertilizer amount from 80 to 120 kg N ha^{-1} for treatment DUUf was 179 %, i.e., for any additional one soum spent on fertilizer, the farmer would recover his costs and would in addition gain 1.79 UZS. Changing the fertilizer source from treatment DUUf to any other source (UUU or DAA) would not be profitable. Only changing the timing (DUUr) and the N rate at the same time would yield 5.67 UZS more for every Uzbek soum invested.

11.2 Winter wheat

The TCV ranged from minimum 7,063 (NPK-0) to maximum 177,734 UZS ha^{-1} (160-DUUu) (Table 11.4). The values increased significantly with increasing N amounts (N-0 > N-20 > N-80, N-120 > N160). The fertilizer treatment had a significant influence, as the TCV were higher for treatments DUUu and DUUr (146,616 and 146,267 UZS ha^{-1}, respectively) than for treatment DAA (143,701 UZS ha^{-1}). The variable costs for treatment UUU were significantly lowest (132,214 UZS ha^{-1}).

The N rate significantly affected net benefit, but this was not affected by the treatment. Benefits were significantly lower for N-0 and N-20 than for the other N rates. The highest (not significant) benefits were obtained for the N rate of 80 and 120 kg ha^{-1}. The lowest net benefit was found for DAP with 181,787 UZS ha^{-1}, while the highest was achieved with treatment 120-DUUr with 370,292 UZS ha^{-1}.

The rate of return was significantly different for the N rates and the fertilizer treatment. A significantly higher rate of return was found for the treatment NPK-0 than for 80-UUU and 160-DAA. The rate of return for N-160 was significantly lower than for N-80 and N-120. The treatment also affected the rate of return; treatment UUU had higher return rates than treatment DAA. The other treatments ranged in between these two.

The dominance analysis shows that four treatments dominated all other treatments (Table 11.4, Figure 11.2): NPK-0, 80-UUU, 80-DUUu and 120-DUUr. Out of these, treatment 120-DUUr had the highest net benefit but also the highest costs, while NPK-0 was lowest values, as the fertilizer costs were zero. Including the standard error in the selection criterion, also the treatments N-0, 120-UUU, 160-UUU and 160-DUUu show better net benefits in relation to TCV than the other treatments. The treatment DAA was always dominated, and treatment UUU was always dominating.

When increasing the fertilizer rate from 80 to 160 kg N ha^{-1}, the marginal rate of return for treatment UUU was 45 %, and for treatment DUUu 227 %. Changing the fertilizer treatment from 80-UUU to 80-DUUu increased the marginal rate of return by 40%.

Table 11.4 Cost analyses of the treatments for winter wheat (n = 4). SE is the calculated standard error. D stands for the dominating treatments.

Treat	**N rate**	**Fert***	**Total costs that vary**			**Net benefit**			**Rate of return**			**D**
			Mean	SE	$p<$ 0.1	**Mean**	SE	$p<$ 0.1	**Mean**	SE	$p<$ 0.1	
	kg ha^{-1}		--- soum ha^{-1}									
1	0	NPK-0	**7063**	923	a	**272468**	35502	a	**38.6**	0.0	d	+
2	0	N-0	**82708**	1345	b	**227277**	51597	a	**2.7**	0.6	abc	+
3	20	DAP	**99974**	467	c	**181787**	17860	a	**1.8**	0.2	abc	
4	80	DUUr	**121969**	807	e	**294633**	31082	a	**2.4**	0.2	abc	
5		UUU	**117068**	1213	d	**338936**	46702	a	**2.9**	0.4	c	+
6		DUUu	**123547**	555	e	**355155**	21408	a	**2.9**	0.2	bc	+
7		DAA	**120795**	961	de	**285885**	36892	a	**2.4**	0.3	abc	
8	120	DUUr	**140424**	1024	g	**370292**	39376	a	**2.6**	0.3	abc	+
9		UUU	**130550**	1126	f	**340138**	43118	a	**2.6**	0.3	abc	+
10		DUUu	**138569**	588	g	**298641**	22559	a	**2.2**	0.2	abc	
11		DAA	**136304**	534	g	**265432**	20429	a	**1.9**	0.1	abc	
12	160	DUUr	**176409**	313	i	**290103**	11926	a	**1.6**	0.1	ab	
13		UUU	**149025**	1368	h	**358162**	52522	a	**2.4**	0.3	abc	+
14		DUUu	**177734**	1003	i	**340669**	38359	a	**1.9**	0.2	abc	+
15		DAA	**174005**	835	i	**270500**	32182	a	**1.6**	0.2	a	

* *DUUr = 3 splits at recommended time, diammonium phosphate, urea, urea fertilizer*
UUU = 3 splits at recommended time, urea, urea, urea fertilizer
DUUu = 4 splits, diammonium phosphate, urea, urea, urea fertilizer
DAA = 3 splits at recommended time, diammonium phosphate, ammonium nitrate, ammonium nitrate
Means with the same letter are not significantly different

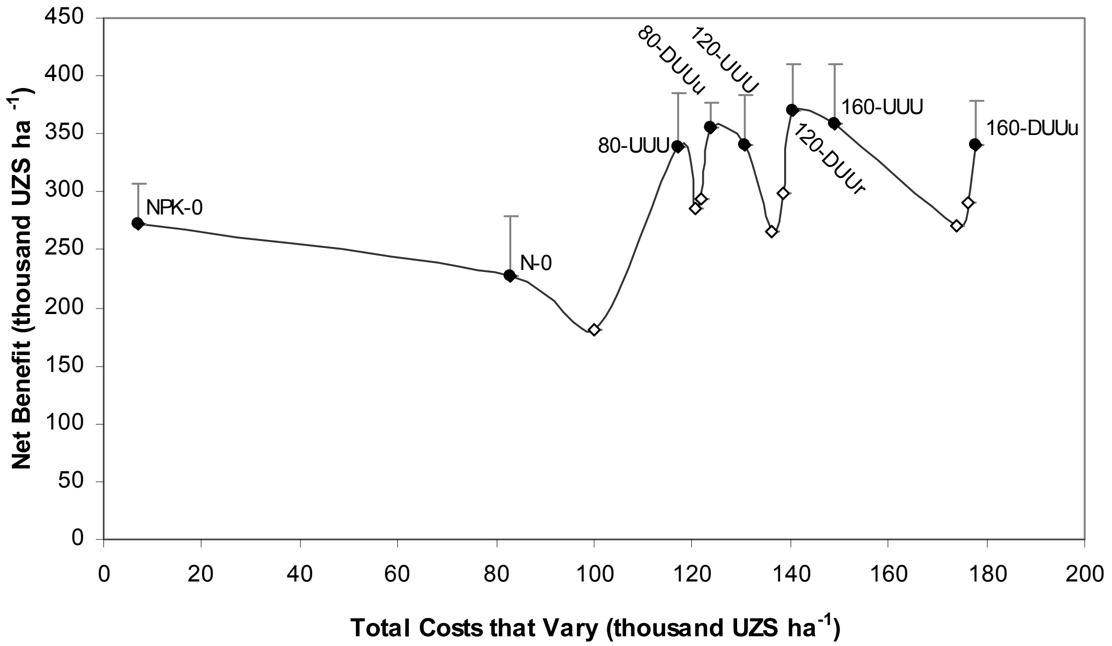

Figure 11.2 Relationship between total cost that vary (Uzbek soum, UZS) and net benefit for cotton (Uzbek soum, UZS) for winter wheat for the different fertilizer treatments in 2006. Error bars represent 1 SE. Black symbols (and labels): dominating treatments (mean + SE).

11.3 Overall financial assessment

In this study, amongst the fertilized treatments, the N-fertilizer rate of 120 kg ha $^{-1}$, which was sufficient to achieve high cotton yields, coincided with the highest returns. However, for the input/output parameters of the late 1960s, Hasanov (1970) calculated highest net benefit and returns for cotton fertilized at the rate of 200 kg N ha $^{-1}$ in the Bukhara region. Based on the input/output parameters for 2004, Kienzler et al. (2006) estimated lower returns of more than 200 kg ha $^{-1}$ in Khorezm, even though these coincided with the highest gross margin, mainly because these lead to a later opening of the cotton bolls. The returns to N investments were highest for those treatments that encouraged fast opening of bolls at pick 1 and pick 2 (i.e., treatments DAA and DUUf). This pick dependency of the return rates is a specific characteristic of the Uzbekistan state-ordered raw cotton production. Cotton prices at the ginneries are fixed for each pick, so that a late opening of cotton bolls does not coincide with the period when the highest cotton price is offered by the ginneries (Table 11.2). Hence, as long as the price-reward system is closely linked to the set picking periods, the lower N-fertilizer rates with the earlier opening of the cotton bolls will lead to higher rates of return to investments. This is in contrast to the actual physiological N demand of cotton (see section 7.1).

In contrast to cotton, the economically most promising wheat treatments were those with higher N rates (N-160), and treatments UUU and DUUu. Together with the positive performance with respect to N uptake and quality (sections 7.3 and 8.3.3), the fertilizer treatment DUUu is thus favorable and most likely to be accepted by the farmers. However, as the response of both crops to the N fertilizer was so variable, most likely due to the subirrigation influence, recommendations based on the marginal rates of returns need to be re-assessed.

12 THE YIELD GAP

The overall trend of declining yields (Figure 2.3) is not supported by the findings in this study. Neither does the official N response (Figure 2.4) or the potential, achievable yields for the recommended N rates match the experimental N response. On the contrary, provided that all inputs, i.e., fertilizer, water, timing, were close to optimum levels, high yields, even with lower inputs, could be achieved in some places in Khorezm. The yield response and dynamics over time that indicate a downward trend thus cannot be explained solely by the commonly proclaimed soil degradation and salinization, or decreasing soil organic matter content, etc. (e.g., Spoor 1998, ZEF 2001, Herrfahrdt 2004, UNEP 2005, Roll et al. 2006). Also, a reduced use of inputs such as N fertilizers (WARMAP and EC-IFAS 1998, FAO 2003, Müller 2006b, Djanibekov 2008) could not have created the downward shift of the official N response curve, as increasing (or decreasing) N applications would only improve (or reduce) yields along the lower response curve, but not lift the curve itself. Technological aspects influencing the cotton yields such as deteriorated equipment and irrigation systems (Conrad 2006, Müller 2006b), electricity cuts, harvest delays, etc., could have contributed to the decline in the reported cotton yields after independence, aside from the impact of soil degradation.

At least equally important to the technological aspects, however, are the non-technological aspects driving the farmers' investments, expenditures and crop management, and the farmers' confinement to the state order in cotton and wheat production. While the government prefers cotton as a marketable crop that brings foreign exchange (Rudenko 2008), winter wheat is commonly prioritized by farmers (Djanibekov 2005, Veldwisch 2008), as it eases the growing livelihood insecurity (Müller 2006b). The wheat preference is reflected particularly in a higher willingness of farmers to use more fertilizers for crops of higher value instead of for cotton (Djanibekov 2005, Djanibekov 2008). Nevertheless, a survey with 252 private Khorezmian farmers conducted by Djanibekov (unpublished data) in 2003 shows that although the average N-application rate in cotton production was 212 kg ha^{-1} (median 205 kg N ha^{-1}), the highest relative frequencies were lower, i.e., between 160 and 200 kg ha^{-1} (Figure 12.1), and the rate 180 kg N ha^{-1} was most favored (26 % of the respondents). However, another peak was visible for the fertilizer rates 240-280 kg N ha^{-1}, which 18 % of the respondents reported as a common application rate. In cotton fertilization, therefore, at least two groups of farmers can be differentiated: those who under-fertilize cotton in relation to the recommended N rate and to its plant-N demand, and those who apply more N fertilizers than recommended.

For winter wheat (Figure 12.2), on the other hand, a farm survey with 213 farmers revealed only one clear peak in the relative frequency at the application rate between 160 and 200 kg N ha^{-1} (average 203 kg N ha^{-1}; median 185 kg N ha^{-1}) (Kienzler et al. forthcoming). This rate, which was favored by the largest share of respondents (26 %), corresponded also to the recommended rate of 160-180 kg N ha^{-1} and to the plant-N uptake.

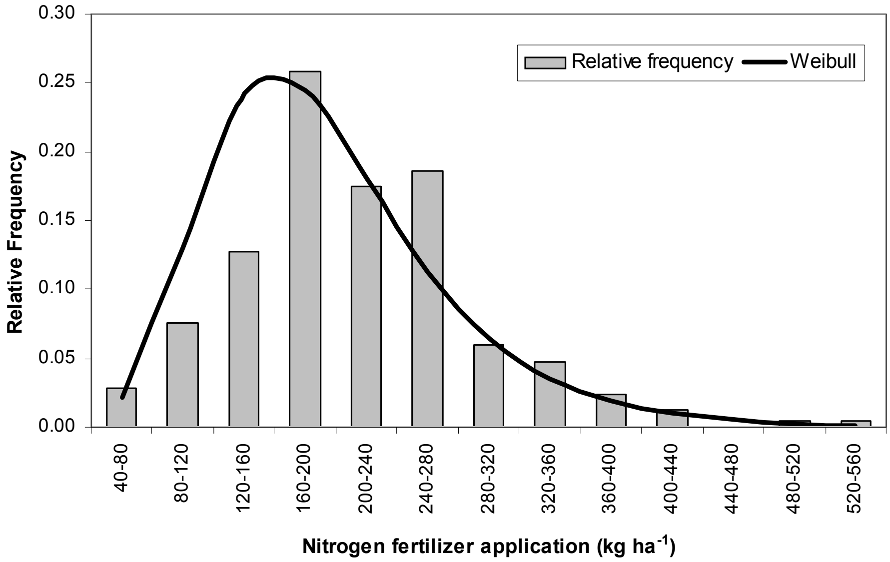

Figure 12.1 Probability density function and Weibull probability distribution function for N applications in cotton (private farm surveys of 252 respondents in Khorezm, 2003, (Djanibekov, unpublished data)

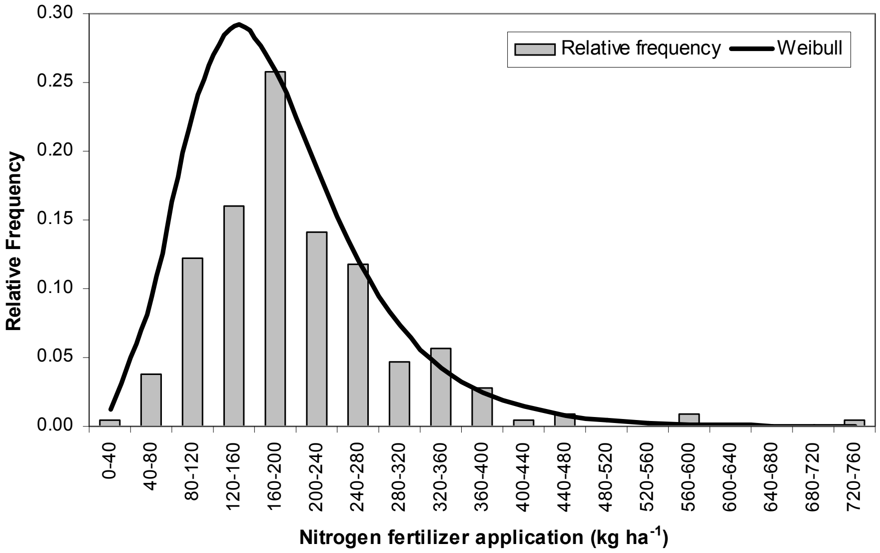

Figure 12.2 Probability density function and Weibull probability distribution function of N fertilizer applications in winter wheat (private farm survey of 213 respondents in Khorezm, 2003 (Djanibekov, unpublished data)

The discrepancies between actual mineral fertilizer use in cotton production by Khorezmian farmers and the recommended quantities have a clear socio-economic reasoning. In contrast to general perceptions, for farmers, optimizing yield does not necessarily mean maximizing yield. A key decision is rather whether or not to fertilize and if yes, when and how much. The revenues from cotton-yield increases due to NPK-fertilization must be significantly higher than the sum of the direct costs (e.g., for fertilizer) plus indirect costs of fertilization (i.e., expenses for transport, application). Other factors affecting the expenditure such as labor, tillage, weed control, picking and harvesting need also to be considered to obtain a sound evaluation of the benefits of raw cotton yield. Furthermore, there is also a divergence in the financial situation and the risk attitude of farmers, which often are difficult to assess but should not be underestimated in rural Uzbekistan. While poorer farmers in Khorezm, who also mostly have a smaller piece of land, tend to apply less fertilizer to cotton, wealthier farmers may apply more hoping to achieve higher crop yields and hence maximize their profit. This attitude, which is reflected in the two peaks of the cotton survey data (Djanibekov, unpublished data), is understandable given the lack of agricultural education of the new private farmers emerging after a period of collective ownership and low farm decision-making autonomy (Adams et al. 1997, Wall 2006).

It is difficult for the government, on the other hand, to meet the farmers' demand for N fertilizers, as only 45 % of the total N supply can be covered (MAWR 2004b). These fertilizers are primarily distributed to those farmers with a state contract for cotton and wheat production. For poorer producers without a contract, the expensive agricultural inputs are often unaffordable, which forces them to substitute these by using cheap alternatives of low quality (Trevisani 2008). The subsidized inputs, however, are often also (illegally) allocated to paddy rice instead of cotton, since it has the highest marketable value and net return (Djanibekov 2005, Guadagni et al. 2005, Trevisani 2008). Such re-allocation of fertilizers in the cropping system is not officially reported, and thus may falsify the official statistics regarding N use on state-ordered crops.

The rotation design of cotton and wheat also has an undeniable influence on yield. Although the cotton-wheat rotation is rather new to the Khorezm region, it is long-practiced in Australia (e.g., Constable et al. 1992) and Pakistan (e.g., Byerlee et al. 1987). Similar to Khorezm, also in the Punjab setting, the two crops are frequently grown in direct sequence (Byerlee et al. 1987). In those years where cotton is directly followed by wheat, however, the last cotton pick regularly interferes with the time of wheat seeding. Wheat that is sown into the cotton rows is known to reduce total yields due to lower plant densities. In the Punjab region, where neither crop is state regulated, and inputs are free of subsidies, farmers often opt for the food crop wheat rather than for the cash crop cotton, and sacrifice the last cotton pick to ensure timely seeding and guarantee high yields of winter wheat (Byerlee et al. 1987).

Khorezmian farmers, who are confined to the state order, on the other hand, do not have the freedom of such trade-offs as in Pakistan, as institutional conflicts may arise when cotton production targets are not met without clear excuses (Trevisani 2008). In the Khorezmian setting, farmers at present, therefore, are caught in the dilemma of being obliged to pay fines when they do not fulfill the cotton or the wheat yield target. Thus, they frequently are under pressure to ensure timely wheat planting in order to reach the required yield, even though high-yielding cotton fields may be economically worth harvesting until the last pick (Rudenko and Lamers 2006). The farmers, therefore, plant cotton on land of lower soil fertility, while more valued crops such as wheat and rice are placed on better-quality sites.

Overall, the agricultural production system in Khorezm is more complex and interwoven than often assumed. It is a factor mosaic, which includes the current agricultural setting, i.e., the changed socio-economic situation and its on-going dynamics, the unclear legal environment, the preference for higher valued crops such as rice or fodder crops, and the financial status that drives the farmers' decision-making in crop management and indirectly influences the reported N use and yields. Consequently, the yield gap between the officially recorded yields and those that technically could be achieved given the agro-ecological conditions in the Khorezm region cannot be narrowed by improving one single aspect such as N-fertilizer management. An analysis of the decline in yields over time that includes only soil degradation as the explaining variable would lead to inadequate recommendations. Only by improving the farmers' knowledge on sustainable practices and efficient management, providing funds for entrepreneurial capital necessary for investments, adjusting the state-order regulations, and ensuring adequate payment for quality and yield, can changes be achieved.

13 CONCLUSIONS AND FURTHER RESEARCH NEEDS

After a history of subsidized inputs and crop production on the state collective farms, the newly established private farmers are challenged by the new land-tenure regulations, and rising costs for fertilizers, pesticides and machinery following Uzbekistan's independence. Stuck between the obligation to fulfill the state's production targets for cotton and winter wheat and the burden of ensuring their livelihood, farmers only sup-optimally apply N fertilizer to cotton and winter wheat from an agronomic viewpoint. Fertilizer recommendations date back to the time before independence. In this setting, sustainable N-fertilizer management and its efficient use are challenging, especially in the irrigated regions of Uzbekistan, where poor N management inevitably leads to losses via denitrification and leaching. This research, therefore, focused on identifying the current N-fertilizer use inefficiencies in irrigated cotton and winter wheat production to improve the N-fertilizer strategies for those crops and product quality while reducing losses to the environment.

In this chapter, the key research results are recapitulated with special reference to the research objectives followed by general conclusions and future research needs.

13.1 Conclusions for the respective research objectives

- Objective 1: *Assess cotton and wheat yield response to increasing N-fertilizer application rates under the current management.*

The official N-fertilizer recommendations for irrigated cotton and winter wheat of 200 and 180 kg N ha^{-1}, respectively, were found to correspond well with the potential N uptake of cotton and winter wheat measured and simulated in this study. The plant-N contents also matched uptake rates reported in the literature.

The initial soil-mineral N content of the experimental sites was low and thus a crop response to N was expected. However, only a limited response of cotton and wheat yield to increasing N-fertilizer rates was observed. The flat response curve can possibly be attributed to supplemental N contribution from the groundwater which most likely influenced the soil-N balance and plant-N uptake. Most of this N is likely to come from N applied to neighboring fields. Although the quantification of these potentially contributing pools was beyond the scope of this study, first approximations suggest this share to be in the range of 5-61 kg N ha^{-1}, i.e., equal to the amount usually applied during one single N-fertilizer application event. Particularly cotton with its long tap root, may profit from such extraneous N sources. This additional N supply depends on many factors such as groundwater depth, its nitrate content, and the field's proximity to the next drain. However, farmers can not collectively rely on this N input and reduce N applications, as continuously low applications of N-fertilizer would diminish the N load of the groundwater and will lead to slow mining of the soil-N resources by the crop.

The reported cotton yields in Khorezm were exceeded, as high yields were measured for both cotton (on average 4.0 t ha^{-1} vs. 2.6 t ha^{-1} on regional level) and wheat (on average 3.4 t ha^{-1} vs. 4.3 t ha^{-1} on regional level) throughout the three study years. However, the recommended N-fertilizer amounts and the response curves of this study exceeded the actual N use in cotton production reported by the local administration in Khorezm.

Moreover, the state-order restriction on cotton and wheat, which also dictates the crop rotation, combined with the farmers' unstable financial status and their preferences for higher-valued crops such as wheat and rice has indirectly influenced N use and yields, and the farmers' crop management, risk attitudes, and expenditures. Consequently, without considering the impact of the economic and legal settings on farmers' decision making, significant institutional and political limitations can occur when trying to implement the recommendations for a more sustainable N-fertilizer management.

- Objective 2: *Evaluate N-fertilizer use efficiency under various N-management practices with special focus on fertilizer timing and N-fertilizer types.*

For both cotton and wheat, the total fertilizer-N recovery was very high (81-84 %). While the plant-N recoveries of cotton (34 %) and winter wheat (33 %) were similar to those measured in other irrigated regions in Uzbekistan and elsewhere, the soil-N recovery rates were comparatively high (50 and 48 %). The large amount of ^{15}N-fertilizer recovered in the soil indicates that immobilization processes and/or pool substitution strongly influenced the recovery rates. Also, more than 70 % of the ammonium- and nitrate-containing N fertilizers applied were recovered in the top 30 cm of the soil. Evidently, leaching of the freshly applied ^{15}N-fertilizer into deeper depths under the experimental irrigation regime (300 mm) was limited, and even under doubled irrigation (600 mm) the modeled leaching losses were estimated to be below 20 % of the applied N. The nitrate found in the groundwater may have originated from re-mineralized soil-organic N (pool substitution) in the experimental field and neighboring fields.

The current N management in cotton practiced by the farmers includes an N application at the 2-4 leaves stage, whereas the recommendation is an application time at the budding stage. The research results show that the farmers' practice leads to 8 % lower ^{15}N-fertilizer uptake and around 22 % lower total ^{15}N recovery in comparison to the N fertilization at budding, as ^{15}N applications at the 2-4 leaves stage coincided with high temperatures and extensive irrigation water application, which substantially enhanced ^{15}N losses. Yields of these two treatments, however, did not significantly differ, which could be attributed to the supplemental N input from other sources (see above). In winter wheat, an additional N application at anthesis/heading, presently not practiced by farmers, yielded highest total ^{15}N recovery rates (46 % of ^{15}N applied).

The results underline that N-fertilizer applications cannot be standardized for a fixed crop growth stage, but have to be carefully synchronized with crop development, location specifications and other agro-technological measures. Also, irrigation practices should be harmonized with N management based on field-N measurements.

The N fertilization using diammonium phosphate before seeding (DUU) showed the highest N-recovery for wheat and cotton compared to the complete urea combination (UUU). Although the yields were generally lower for nitrate-N-containing fertilizers, these fertilizers were taken up more efficiently during the growing season than those containing ammonium-N. Following N fertilization and irrigation of dry soil, the nitrate-N source became more rapidly available to the plant roots.

- Objective 3*: Determine cotton fiber and wheat kernel quality at different N-fertilizer rates and timing.*

The cotton fiber quality depended strongly on the time of picking and showed an optimum at the first pick. It decreased with each picking event due to decreasing fiber maturity. However, it was not affected by N treatments. In contrast, the seed to fiber ratio significantly increased with N applications. Increased N fertilization also delayed the opening of cotton bolls, so that in this case the highest yield did not coincide with the period during which the ginneries offer the highest price for cotton (see financial section below). Differently timed N-fertilizer splits or N-fertilizer types did not noticeably influence fiber quality. Overall, the fiber quality of the variety *Khorezm-127* was classified as lowest grade according to the Uzbek classification, so that it could be used mainly for cheap cotton goods, mélange fabrics, towels, sateen, gauze or diagonal cloth.

The protein and gluten results show that the winter wheat variety Kupava R2 grown in Khorezm only met the criteria of a satisfactory to good wheat filler and low to medium quality flour thickener. Late applications of N at anthesis/heading significantly increased the fertilizer-N uptake efficiency and protein content in the kernels. Also, increased N rates enhanced kernel protein content, while gluten content was less affected by higher N rates. However, for this variety, protein content and yield were negatively related, i.e., the maximum protein content did not coincide with maximum yield, showing the need for breeding wheat varieties with higher quality and yield potential suitable for irrigated conditions of the irrigated lowland areas of the region. Furthermore, the lack of machinery for wheat harvest caused serious delays, which at the prevailing high temperatures in June/July increased kernel shattering and reduced the kernel moisture below those optimal for the milling process.

At present, farmers are only interested in producing maximum yields at lower (fertilizer) costs and not in higher protein and quality grain as they are not reimbursed for the additional costs for protein production.

- Objective 4: *Simulate the effects of alternative N applications, irrigation water quantities and groundwater levels on N dynamics in the soil and on crop yield.*

A cotton-specific routine for the crop-soil simulation model CropSyst was developed and successfully verified for Khorezm conditions. CropSyst predicted the experimental yields with a high accuracy, except for those of the non-fertilized and low-fertilized treatments (RMSE = 1.08 Mg ha^{-1}). This was likely due to the fact that possible NO_3-N supply through irrigation and groundwater had not been incorporated into the model. Such a sub-routine would allow incorporation of N contributions via (sub-surface) irrigation. Since no sufficient data on mineralization, nitrification and denitrification rates and the mineralization of organic matter fractions were available, these processes could only be incorporated conservatively. Despite these limitations, the cotton routine proved to be a useful tool in filling the gaps in the N balance.

The potential and actual evapotranspiration and crop transpiration as simulated showed a potential contribution of the groundwater to crop water demand of between 283 and 335 mm depending on the N-fertilizer rate. Cotton yields may be increased without simultaneously increasing N losses when the total irrigation amounts are reduced and the irrigation application patterns adjusted to the actual crop water demands.

Overall, the developed cotton-specific routine in CropSyst can be seen to be a very useful tool for demonstrating changing environmental conditions and yields under different agricultural practices and, therefore, can be applied to encourage farmers in changing their current management system.

- Objective 5: *Determine the financial feasibility of different N-fertilizer management practices.*

The N uptake from sources other than the N fertilizer applied constrained the determination of an optimum economic N rate. For cotton, the returns to N investments were highest for those treatments that encouraged fast opening of bolls at pick 1 and pick 2, i.e., N-fertilizer rate of 120 kg ha^{-1}, and application of N at the 2-4 leaves stage (farmers' practice). However, this rate was below the actual N uptake of cotton of around 200 kg ha^{-1}. In addition, the farmers' practice proved to be the most inefficient application strategy in terms of timing (see above). The dependency of the rates of return on the time of harvest is a specific characteristic of the Uzbekistan state-ordered raw cotton marketing system. Hence, as long as the present price-reward system is closely linked to the set picking periods, the lower N-fertilizer rates, which provoke an earlier opening of the cotton bolls, will result in higher rates of return to investments. However, this practice will also result in soil nutrient mining and inefficient N-fertilization practices.

In contrast to cotton, the economically most promising wheat treatments were those with higher N rates, i.e., 160 kg N ha^{-1}, and those receiving an additional N application during anthesis (Zadoks-60, Feekes-10.51).

13.2 Impact of different N-fertilizer combinations on selected parameters

The overall performances of the different N-fertilizer combinations for the ^{15}N cotton and winter wheat experiments are summarized in Table 13.1 and Table 13.2.

Table 13.1 Relative performance of four fertilizer treatments of ^{15}N cotton experiment. Symbols indicate the impact of the respective fertilizer combination on various parameters as very high (++), high (+), satisfactory (-), low (--).

Parameter	**Fertilizer combination***			
	DUUr	UUU	DUUf	DAA
Total yield	+	+	++	+
Yield at pick 1	-	-	+	+
Biomass (cotton)	-	+	++	+
Biomass (leaves, stems)	+	++	+	-
N uptake into biomass	++	+	+	-
Total N recovery	++	+	-	+
N recovery in biomass	+	+	+	+
N recovery in soil	+	++	-	+
N gaseous losses (CropSyst)	+	+	++	-
Fiber quality	+	+	+	+
Net benefit	+	-	++	+

* *DUUr = 3 splits at recommended time, diammonium phosphate, urea, urea fertilizer*
UUU = 3 splits at recommended time, urea, urea, urea fertilizer
DUUf = 3 splits, farmers' practice, diammonium phosphate, urea, urea fertilizer
DAA = 3 splits at recommended time, diammonium phosphate, ammonium nitrate, ammonium nitrate

Table 13.2 Relative performance of four fertilizer treatments of ^{15}N winter wheat experiment. Symbols indicate the impact of the respective fertilizer combination on various parameters as very high (++), high (+), satisfactory (-), low (--).

Parameter	**Fertilizer combination***			
	DUUr	UUU	DUUu	DAA
Total yield	+	++	++	-
Biomass (wheat kernels)	+	+	++	-
Biomass (stems)	+	+	+	+
N uptake into biomass	+	+	++	-
Total N recovery	+	-	+	++
N recovery in biomass	-	-	+	++
N recovery in soil	+	-	-	+
N recovery in kernels	+	+	++	+
Kernel quality	-	-	+	-
Net benefit	-	+	++	--

* *DUUr = 3 splits at recommended time, diammonium phosphate, urea, urea fertilizer*
UUU = 3 splits at recommended time, urea, urea, urea fertilizer
DUUu = 4 splits, diammonium phosphate, urea, urea, urea fertilizer
DAA = 3 splits at recommended time, diammonium phosphate, ammonium nitrate, ammonium nitrate

13.3 Conclusions and further research needs

The efficiency and sustainability of the farmers' current N-management practices differed for cotton and winter wheat. In cotton production, N-fertilizer amounts necessary for satisfying plant-N demand substantially diverge from the economic optimum to produce highest yields. As high yields and fast maturation of cotton bolls can be achieved at lower N rates, profit maximization encourages an undersupply of cotton at the expense of reducing soil fertility. The officially recommended N-fertilizer rates, which are more in line with plant-N demand, are not supported by the present state-imposed reward system. Also, the N-application timing practiced by the farmers has shown to be less efficient than the officially recommended split.

The farmer's current N-fertilizer management practices with winter wheat, on the other hand, are in line with the official recommendations and economically most profitable. Even with respect to proper plant nutrition and maintenance of soil fertility, the present practices can be considered suitable for maximum wheat yields. However, the efficiency of N-uptake into the kernels and the subsequent wheat quality remain low with the present N-fertilizer recommendations. Buyers of winter wheat, mills, do not offer incentives to improve yields with late N applications as they do not offer quality-based prices.

There is scope for improving N management, N-use efficiency, and cotton quality through better irrigation scheduling and application rates that correspond with loss-sensitive periods such as the 2-4 leaves stage (see above), by ensuring timely planting of cotton, and by changing the payment system of the ginneries to encourage N-application practices that suit crop-N demand. Nevertheless, the mismatch of N supply in cotton demands a more detailed macro-economic analysis of the long- and short-term losses and gains of more efficient N-fertilizer use.

In irrigated winter wheat, N management can be optimized and N-use efficiency and kernel quality enhanced by improving the irrigation scheduling and promoting late application of N. Offering adequate reimbursement for higher wheat quality rather than quantity to the farmers, regularly monitoring protein content and other quality aspects of wheat would lead farmers to change their current practices. A systematic breeding program is called for to generate more suitable varieties that are less water demanding (such as synthetic wheat) and varieties that can more easily produce high quality grains under Khorezm conditions.

Further research should also include the use of slow-release fertilizers, or denitrification inhibitors, and foliar-N applications in wheat as approaches to improve N-use efficiency. In-season measurements of crop and soil-N status using non-destructive absorbance (chlorophyll measurements) and reflectance (portable reflectometer) methods would further help to adjust N-fertilizer application to actual crop-N demand.

To render the present version of the CropSyst cotton model even more effective, a follow-up study should determine the mineralization rate and capture the seasonal dynamics of mineral N in the soil and nitrate in irrigation and groundwater. Such datasets would allow further validation and improvement of the accuracy of the estimated parameters of the CropSyst simulations. Once parameterized and calibrated for irrigated winter wheat, the model could be applied to simulation of crop rotations and impacts of management practices within the dominating winter wheat rotation also on a wider regional scale. Also, the impact of conservation agriculture practices including improved residue management on N-use efficiency and soil fertility in an irrigated production system needs to be investigated. In combination with alternative crop rotations, these practices could prove a valuable approach to improve N-use efficiency and sustainable management in irrigated agriculture.

This study further emphasizes the importance of assessing the income increase per quality increase in wheat production necessary for farmers to adapt their management strategy.

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15 APPENDIX

Appendix 15.1 Irrigation norms for cotton for light saline soils with shallow groundwater (MAWR 2000, HydroModRay 2003)

Irrigation event	**Irrigation**	**Irrigation period (date)**		**Irrigation period length**	**Phase**
	mm	from	to	Days	
1	100	May 25	June 15	22	2-4 leaves
2	100	June 16	June 30	15	budding
3	110	July 1st	July 15	15	fruiting
4	120	July 16	July 31	16	flowering
5	110	Aug 1st	Aug 15	15	flowering
6	100	Aug 16	Sept 5	21	maturation

Appendix 15.2 Irrigation norms for winter wheat for light saline soils with shallow groundwater (HydroModRay 2003)

Irrigation event	**Irrigation amount**	**Irrigation period (date)**		**Irrigation period**	**Phase**
	mm	**from**	**to**	**days**	
1	80	1.4	12.4	12	tillering
2	80	13.4	24.4	12	booting
3	80	25.4	6.5	12	heading
4	80	7.5	18.5	12	flowering
5	80	19.5	31.5	13	grain filling

Appendix 15.3 Fertilizer research (source: Djumaniyazov 2004)

Year	**Author**	**Variety**	**N** (kg ha^{-1})	**P** (kg ha^{-1})	**K** (kg ha^{-1})	**Yield** (t ha^{-1})	**Comments**
1931	Zverlin	1306				2.71	100 kg ammonium sulphate, 90 kg SSP per kg N
1928-30	Zverlin	N-169, Navro, 1306	90	90	-	2.0	
1931	Zverlin	N-169	45	45	-	2.73	Given the after-effect of high rates in previous years, the application of 45 kg ha^{-1} sufficiently supplied the necessary nutrients for cotton
1934	Zverlin		90	90	-	3.0-3.5	
1936	Novikov and Tumbinsky	N-8517	240	180	-	3.16	
1954	H. Taktashev		120	60	-		Field history 1950-1953: old irrigated site: Alfalfa-alfalfa-melons-cotton; newly irrigated site: fallow-melons-melons-alfalfa
1960	Khaitbayev	Khorezm-8	120	90	40	2.87	Field history: 5 years of legumes; K fertilizer delays maturing
1965	A.R.Yusupov	108-f	200	150	50	6.02	Field history: 3 years of legume (alfalfa)
1965	K. Yakubov and J. Madaminov		268	133			Calculated as average over Khorezm from statistical data
1969	A.R. Yusupov		200	200	75	3.38	Research conducted for 2 years; according to the data from the research station, N norms more than 200 kg ha^{-1} were not effective as expected, decreased the efficiency of fertilizers, and delayed the maturing of bolls.
							In the years 1965-1968, the Khorezm region reached the record high cotton yields while application of high rates of mineral fertilizers
1969	S. Ruzmetov	108-f	225	150	-	4.34	

Appendix 15.3 continued

1969	A.R.Yusupov and H.H. Tahtashev	108-f	200	160	-	3.2-3.9	
1970	A.R.Yusupov and H.H. Tahtashev	108-f	200	160	-	4.6-5.3	Set-up on the same fields as the year before
1970	S.Ruzmetov		225	150	-	4.3-4.4	For the soils of Khorezm it is advisable to apply about 30 % of the annual norm of N fertilizers during spring ploughing
1970	D. Madaminov		240	140	75		
1970	D. Madaminov		288	162	22		From statistics 1950-1970
1972	Sabirov	108-f	350	280	-	4.86	
1974-75	M. Sabirov	Tashkent-3	350	250	-	4.6-5.1	The cotton variety Tashkent was introduced because the variety *108-f* was vulnerable to weeds
1974-75	M. Sabirov	Tashkent-1	400	200	50	4.0-5.3	
1978	Sabirov	Tashkent-1	350	280	175	3.1-3.6	
1979-81	Nazarov	Tashkent-1	450	450	225	4.6-4.7	
1971-1974	Zaynieva		150	100	75		
1977	M. Sabirov		400	nn	nn		
1976-1979	I.Sabirov		300	nn	nn		
1981	Azizjanov	Tashkent-1	300	300	150		Field history: 3 years of cotton
1983	Atajanov	175-f	275	150	125	4.0-4.5	
1984	Atajanov	175-f	250	210	125	4.89	
1985	Tashpulatova	175-f	250-350	150-250	100-140	4.0	
1988	Ibragimov and Rustamova	175-f	250	160	120	4.38	
1990	E.N. Masharipov and A. Egamov	175-f/C-6524	350	330	175	4.2-4.4	
1990	E.N. Masharipov and A. Egamov	175-f	250	175	125	4.0-4.2	
1991	Allayarov	175-f	250	200	100	3.8-4.7	With 10-15 t ha^{-1} manure
1992	Masharipov		150	100	75	3.14	
1992	Masharipov		250	175	125	3.39	

Appendix 15.3 continued

1993	Alloerov, Madaminov, Ibragimov, Jumaniezov	175-f	240	160	120	3.46	
1997	Masharipov	175-f	250	175	125	3.22	
1997	Masharipov	Khorezm-126	250	175	125	3.27	
2000	Sabirov and Masharipov	Khorezm-127	250	175	125	3.6-3.9	
2000	Sabirov and Masharipov	175-f	250	175	125	3.6-3.7	
2002	Sabirov and Rustamova	Khorezm-127	250	175	125	3.9-4.2	
2002	Sabirov and Rustamova	Khorezm-150	250	175	125	4.1-4.6	
2002	Sabirov and Rustamova	Oktaryo-6	250	175	125	3.8-4.1	
2004	Masharipov	Khorezm-127	250	175	125	3.4-3.5	
2004	Masharipov	C-6524	250	175	125	3.3-3.4	
2004	Masharipov	Khorezm-150	250	175	125	3.6-3.7	
Approx. 1986-2006	Official recommendations from the Ministry of Agriculture and Water Resources of Uzbekistan	Any variety	200-250	140-175	100-125	2.5-3.5	Adjustments depending on soil type, crop rotation, use of manure, etc.

Appendix 15.4 Phenological observation dates for the cotton minus-1 and response experiments by location, 2004

Experiment	**Name**		**Phenological stages**				
			sowing	**2-4 leaves**	**budding**	**fruiting / flowering**	**maturing**
Minus-1	Khonka	Date	03.04.	02.06.	26.06.	26.07.	10.09.
		DAS		60	84	114	160
Minus-1	Kushkupir-HL	Date	14.04.	05.06.	25.06.	30.07.	03.09.
		DAS		52	72	107	142
Minus-1	Kushkupir-LL	Date	14.04.	05.06.	25.06.	30.07.	03.09.
		DAS		52	72	107	142
Minus-1	Shavot	Date	07.04.	09.06.	25.06.	06.08.	09.09.
		DAS		63	79	121	155
Minus-1	Urgench	Date	28.04.	05.06.	30.06.	06.08.	08.09.
		DAS		38	63	100	133
Minus-1	Yangibozor	Date	26.04.	08.06.	28.06.	27.07.	02.09.
		DAS		43	63	92	129
Minus-1	Yangiaryk	Date	30.04.	10.06.	24.06.	28.07.	11.09.
		DAS		41	55	89	134
Response	Response-LL	Date	10.04.**	09.-10.06.	07.-08.07.	02.-03.08.	13.-16.09.
		DAS					
Response	Response-ML	Date	10.04.**	11.-12.06.	09.-10.07.	04.-05.08.	17.-20.09.
		DAS					

* *DAS: days after sowing*

** *Reseeding on April 28 due to heavy rains on April 15, 2004*

Appendix 15.5 Phenological observation dates for the cotton ^{15}N experiments, 2005.

Phenological Stages	**Date of observation**	**Main plot**	**Microplot**
		DAS*	**DAS**
Sowing	22.04.		
2-4 leaves	03. - 10.06.	45	42
Budding	23. - 24.06.	62	62
Flowering	07. - 11.07.	78	76
Fruiting/flowering	05. - 06.08.	105	105
Maturing	29. - 31.08.	130	129

* *DAS: days after sowing*

Appendix 15.6 Winter wheat seeding dates for the minus-1, response and ^{15}N experiments in 2004/05 and 2005/06

Experiment	Name	Seeding
Minus-1	Urgench-LL	08.10.04
Minus-1	Urgench-ML	25.09.04
Minus-1	Yangibozor	22.09.04
Response	Response-LL	08.10.04
Response	Response-ML	25.09.04
^{15}N experiment	^{15}N	14.09.05

Appendix 15.7 Harvest dates (picks) for the minus-1 and response experiments in 2004

Experiment	Name	Harvest date			
		Pick 1	Pick 2	Pick 3	Pick 4
Minus-1	Khonka	13.09.	30.09.	22.10.	27.10.
Minus-1	Kushkupir-HL	24.09.	05.10.	21.10.	26.10.
Minus-1	Kushkupir-LL	24.09.	05.10.	21.10.	26.10.
Minus-1	Shavot	21.09.	08.10.	20.10.	27.10.
Minus-1	Urgench	23.09.	04.10.	18.10.	28.10.
Minus-1	Yangibozor	21.09.	08.10.	19.10.	26.10.
Minus-1	Yangiaryk	17.09.	28.09.	13.10.	-
Response	Response-LL	30.09.	09.10.	18.10.	26.10.
Response	Response-ML	30.09.	09.10.	18.10.	26.10.

Appendix 15.8 Harvest dates (picks) for the ^{15}N experiment 2005

Harvest	Date of observation	Main plot	Microplot
		DAS*	DAS
Pick 1	13. - 14.09.	144	144
Pick 2	04. - 05.10.	165	165
Pick 3	24. - 25.10.	185	185

* *DAS: days after sowing*

Appendix 15.9 Winter wheat harvest dates for the minus-1, response and ^{15}N experiments in 2004/05 and 2005/06

Experiment	Name	Harvest date
Minus-1	Yangibozor	21.06.2005
Minus-1	Urgench-ML	16.06.2005
Minus-1	Urgench-LL	16.06.2005
Response	Response-ML	16.06.2005
Response	Response-LL	16.06.2005
^{15}N experiment	^{15}N	12-13.06.2006.

Appendix 15.10 Average total raw cotton yield (t ha^{-1}) for the minus-1 treatments for four picking times in Khorezm (n = 4) in 2004.

Pick	**Treatment**	**Mean**	**SE**
		kg ha^{-1}	
1	-N	1.4	0.08
	-P	1.4	0.10
	-K	1.5	0.11
	NPK	1.4	0.12
2	-N	1.1	0.07
	-P	1.2	0.08
	-K	1.2	0.07
	NPK	1.1	0.06
3	-N	0.9	0.07
	-P	1.1	0.10
	-K	1.2	0.12
	NPK	1.2	0.13
4	-N	0.3	0.05
	-P	0.4	0.07
	-K	0.4	0.07
	NPK	0.5	0.08

Appendix 15.11 Irrigation events and amounts (mm) for the ^{15}N cotton experiment for the quadratic weirs, flumes, plot (T) and replication (R) in Maksud Garden, 2005.

Event	**DAS***	**Date**	**Quad. weir**	**Quad. weir**	**SANIIRI flume**	**RBC flume**	**Average**
			T7-R1	T12-R1	T13-R1	T15-R1	
1 a	34	26.05.	18.3	20.4	**	**	19.4
1 b	34	26.05.	18.9	20.8	15.4	32.4	21.9
1 c	35	27.05.	17.2	17.8	17.5	33.0	21.4
2 a	64	25.06.	16.5	29.3	12.4	34.1	23.1
2 b	65	25.06.	16.5	29.3	12.4	34.1	23.1
3 a	82	12.07.	**	36.9	**	***	36.9
3 b	85	12.07.	**	25.4	17.3	-	21.3
4 a	97	28.07.	27.3	28.3	31.9	-	29.2
4 b	98	29.07.	20.2	24.7	24.3	-	23.1
5 a	115	15.08.	20.1	27.2	38.1	-	28.5
5 b	116	16.08.	28.7	24.6	28.4	-	27.3
Total (mm)			**183.6**	**284.9**	**197.6**		**274.9**

* *DAS: days after sowing*

** *no readings taken, as the soil was too dry and cracked*

*** *dismounted, as water was frequently flowing around due to large cracks in the soil*

Appendix 15.12 Average total raw cotton yield (t ha^{-1}) for N rates (kg ha^{-1}) of the minus-1 experiments (2004), the response experiments (2004) and the ^{15}N experiment (2005). SE denotes standard error of the mean.

Year of experiment	**N rate**	**n**	**Average yield**	**SE**
	kg ha^{-1}		t ha^{-1}	
2004	0	36	3.5	0.1
	80	8	3.6	0.3
	120	8	3.4	0.3
	160	8	3.7	0.3
	200	36	4.0	0.1
	250	8	3.6	0.3
2005	0	4	4.3	0.4
	80	16	4.3	0.2
	120	16	4.7	0.1
	160	16	4.5	0.2
Total	0	40	3.6	0.1
	80	24	4.1	0.2
	120	24	4.3	0.2
	160	24	4.2	0.2
	200	36	4.0	0.1
	250	8	3.6	0.3

Appendix 15.13 Irrigation events and amounts (mm) in the ^{15}N winter wheat experiment in Maksud Garden, 2005/06.

Irrigation event	**DAS***	**Date**	**Amount**	**Comment**
			mm	
1	16	30.09.05	142.2	following fertilization
2	35	19.10.05	95.5	
3	168	01.03.06	137.3	
4	187	20.03.06	107.8	following fertilization
5	204	06.04.06	86.7	following fertilization
6	233	05.05.06	75.9	following fertilization
7	248	20.05.06	128.4	
8	259	31.05.06	145.6	
Total			**919.3**	

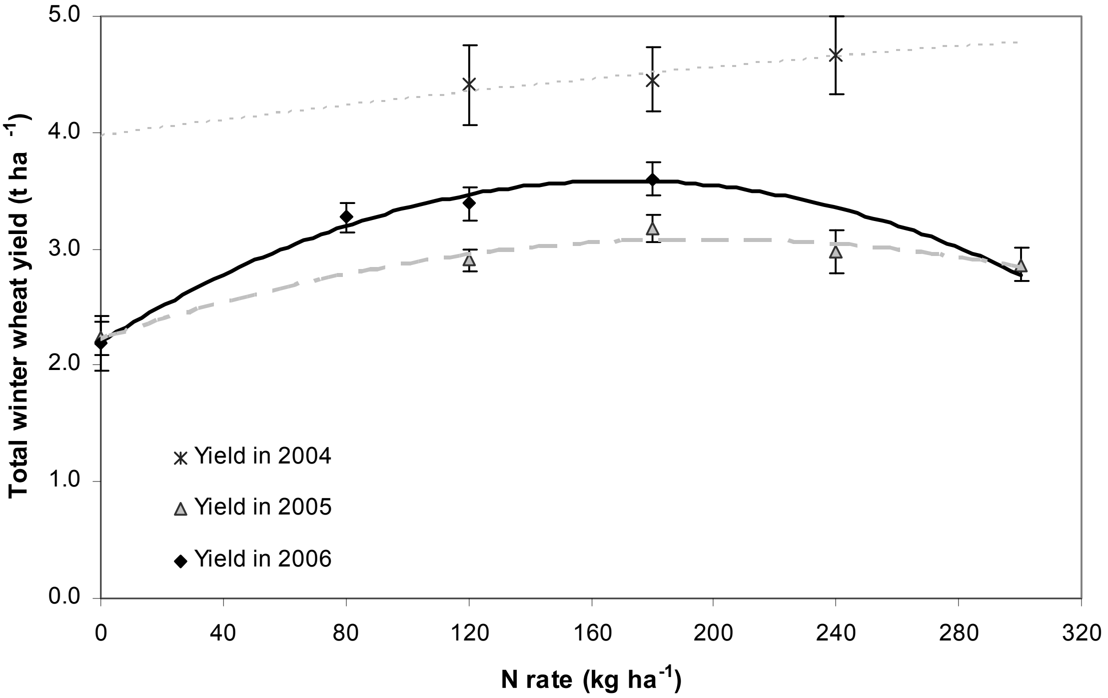
* *DAS: days after sowing*

Appendix 15.14 Measured and adjusted winter wheat yield (t ha^{-1}) for the respective N rates (kg ha^{-1}) from the rotation experiments (2003/04), the minus-1 experiments (2004/05), the response experiments (2004/05) and the ^{15}N experiment (2005/06).

Year of experiment	**N rate**	**n**	**Average winter wheat yield (measured)**	**SE**	**Average winter wheat yield (adjusted*)**	**SE**
	kg ha^{-1}		t ha^{-1}			
2004	120	6	4.4	0.3	4.4	0.3
	180	6	4.5	0.3	4.5	0.3
	240	6	4.7	0.3	4.7	0.3
2005	0	20	2.2	0.1	1.5	0.1
	120	8	2.9	0.1	2.3	0.1
	180	20	3.2	0.1	3.0	0.2
	240	8	3.0	0.2	2.9	0.3
	300	8	2.9	0.1	3.0	0.3
2006	0	4	2.3	0.4	1.8	0.4
	80	16	3.3	0.1	3.8	0.1
	120	16	3.4	0.1	4.5	0.2
	160	16	3.6	0.1	5.5	0.2
Total	0	24	2.2	0.1	1.6	0.1
	80	16	3.3	0.1	3.8	0.1
	120	30	3.5	0.1	3.9	0.2
	160	16	3.6	0.1	5.5	0.2
	180	26	3.5	0.2	3.4	0.2
	240	14	3.7	0.3	3.7	0.3
	300	8	2.9	0.1	3.0	0.3

* *outlier-corrected and plant-density-adjusted yield (see section 4.5.2)*

Appendix 15.15 Total (adjusted) winter wheat yields (t ha^{-1}) for the respective N rates (kg ha^{-1}) from the rotation experiments (2003/04), the minus-1 experiments (2004/05), the response experiments (2004/05) and the ^{15}N experiment (2005/06).



Appendix 15.16 Physico-chemical soil properties before ^{15}N cotton seeding (n = 3), February 2005. Soil texture classified according to the USDA.

Depth	**Sand**	**Silt**	**Clay**	**SOM**	**Total N**	**NO_3-N**	**NH_4-N**	**P_2O_5**	**K_2O**	**pH_{H2O}**	**ECe**	**CEC**
cm	%					mg kg^{-1}					dS m^{-1}	cmol$_c$ kg^{-1}
0-30	47	37	16	0.9	0.07	3.2	0.31	39	180	6.5	1.0	21.9
30-50	43	43	14	0.7	0.07	2.8	0.33	34	160	6.5	1.0	18.8
50-70	50	34	16	0.6	0.05	2.5	0.31	32	160	6.5	1.0	20.3
70-100	44	37	18	0.5	0.05	2.3	0.31	26	140	6.5	1.0	

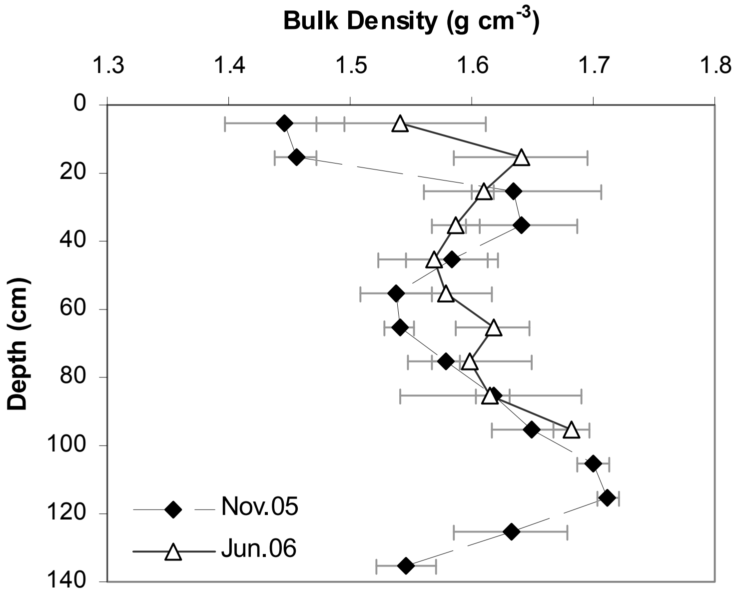
Appendix 15.17 Physico-chemical soil properties after ^{15}N cotton harvest (n = 8), November 2005

Depth	**ECe**	**Total N**	**NO_3-N**	**NH_4-N**	**P_2O_5**	**K_2O**
cm	dS m^{-1}	%	mg kg^{-1}			
0-10	5.8	0.10	10.5	1.07	37.1	171.5
10-20	2.9	0.09	8.6	0.91	29.4	146.8
20-30	2.5	0.07	6.3	0.67	23.8	109.3
30-40	2.0	0.06	5.4	0.53	19.5	90.8
40-60	2.1	0.05	4.1	0.37	12.1	87.9

Appendix 15.18 Physico-chemical soil properties after ^{15}N winter wheat harvest (n = 8), June 2006.

Depth	**SOM**	**Total N**	**NO_3-N**	**NH_4-N**	**K_2O**
cm	%		mg kg^{-1}		
0-10	0.83	0.07	10.8	1.3	161.5
10-20	0.72	0.06	9.0	0.9	114.2
20-30	0.63	0.05	9.0	1.0	110.6
30-40	0.52	0.04	8.2	0.9	91.4
40-60	0.39	0.03	6.7	0.7	69.6

Appendix 15.19 Mean soil bulk density (g cm^{-3}) of three soil profiles after cotton and winter wheat harvest, November 2005 and June 2006, respectively. Error bars represent the standard error of the mean.



Appendix 15.20 Average N-fertilizer recovery (%) in cotton plant components at different fertilizer application times (n = 4). SE denotes the standard error of the mean.

Plant components	**Plant ^{15}N**					
	before seeding		**2-4 leaves/budding**		**flowering**	
	Mean	SE	Mean	SE	Mean	SE
	% recovery of ^{15}N applied					
leaves	5.2	1.0	7.6	0.8	11.9	1.6
stems	1.6	0.3	1.6	0.3	3.7	0.6
squares	1.6	0.3	2.8	0.4	4.0	0.8
fiber	1.5	0.7	1.5	0.2	2.5	0.5
seed	9.3	1.5	13.4	1.7	26.7	3.7
fruits	0.2	0.1	0.2	0.0	0.3	0.1
roots 0-10cm	0.2	0.0	0.3	0.0	0.4	0.0
roots 10-20cm	0.4	0.1	0.5	0.1	0.7	0.1

Appendix 15.21 Average N-fertilizer recovery (% of ^{15}N applied) in winter wheat plant components at different fertilizer application times in 2006 (n = 4). SE denotes the standard error of the mean.

Plant components	**Plant ^{15}N**							
	before seeding		**tillering**		**booting**		**booting**	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
	% recovery of ^{15}N applied							
stems	1.5	0.1	4.0	0.2	4.6	0.3	3.2	0.5
chaff	2.0	0.2	5.5	0.5	8.4	1.0	5.6	0.6
kernels	7.5	0.4	24.4	1.6	35.7	2.9	42.4	7.9
weeds	0.3	0.1	1.1	0.3	1.8	0.5	13.9	10.9
roots 0-10cm	0.4	0.0	0.5	0.0	0.4	0.0	0.6	0.1

Appendix 15.22 Winter wheat protein content (%) and respective yield (t ha^{-1}) for the respective N rates (kg ha^{-1}) from the rotation experiments (2003/04), the minus-1 experiments (2004/05), the response experiments (2004/05) and the ^{15}N experiment (2005/06)

Year of experiment	**N rate**	**Wheat protein content**			**Wheat yield***		
		n	**Mean**	SE	n	**Mean**	SE
	kg ha^{-1}		%			t ha^{-1}	
2004	120	6	11.8	0.3	6	4.2	0.3
	180	6	13.0	0.3	6	4.5	0.3
	240	4	13.7	0.5	4	4.2	0.3
2005	0	5	11.7	1.1	5	2.5	0.3
	120	2	13.5	1.1	2	3.1	0.1
	180	4	11.8	0.4	4	3.1	0.2
	240	1	14.1		1	2.9	
	300	2	15.2	1.3	2	2.6	0.5
2006	0	8	9.6	0.2	8	2.2	0.2
	24	4	8.9	0.9	4	2.1	0.1
	80	16	9.8	0.3	16	3.3	0.1
	120	16	10.2	0.3	16	3.4	0.1
	160	16	11.1	0.3	16	3.6	0.1
Total	0	13	10.4	0.5	13	2.3	0.2
	24	4	8.9	0.9	4	2.1	0.1
	80	16	9.8	0.3	16	3.3	0.1
	120	24	10.9	0.3	24	3.6	0.1
	160	16	11.1	0.3	16	3.6	0.1
	180	10	12.5	0.3	10	3.9	0.3
	240	5	13.8	0.4	5	4.0	0.3
	300	2	15.2	1.3	2	2.6	0.5

* *adjusted yield (see section 4.5.2), adjustment according to Appendix 15.23*

Appendix 15.23 Observed and adjusted winter wheat density (plants m^{-2}) from the rotation experiments (2003/04), the minus-1 experiments (2004/05), the response experiments (2004/05) and the ^{15}N experiment (2005/06)

Year of experiment	**N rate**	**Wheat plant density, observed**			**Wheat plant density, measured**		
		n	**Mean**	SE	n	**Mean**	SE
	kg ha^{-1}		plants m^{-2}			plants m^{-2}	
2004	120	6	410	44			
	180	6	438	47			
	240	6	446	48			
2005	0	20	286	23	20	245	17
	120	8	304	20	8	275	13
	180	20	349	19	20	344	21
	240	8	307	34	8	309	35
	300	8	366	31	8	366	31
2006	0	8	355	30	8	286	32
	24	4	376	31	4	337	48
	80	16	451	19	16	423	17
	120	16	497	21	16	492	20
	160	16	532	12	16	545	14
Total	0	28	306	19	28	256	15
	24	4	376	31	4	337	48
	80	16	451	19	16	423	17
	120	30	428	21	24	420	25
	160	16	532	12	16	545	14
	180	26	369	19	20	344	21
	240	14	367	33	8	309	35
	300	8	366	31	8	366	31

* *adjustment as described in section 4.5.2*

Appendix 15.24 Averaged harvest indices and total raw cotton yield (t ha^{-1}) of the response experiments for the respective N rates (kg ha^{-1}) in 2004 (n = 4). SE denotes standard error of the mean.

Location	**N rate**	**Harvest index**		**Cotton yield**	
		Mean	SE	Mean	SE
	kg ha^{-1}			kg ha^{-1}	
1	0	0.42	0.03	3.4	0.5
	80	0.38	0.03	3.9	0.9
	120	0.42	0.04	3.1	0.6
	160	0.45	0.06	3.4	0.3
	200	0.36	0.03	3.6	0.0
	250	0.42	0.03	3.3	0.5
2	0	0.44	0.07	2.9	0.8
	80	0.42	0.02	3.0	0.4
	120	0.43	0.04	3.1	0.1
	160	0.44	0.01	3.5	1.1
	200	0.44	0.00	3.9	0.3
	250	0.34	0.03	3.4	0.4
Total	0	0.43	0.03	3.1	0.4
	80	0.40	0.02	3.5	0.5
	120	0.42	0.02	3.1	0.2
	160	0.44	0.03	3.4	0.5
	200	0.40	0.03	3.7	0.1
	250	0.38	0.03	3.4	0.3

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