Mineral nitrogen fertilization and stover management effects on maize production under irrigated mediterranean conditions. Simulation of yields

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Mineral Nitrogen Fertilization and Stover Management effects on Maize Production under Irrigated Mediterranean Conditions.

Simulation of Yields.

Thesis Doctoral:

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A mi familia

A mi país: Siria

إلى عائلتي

إلى وطني الغالي سوريا

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SUMMARY

Nitrogen (N) fertilizer is one of the most costly and important inputs in maize (*Zea mays* L.) production. If an insufficient quantity of N is applied, yields can be reduced; but if too much is added, the excess can be detrimental for the environment, since some of it can be lost to groundwater or to the atmosphere. It is therefore both economically and environmentally important to achieve accurate recommended N application rates. Crop stover plays an important role in maintaining soil fertility and, as a result, has an important influence on present and future crop production. Returning maize stover to the soil favourably influences its organic matter (OM) levels and, in consequence, its structure and other factors that determine soil productivity. Returning maize stover to the soil also contributes to carbon (C) sequestration and helps to reduce the release of greenhouse gases. Interactions between crop stover management and nitrogen (N) fertilization could therefore help to improve the efficiency of N use while, at the same time, increasing crop production and maintaining the sustainability of cropping systems. In order to determine the optimal N application rate and to investigate the effects of stover management on maize production and its possible interaction with N fertilization, a field experiment was conducted from 2010 to 2014 in the irrigated areas of the Ebro valley (Almacelles, NE Spain, 41°43’ N, 0°26’ E). The rates of mineral N fertilization applied were: 0 (control), 100, 200 and 300 kg N ha^{-1} year^{-1} (N0, N100, N200, and N300) in 2010, 2011, and 2012; and 0 (control), 100, 200, 300, and 400 kg N ha^{-1} year^{-1} (N0, N100, N200, N300, and N400) in 2013 and 2014. Our results suggested that grain yield, biomass, grain and plant N uptake and SPAD-units were all greatly affected by N fertilization rates. Maximum yield values (19.93 and 19.20 Mg ha^{-1}) were achieved with N application rates of 200 kg ha^{-1} (198 and 192 kg ha^{-1} in 2013 and 2014, respectively), when applying lineal plateau techniques. N lost was significantly affected by N rates and ranged from 44 Kg N ha^{-1} for N100 to 138 kg N ha^{-1} for N400. Apparent N recovery and agronomic N efficiency were significantly affected by N rates and ranged from 0.40, 33.87 kg kg^{-1} for N400 to 0.57, 68.23 kg kg^{-1} for N100, respectively. Maize yield and biomass at maturity were strongly related to plant height and SPAD-unit measurements made at silking (R^2 = 0.61, 0.72 for plant height and 0.76, 0.71 for SPAD-units, respectively). In conclusion, maize SPAD-units and plant height at silking can help to predict yield and biomass for maize production under irrigated, high-yielding conditions. Under our conditions, our results suggested that returning stover to the soil over a period of five years had a positive impact on SOC (soil organic matter) levels, without any yield penalties. We used data collected from two experimental maize fields (Ap, Ac) in Almacelles, Lleida, (NE Spain, 41°43' N, 0°26' E, altitude: 286 m) over a period of three consecutive years (2010, 2011, and 2012). With this date we evaluated the performance of the CSM–CERES and CSM-IXIM maize models in their DSSAT (Decision Support System for Agrotechnology Transfer) version 4.5 to simulate high yielding conditions and we also tested the IXIM model using an alternative approach for estimating crop N demand based on Plénet and Lemaire (2000).The fertilization treatments applied in these two fields included two mineral fertilizer treatments: 300 kg N ha^{-1} (N300) and a N-free fertilized control (N0). Crop residues were either removed (R) or incorporated (I). Under our high-yielding irrigated maize conditions (11 to 20 Mg ha^{-1}), the CSM–CERES and CSM-IXIM models accurately predicted the phenology, grain yield and biomass content, whereas they were less efficient at estimating crop N uptake. The CSM-IXIM model proved better at simulating the total aboveground biomass content and crop N uptake than the CSM–CERES model. The IXIM model incorporating an alternative approach for estimating crop N demand based on Plénet and Lemaire (2000) simulated grain yield and crop N uptake better than the IXIM model with the current approach based on Jones (1983).

RESUMEN

La fertilización nitrogenada (N) es uno de los mayores costes de producción en el maíz (*Zea mays* L.). Una disponibilidad insuficiente de N puede ocasionar grandes pérdidas en los rendimientos del cultivo. Un exceso de N, en cambio, puede originar pérdidas económicas e incluso provocar problemas medioambientales y en las aguas subterráneas. Los restos de la cosecha de los cultivos tienen un papel muy importante en el mantenimiento de la fertilidad del suelo y en la actual y futura producción de los cultivos. Incorporar los restos de la cosecha al suelo puede afectar favorablemente los niveles de materia orgánica (MO) y por tanto la estructura del suelo, y otros determinantes de la productividad del suelo. Devolver los restos de la cosecha de maíz al suelo también contribuye al secuestro de carbono (C) favoreciendo la reducción de la emisión de gases de efecto invernadero. La interacción entre la gestión de los restos de la cosecha y la fertilización nitrogenada (N) puede ayudar a mejorar la eficiencia de uso del N, y al mantenimiento de la sostenibilidad de los sistemas de cultivo. Con el fin de determinar la dosis óptima de N y de investigar los efectos de la gestión de los restos de la cosecha en la producción de maíz y su posible interacción con la fertilización N, se llevó a cabo un ensayo de campo, desde 2010 hasta 2014, en los regadíos del Valle del Ebro (Almacelles, NE españa, 41°43' N, 0°26' E). La fertilización mineral consistió en: 0 (control), 100, 200 y 300 kg N ha^{-1} año^{-1} (N0, N100, N200 y N300) y en 0 (control), 100, 200, 300 y 400 kg N ha^{-1} año^{-1} (N0, N100, N200, N300 y N400) in 2013, y 2014. Los resultados sugieren que, el rendimiento de grano, biomasa, N absorbido por el grano y por la planta entera y las unidades SPAD resultaron fueron muy afectados por las dosis de fertilización nitrogenada. Los máximos rendimientos (19,93 y 19,20 Mg ha^{-1}) se lograron con dosis de 198 y 192 kg N ha^{-1} en 2013 y 2014, respectivamente. El N perdido fue afectado significativamente por las dosis de N y varió de 44 kg N ha^{-1} para N100 a 138 kg N ha^{-1} para N400. Recuperación aparente de N y la eficiencia agronómica de uso del N fueron afectados significativamente por las dosis de N y variaron de 0,40, 33,87 kg kg^{-1} para N400 a 0,57, 68,23 kg kg^{-1} para el N100, respectivamente. El rendimiento y la biomasa de maíz en la madurez estuvieron muy relacionados con la altura de la planta y con las unidades SPAD en el estado de floración femenina (R^2 = 0,61, 0,72 para la altura de la planta y 0,76 y 0,71 para las unidades SPAD, respectivamente). En conclusión, las unidades SPAD y la altura de la planta en el estado de floración femenina pueden ayudar a predecir el rendimiento y la biomasa del maíz en condiciones de altos rendimientos en regadío. Los resultados sugieren que, bajo nuestras condiciones, devolver los restos de la cosecha al suelo durante 5 años tiene un impacto positivo en los niveles de SOC (C orgánico del suelo) sin cambios en los rendimientos. Se han utilizado los datos de dos campos de maíz experimentales (Ap, Ac) en Almacelles, Lleida, (NE de España, 41 ° 43 'N, 0 ° 26' E, altitud: 286 m) durante tres años consecutivos (2010, 2011, y 2012) para evaluar los modelos de maíz CSM-CERES y CSM-IXIM disponible en DSSAT (Sistema de Apoyo para la Toma de Decisiones en la Transferencia Agrotecnológica, por su sigla en inglés) versión 4.5, bajo los condiciones de alta rendimiento del maíz, y probar el modelo IXIM con una versión alternativa para estimar la demanda de N de la planta. Los tratamientos de fertilización nitrogenada en estos dos campos incluidos en los modelos de predicción fueron: 300 kg N ha^{-1} (N300), y el control sin fertilización. Los residuos de cultivos fueron retirados (R) o incorporadas (I). Bajo los condiciones de alta rendimiento del maíz (11 a 20 Mg ha^{-1}), los modelos CSM-CERES y CSM-IXIM predijeron correctamente la fenología, rendimiento de grano y biomasa, mientras que eran menos eficientes en estimar N absorbido por la planta entera. El modelo CSM-IXIM fue capaz de simular la biomasa aérea total, y N absorbido por la planta entera mejor que CSM-CERES. El modelo IXIM con un approach alternativo para estimar la demanda de N de la planta, basado en Plénet y Lemaire (2000), simuló el rendimiento de grano y N absorbido por la planta entera mejor que el IXIM con el approach actual, basado en Jones (1983).

ملخص

السماد الآزوتي (N) هو واحد من اكثر مستلزمات إنتاج الذرة الصفراء (*Zea mays* L.) أهمية وتكلفة. تطبيق كميات غير كافية من السماد الآزوتي من الممكن ان يسبب انخفاض في الغلة، في المقابل فإن إضافة كميات زائدة تؤدي إلى حدوث تلوث في المياه الأرضية أو في الغلاف الجوي. ولذلك فإنه من المهم إقتصاديا وبيئيا الوصول إلى تطبيق المعدلات الموصى بها من السماد الآزوتي. بقايا حصاد المحاصيل تلعب دورا هاما في الحفاظ على خصوبة التربة، وبالتالي ، لديها تأثير هام على إنتاج المحاصيل في الحاضر والمستقبل. إعادة بقايا الحصاد الى التربة يؤثر إيجابياً على مستويات المادة العضوية في التربة، وبالتالي ، يؤثر ايجابيا على تركيب التربة وإنتاجيتها. إعادة بقايا الحصاد الى التربة يساهم أيضاً في عزل الكربون مما يساعد على الحد من انبعاث غازات الاحتباس الحراري. التفاعلات بين إدارة بقايا حصاد المحصول والتسميد الآزوتي ممكن أن يساعد على تحسين فعالية إستخدام النتروجين، حيث أنه يزيد من إنتاج المحصول، وفي نفس الوقت، يحافظ على استدامة النظم الزراعية. ومن أجل تحديد أفضل معدل لتطبيق التسميد الآزوتي وللبحث في تأثيرات إدارة بقايا الحصاد في إنتاج الذرة الصفراء وتفاعلها المحتمل مع التسميد الآزوتي، تم إجراء تجربة حقلية في الفترة من عام 2010 إلى عام 2014 في المناطق المروية من وادي ايبرو في شمال شرق إسبانيا (Almacelles, 41°43’ N, 0°26’ E). وكانت معدلات التسميد النيتروجيني المعدنية التي تم تطبيقها: 0 (الشاهد) و 100 و 200 و 300 كغ N هـ$^{-1}$ سنة$^{-1}$ (N0، N100، N200، N300) في عام 2010 و 2011 و 2012؛ و0 (الشاهد)، 100 و 200 و 300 و 400 كغ N هـ$^{-1}$ سنة$^{-1}$ (N0، N100، N200، N300، N400) في عامي 2013 و2014. وأشارت نتائجنا أن، الغلة الحبية والكتلة الحيوية ومحتوى الحبوب والنبات الكامل من النتروجين ولون الورقة (SPAD) كلها تأثرت بشكل إيجابي بمعدلات التسميد الآزوتي. الغلة القصوى (19.93 و 19.20 طن/هـ) تم تحقيقها مع المعدلات 200 كغ N هـ$^{-1}$ (198 و 192 كغ N هـ$^{-1}$ في 2013 و2014 على التوالي). النيتروجين الضائع تأثر بشكل إيجابي بمعدلات التسميد الآزوتي وتراوح بين 44 كغ N هـ$^{-1}$ مع التسميد بـ 100 كغ N هـ$^{-1}$ إلى 138 كغ N هـ$^{-1}$ مع معدل 400 كغ N هـ$^{-1}$ سماد آزوتي. إستعادة النتروجين الظاهرية وكفاءة أستخدام النتروجين الزراعية تأثرت بشكل ايجابي بمعدلات التسميد الآزوتي وتروواحت بين 0.40، 33.87 كغ/كغ مع معدل تسميد 400 كغ N هـ$^{-1}$ و 0.57، 68.23 كغ/كغ من أجل 100 كغ N هـ$^{-1}$ ، على التوالي. غلة الذرة والكتلة الحيوية في فترة النضج إرتبطت بشكل قوي مع إرتفاع النبات و لونة الورقة (SPAD) المقاسة في فترة الإزهار المؤنث مع معامل إرتباط ($R^2 = 0.61$, 0.72 لإرتفاع النبات و 0.76, 0.71 من أجل SPAD، على التوالي. وكنتيجة يمكن إستخدام إرتفاع النبات ولون الورقة (SPAD) المقاسة في مرجلة الإزهار المؤنث في التنبؤ بإنتاج الذرة الصفراء تحت ظروف الري والإنتاج العالي. في ظل ظروف تجربتنا فان إعادة بقايا حصاد الذرة الصفراء إلى التربة على مدى خمس سنوات كان له دور إيجابي على محتوى المادة العضوية في التربة، ولكن دون اي زيادة في الغلة. تم إستخدام بيانات جمعت من حقلين (Ap, Ac) في Almacelles في ليردة، إسبانيا خلال ثلاث سنوات متتابعة (2010, 2011, 2012). بهذه البيانات تم تقييم أداء نماذج المحاكاة للذرة الصفراء CSM–CERES و CSM-IXIM الموجودة في برنامج DSSAT (نظام دعم اتخاذ القرارات من أجل نقل التكنولوجيا الزراعية) الاصدار 4.5 في محاكاة الغلة العالية وايضاً تم إختبار النموذج IXIM مع استخدام معادلة بديلة من أجل تقدير احتياجات المحصول من النتروجين على أساس Plénet and Lemaire (2000). وتتضمن معملات هذه التجربة جرعتين من السماد الآزوتي 0 و 300 كغ N /هـ إضافة إلى إدارة بقايا حصاد محصول الذرة الصفراء : إزالة بقايا حصاد محصول الذرة الصفراء (R) أو إعادتها الى التربة (I). تحت ظروف إنتاجنا العالي (من 11 إلى 20 طن/هـ)، النموذجين CSM–CERES و CSM-IXIM تنبأ مراحل تطور النبات الفينولوجية و الغلة الحبية و الكتلة الحيوية بدقة، بينما تبأ بشكل أقل فعالية بإمتصاص النتروجين من قل النبات. النموذج CSM-IXIM كان أفضل من النموذج CSM–CERES بتقدير كل من الكتلة الحيوية و امتصاص النتروجين من قبل النبات. نموذج IXIM بالمعادلة البديلة من أجل تقدير احتياجات المحصول من النتروجين على أساس Plénet and Lemaire (2000) كان أفضل من

النموذج IXIM بالمعادلة الحالية من أجل تقدير احتياج ات المحصول من النتروجين على أساس Jones (1983) بتقدير الغلة الحبية وإمتصاص النتروجين من قبل النبات.

RESUM

La fertilització nitrogenada (N) és un dels majors costos de producció en el blat de moro (Zea mays L.). Una disponibilitat insuficient de N pot ocasionar grans pèrdues en els rendiments del cultiu i en canvi un excés, pot originar pèrdues econòmiques i fins i tot provocar problemes mediambientals i en les aigües subterrànies. Les restes de la collita dels cultius tenen un paper molt important en el manteniment de la fertilitat del sòl i en l'actual i futura producció dels cultius. L’incorporació del rostoll al sòl afecta favorablement els nivells de matèria orgànica (MO) i per tant l'estructura del sòl, l'emmagatzematge i el moviment d'aigua i aire, i altres determinants de la productivitat del sòl. Retornar el rostoll de blat de moro al sòl també contribueix al segrest de carboni (C) afavorint la reducció de l'emissió de gasos d'efecte hivernacle. La interacció entre la gestió del rostoll i la fertilització nitrogenada (N) pot ajudar a millorar l'eficiència d'ús de N, alhora que augmentar la producció i el manteniment de la sostenibilitat dels sistemes de cultiu. Amb l’objectiu de determinar la dosi òptima de N i d'investigar els efectes de la gestió de les restes de la collita en la producció de blat de moro i la seva possible interacció amb la fertilització N, es va dur a terme un assaig de camp, des de 2010 fins 2014, en els regadius de la Vall de l'Ebre (Almacelles, NE Espanya, 41 ° 43 'N, 0 ° 26' E). La fertilització mineral va consistir en: 0 (control), 100, 200 i 300 kg N ha^{-1} any^{-1} (N0, N100, N200 i N300) i en 0 (control), 100, 200, 300 i 400 kg N ha $^{-1}$ any^{-1} (N0, N100, N200, N300 i N400) al 2013, i 2014. Els resultats suggereixen que, el rendiment de gra, biomassa, N absorbit pel gra i per la planta sencera i les unitats SPAD van resultar ser molt afectats per les dosis de fertilització nitrogenada. Els màxims rendiments (19,93 i 19,20 Mg ha^{-1}) es van aconseguir amb dosis d’uns 200 kg N ha^{-1}), 198 i 192 kg N ha^{-1} el 2013 i 2014, respectivament. El N perdut va ser afectat significativament per les dosis de N i va variar de 44 kg N ha^{-1} per N100 a 138 kg N ha^{-1} per N400. Recuperació aparent de N i l'eficiència agronòmica d'ús del N van ser afectats significativament per les dosis de N i van variar de 0,40, 33,87 kg kg^{-1} per N400 a 0,57, 68,23 kg kg^{-1} per al N100, respectivament. El rendiment i la biomassa de blat de moro a la maduresa van estar molt relacionats amb l'altura de la planta i amb les unitats SPAD a l'estat de floració femenina (R^2 = 0,61, 0,72 per a l'altura de la planta i 0,76 i 0,71 per a les unitats SPAD, respectivament). En conclusió, les unitats SPAD i l'alçada de la planta a l'estat de floració femenina poden ajudar a predir el rendiment i la biomassa del blat de moro en condicions d'alts rendiments en regadiu . Els resultats suggereixen que, sota les nostres condicions, tornar les restes de la collita a terra durant 5 anys té un impacte positiu en els nivells de SOC (C orgànic del sòl) sense canvis en els rendiments. S'han utilitzat les dades de dos camps de blat de moro experimentals (Ap, Ac) a Almacelles, Lleida, (NE d'Espanya, 41 ° 43 'N, 0 ° 26' E, altitud: 286 m) durant tres anys consecutius (2010, 2011, i 2012) per avaluar els models de blat de moro CSM-CERES i CSM-IXIM disponible a DSSAT (Sistema de Suport per a la Presa de Decisions en la Transferència Agrotecnológica, en la sigla en anglès) versió 4.5, sota els condicions d'alta rendiment del blat de moro, i provar el model IXIM amb una versió alternativa per estimar la demanda de N de la planta. Els tractaments de fertilització nitrogenada en aquests dos camps inclosos en els models de predicció els tractament de N emprats van ser: 300 kg N ha-1 (N300), i el control sense fertilització. Els residus de cultius van ser retirats (R) o incorporades (I). Sota els condicions d'alta rendiment del blat de moro (11 a 20 Mg ha^{-1}), els models CSM CERES i CSM-IXIM van predir correctament la fenologia, rendiment de gra i biomassa, mentre que eren menys eficients a estimar N absorbit per la planta sencera. El model CSM-IXIM va ser capaç de simular la biomassa aèria total, i N absorbit per la planta sencera millor que CSM-CERES. El model IXIM amb un approach alternatiu per estimar la demanda de N de la planta, basat en Plénet i Lemaire (2000), va simular el rendiment de gra i N absorbit per la planta sencera millor que el IXIM amb l'approach actual, basat en Jones (1983).

1. GENERAL INTRODUCTION

1.1. Ebro Valley

The Ebro Valley region is located in the North East of Spain (Fig. 1.1); it is characterized by its Mediterranean climate, with average annual rainfall ranging from 200 to 400 mm. This is one of the most important agricultural regions for maize production in Spain, with about 100,000 ha (MARM, 2010). Average yields for irrigated maize (*Zea mays* L.) grown in the Ebro Valley are within 12-15 Mg ha^{-1} of grain (14% moisture) per farm (Cela et al., 2011; Daudén and Quílez, 2004), with the best fields producing up to 19-20 Mg ha^{-1} (Biau et al., 2013).

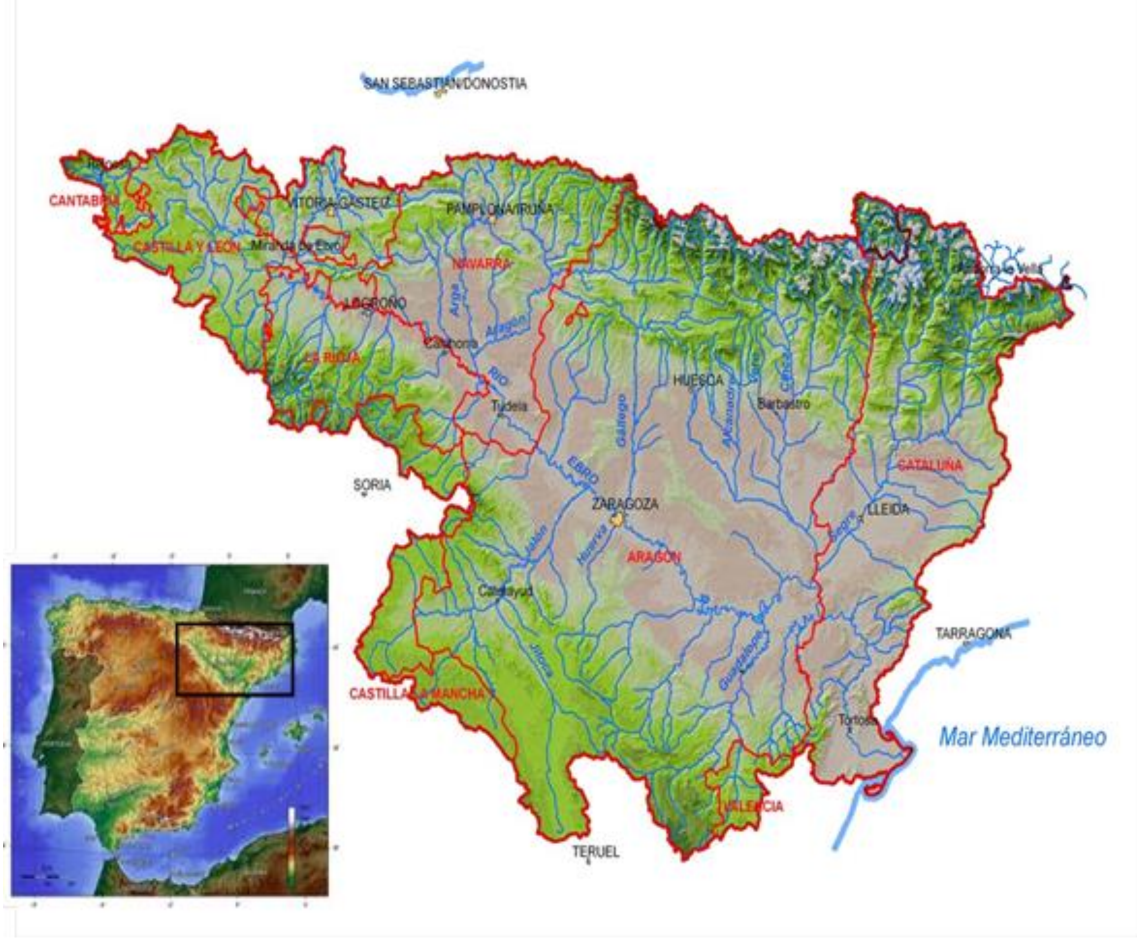

Figure 1.1. Ebro river basin (MAPA).

Source: Confederación Hidrográfica del Ebro.

1.2. Mineral nitrogen fertilization

Nitrogen (N) fertilization of maize is an important topic of research because N, together with genetic improvement, is one of the two most relevant factors affecting maize production, and can represent up to 30% of total production costs (Cardwell, 1982; Lloveras and Cabases, 2014). In crops with a high demand for N, such as maize, N fertilizer represents an important input cost and increases in yield are normally observed following N fertilizer applications (Ziadi et al., 2008; Nyiraneza et al., 2009; Gagnon and Ziadi, 2010; ; Cela et al., 2011; Gagnon et al., 2012).

N is one of the macronutrients that most limits maize grain yields (Uhart and Andrade, 1995; Varinderpal-Singh et al., 2011). The greatest N effects are evident in: crop growth, which is measured by the leaf area index (LAI); biomass production (Lawlor, 1995); and grain yield. The effects of N on kernel numbers also strongly correlated with crop growth rate during the critical period for kernel set, which is around the silking stage (Andrade et al., 2002).

The N requirement for maize is influenced, among other aspects, by previous crops, soil mineral N content in spring, soil organic matter (SOM), clay content, landforms and soil drainage (Franzluebbers et al., 1995; Jarvis et al., 1996; St. Luce et al., 2011). An insufficient N supply reduces crop leaf area (Fernandez et al., 1996; van Delden 2001), photosynthesis (Ciompi et al., 1996; Lu et al., 2001), plant development, and biomass production (Dev and Bhardwaj, 1995), resulting in a low grain yield. On the other hand, applying N fertilizer in excess of crop N needs has been linked to environmental concerns because unused N can be lost due to leaching, denitrification or volatilization (Chantigny et al., 1998; Gagnon et al., 2011; Ziadi et al., 2012). High pre-planting soil N contents are the result of excessive N application in previous crops, with N tending to accumulate in the soil (Berenguer et al., 2008). As a result, ground waters in these areas are frequently polluted with nitrate (Ferrer et al., 1997). Studies, which have mainly been conducted in the USA, have reported that N fertilizer recovery normally ranges from 40 to 65% of that applied to irrigated maize crops. The percentage tends to depend on the amount of N applied and on the soil N content (Tran et al., 1997; Isfan et al., 1995; Baligar et al., 2001; Berenguer et al., 2006; Nyiraneza et al., 2010), while the economic optimum N application rate is almost inevitably below that applied (Gagnon and Ziadi, 2010; Varvel and Peterson, 1990).

Because of environmental pollution due to excess of N fertilization, an EU nitrate directive (European Union, 1991) now limits the amount of N that can be applied to soils such as those of several the irrigated areas in the Ebro Valley. Within this area, the ground waters are frequently polluted with nitrate (Ferrer et al., 2003), with concentrations often exceeding 50 mg NO^{-3} L^{-1}, the maximum level permitted by the European Union (1991). Consequently, as in many other regions of the EU, parts of the Ebro Valley have now been declared nitrate vulnerable. In these vulnerable zones, it is not permitted to apply more than 350 kg N ha^{-1} $year^{-1}$, of which no more than 180-210 kg N ha^{-1} $year^{-1}$ should derive from organic materials (Diari Oficial de la Generalitat de Catalunya, 2004).

Maize yield responses to N application rates largely depend on the environmental conditions encountered (Schröder et al., 2000) and N fertilizer requirements must be considered for specific production situations (Bundy and Malone, 1988; Schröder et al., 2000). Moreover, N rates need to be tested in order to accurately predict yield responses to increasing N rates and to adjust yield response models (Cerrato and Blackmer, 1990).

Nitrogen can be lost mainly through leaching, runoff, denitrification and ammonia volatilization. Excess of nitrogen supply respect to the plant demand can lead to nitrogen losses, especially in the form of nitrate (NO_3^-), dissolved in leaching water

(Addiscott et al., 1991). Calculation of N balance is one potentially useful method for predicting the risk of nitrate leaching into groundwater (Barry et al., 1993; Puckett et al., 1999). Nitrogen losses are affected by many factors, including soil type, climate, and type, timing and amounts of fertilizers and type of irrigation (Owens, 1994; Cela et al., 2011).

Several studies carried out at watershed level under different conditions in Europe and United States and have reported a wide range of N losses, from less than 10 kg ha^{-1} (Beaudoin et al., 2005), to more than 100 kg ha^{-1} (Bechmann et al., 1998). In Spain, several studies about N balances have been published and have reported N losses up to 160 kg ha^{-1} (de Juan Valero et al., 2005; Isidoro et al., 2006; Isla, et al., 2006; Quemada, 2006; Berenguer et al., 2009).

On the other hand, efficiency of fertilizer N is becoming increasingly important in modern agricultural production owing to increasing food requirement and growing concern about environments (Liu et al., 2010). Nitrogen use efficiency generally decreased with increasing level of available N (Anderson et al., 1984; Sisson et al., 1991; Halvorson et al., 2005; Berenguer et al., 2009). Efficient use of N for maize production is important for increasing grain yield, maximizing economic return and minimizing NO_3 leaching to ground water (Gehl et al., 2005; Quemada, 2006). Low N use efficiency in corn can also contribute to soil NO_3 losses, especially when N application rates exceed crop needs (Andraski et al. 2000; Hong et al. 2007). The reasons for the relatively low N use efficiency were likely (1) high-N application rates in high-yield farmlands with possible large N losses and (2) limiting factors for plant growth other than N (Zhu and Chen, 2002).

Surveys conducted in the Ebro Valley (Sisquella et al., 2004) show that about 50% of the maize-producing land in this area is only fertilized using mineral N. In general, N is applied at rates of over 300 kg N ha^{-1} in fields that are only fertilized with mineral N and at more than 400 kg N ha^{-1} in those fertilized with manure (Sisquella et al., 2004). The agricultural areas with the highest nitrate exports are those associated with irrigated systems growing crops with a high N use, such as maize. There is therefore a need for further studies into the development of agronomic practices that would enable these areas to increase the efficiency of their N fertilization while at the same time reducing nitrate leaching and N gas emissions from maize plots to water bodies.

1.3. Stover management

In some agricultural systems, there is increasing interest in using crop residues to improve soil productivity as this can help reduce the use of external inputs of inorganic fertilizer (Tetteh, 2004; Fening et al., 2005). These crop residues are often present in sufficient abundance in farmers' fields at the end of the growing season and can play an important role in soil fertility management through their short term effects on nutrient supply and longer term contribution to soil organic matter (Karanja et al., 2006). Maize stover is also an important source of macronutrients (NPK) and micronutrients such as S, Cu, B, Zn, and Mo (Mubarak et al., 2002). Maize stover also contains about 17.7 g N kg^{-1}, 1.82 g P kg^{-1}, and 28.36 g K kg^{-1} of the fertilizer applied to crops (Johnson et al., 2010). However, not all of the nutrients are available to subsequent crops. Most of the N remains in organic forms and mineralization is required before its absorption; this leads to a short-term N deficit which affects grain yield in the following crop (Van Den Bossche et al., 2009).

Crop residues that are returned to croplands can sustain their soil organic carbon (SOC) content and improve soil fertility and biological activity. Incorporating plant residues into agricultural soils can sustain their organic carbon (C) content, improve the physical properties of the soil, enhance biological activity, and increase nutrient availability (Hadas et al., 2004; Cayuela et al., 2009).

Surface residues increase both infiltration and the retention of water on the soil surface, thereby reducing surface run off following storm events. As a result, leaving enough residue to cover the soil surface is one of the most effective agricultural management strategies for reducing soil erosion (Gilley et al., 1986). The amount of surface residue also influences the radiation balance, buffering surface soil temperatures and reducing water losses due to evaporation. These processes increase soil moisture levels and this is generally beneficial for crop growth, although it can delay planting and increase denitrification during wet springs (Tisdall et al., 1986; Johnston et al., 2009).

Residues, whether on the surface or incorporated into the soil by tillage, are the primary substrate for microorganisms, earthworms and other soil fauna. The biologically mediated mineralization of residue releases humic monomers to the soil solution. These subsequently form new soil organic matter (humus) through hetero polymerization and/or aggregation (Piccolo, 2001; Simpson, 2002).

Soil organic matter contributes to soil quality and agricultural productivity through numerous physical, chemical, and biological processes. Organic matter enhances stabilization of the soil structure (Tisdall and Oades, 1982; Hammerbeck et al., 2012), which – in turn - increases aeration, drainage, and the water holding capacity and reduces penetration resistance, thereby providing a better rooting environment for plants. Soil organic matter also contributes to the cation exchange capacity and pH buffering capacity of the soil. It is also a reservoir for plant nutrients that are released during microbially mediated nutrient cycling (Tisdall et al., 1986).

The variable impact of harvest residue on yields also attests to the complex nature of residue-microbiology-soil-climate-crop interactions and to the slow rate of change in levels of soil organic matter in response to management. As crop yields are governed by numerous interactions, short-term changes in crop yields are not generally a good indicator of the long-term impact of a particular management system on soil quality. Careful analysis of changes in soil quality in well-managed long-term plots offers a far more reliable means of assessing the impact of management on soil quality.

Stover management is an important aspect of maize production because, apart from its agronomical effects relating to soil improvement, it may also help to increase the profitability of maize farming, although this depends on the year. For instance, in 2012, the maize stover produced in the Ebro Valley commanded prices of around €18 Mg^{-1}. The quantity of the maize stover produced in the Ebro Valley is normally high, ranging from about 13 to 17 t ha^{-1} $year^{-1}$ (Lloveras et al., 2012), depending on the maize production. According to a survey by Sisquella et al. (2004), stover is incorporated into the soil profile in 50% of the land in the Ebro Valley. The amount of stover available as feedstock has been estimated at around 40% of the total, with only a relatively small portion of this being available as pasture (Sisquella et al., 2004). However, these proportions can change from year to year and depend on its price. Other aspects of maize stover management are its interaction with N fertilization (Wilhelm et al., 2004); its impact on greenhouse gas emissions into the atmosphere; and its role in carbon (C) sequestration.

Agricultural practices have been cited as both sources and sinks for greenhouse gases, and especially for CO_2 (Follett and Hatfield, 2001; Lal et al., 1998). Stover management and soil organic matter (SOM) content account for a significant percentage of total terrestrial C (Wilhelm et al., 2004). By increasing the amount of maize stover returned to the soil, the SOM content could be increased, as could the quality of the soil, while - at the same time – C pools in the atmosphere C could be reduced.

For all of these reasons, we think that it is very important to study the effects of maize stover management, N use, and their interactions, in areas of high maize production.

1.4. Simulation models

Simulation models are increasingly used in large area agroenvironmental applications to support decision making. Crop models are mathematical representations of the main processes involved in the development, growth, and production of a crop. Mathematical modelling entails quantitative integration of the mechanisms at the various hierarchical levels to provide an explanation of system behaviour (Bouman et al., 1996).

By the end of the 1960s, computers had evolved sufficiently to allow the first attempts to synthesize detailed knowledge on plant physiological processes, in order to explain the functioning of crops as a whole (Bouman et al., 1996). The first steps toward crop modelling involved models developed to estimate light interception and photosynthesis in crop canopies (Loomis and Williams, 1963; De Wit 1965; Duncan et al., 1967).

The first examples of crop growth models, most of which were intended for use by the agriculture research community, became available during the 1970s and mainly constituted theoretical approaches (Stöckle et al., 2003). Early models focused on leaf to canopy assimilation, with the main emphasis on light interception and canopy architecture (Boote et al., 2013). Later, advances in describing crop mass accumulation and the factors that govern and can alter plant growth were incorporated into the models. This paved the way for the development of whole crop models in which life cycle prediction, life-long C balances and the growth of different organs were emphasized (Hesketh, Baker and Duncan 1971, 1972).

Crop yield is influenced by temporal interactions relating to management, soil properties and the environment (Batchelor et al. 2002; Liu et al. 2011). For this reason, crop and soil simulation models have been developed and used to simulate crop growth and soil carbon, nitrogen and soil water dynamics on a daily or even hourly basis. They also offer options to examine the impact of different crop management practices (i.e., of fertilization, irrigation and tillage, etc.) under different environmental conditions (i.e., soil properties and climate conditions) on crop yields.

Crop simulation models consider the complex interactions between climate, soil properties and (water and N) management factors that influence crop performance. Studies to understand the role of N in different cropping systems can be successfully conducted with dynamic simulation models (Morari and Giupponi, 1997; Smith et al., 1997; Acutis et al., 2000).

Cropping system simulation models can be used to predict the effects of climate, soil properties, plant characteristics and management practices on the soil water balance, nutrient dynamics and crop growth. They can therefore enhance our understanding of cropping system performance under different water and nitrogen regimes.

Models may also be used to assess the effects of management practices and plant characteristics on crop performance over a period that is long enough to characterize the climatic variability of a particular site (van Keulen and Seligman, 1987); this will pave the way for improvements in the efficacy of decision-making concerning fertilizer and water management.

Simulation models have been used to analyse the role of different plant traits for the adaptation of crops to their environment. Knowledge of different crop ideotypes which combine characteristics for optimum performance under defined environmental conditions can help to improve management decisions and breeding efforts (Boote et al., 2001).

The decision support system for agrotechnology transfer (DSSAT) (Tsuji et al., 1994; Jones et al., 2003; Hoogenboom et al., 2004, 2010) is a well-known and widely used collection of crop simulation models and computer programs integrated into a single software package with the aim of facilitating the application of crop simulation models for research and decision making (Tsuji et al., 1994; Hoogenboom et al., 2004). It was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project (IBSNAT, 1993; Tsuji, 1998; Uehara, 1998; Jones et al., 1998), seeking to facilitate the application of crop models in a systems approach applied to agronomic research.

The first DSSAT release (version 2.1) was in 1989 (IBSNAT, 1989) and included models of four crops: maize (Jones and Kiniry, 1986), wheat (Ritchie and Otter, 1985), soybean (Wilkerson et al., 1983) and peanut (Boote et al., 1986). Later, models for other crops, such as potato, rice, dry beans, sunflower and sugarcane were developed (Hoogenboom et al., 1994; Jones et al., 1998; Hoogenboom et al., 1999). The latest version of DSSAT (v4.5) (Hoogenboom et al., 2010) includes models for 28 different crops and a bare fallow simulation.

This software package integrates crop-soil models, databases, database tools and application programs to estimate production and economic risks associated with different climatic, soil, and management practices at the field scale.

The DSSAT software has been distributed in over 90 countries and has been used by numerous researchers since the late 1980's (Jones et al., 2003). Jones et al. (2003) listed more than 120 studies that have been conducted around the world using DSSAT, in areas ranging from North America to Africa. In these studies, the DSSAT crop simulation models were used to determine optimum crop management practices (Alagarswamy et al., 2000) for fertilizer management (Hodges, 1998), irrigation management (Steele et al., 2000), precision agriculture (Paz et al., 2001), pest management (Batchelor et al., 1993), climate change and variability (Alexandrov and Hoogenboom, 2001), long-term sustainability (Hasegava et al., 2000), tillage management (Andales et al., 2000), variety evaluation (Mavromatis et al., 2001), environmental pollution (Pang et al., 1998), genomics (Hoogenboom et al., 1997), space technology (Fleisher et al., 2000), and education (Oritz, 1998).

The input data required to run DSSAT include daily weather data (maximum and minimum temperatures, rainfall, and solar radiation); soil characterization data (physical, chemical and morphological properties for each layer); a set of cultivar coefficients characterizing the crop cultivar in terms of plant development and grain biomass; and crop management information, such as plant population, row spacing, seeding depth, and the application of fertilizer and irrigation (Fig. 1.2).

DSSAT version 4.5 is composed of various crop models that are executed under a single shell. The crop models available are: the CERES models for cereals (barley, maize, sorghum, millet, rice and wheat); the CROPGRO models for legumes (dry bean, soybean, faba bean, velvet bean, peanut, cowpea and chickpea); models for root crops (cassava, tanier, taro, potato) and other crop models (sugarcane, tomato, sunflower, pasture, etc).

Maize simulation models, such as CERES-Maize (Jones and Kiniry, 1986) and IXIM (Lizaso et al., 2011), included in DSSAT V4.5 (Hogenboom et al., 2010), are effective tools for analysing cropping systems for efficient resource management. However, these models should be tested for the correct simulation of major components such as growth, yield, and plant N dynamics.

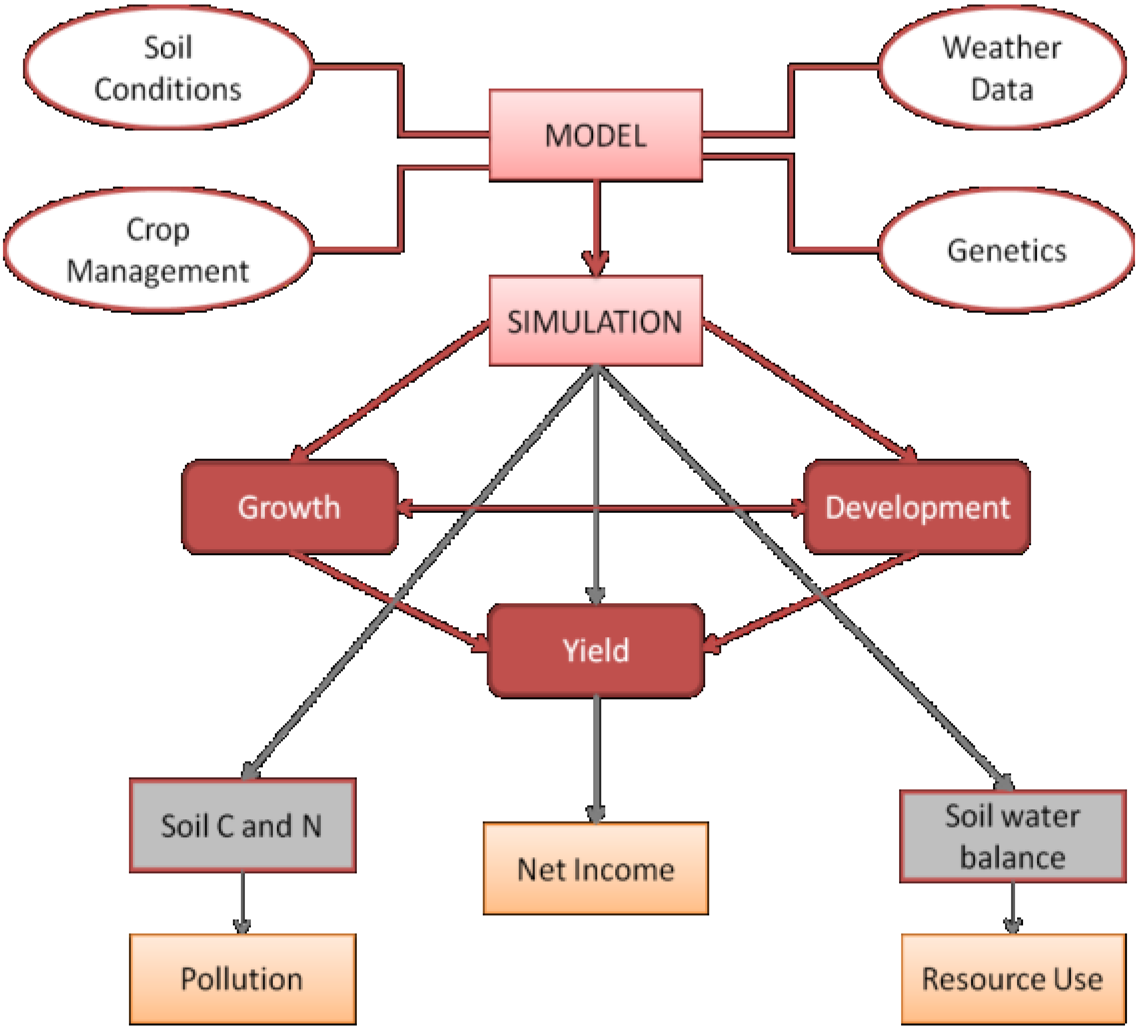

Figure 1.2. Diagram of the database and its components and their applications in DSSAT.

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2. GENERAL OBJECTIVES

2. General objectives

The main objective of this thesis is to help to improve N management and the profitability of growing high yielding irrigated maize. Other objectives include reducing the impact of this production on soils and the environment and evaluating the performance of the DSSAT version 4.5 modeling system for high yielding irrigated maize.

In order to achieve these goals, we conducted a field trial with different mineral N fertilization rates and stover management systems.

The specific objectives were:

1. To evaluate the effects of the application of high rates of mineral N fertilizer (up to 400 kg N ha^{-1}) on: grain yield, above ground biomass, N uptake, soil NO_3^--N content before planting (Nini) and after harvest (Nresi), and SPAD-units on high-yielding irrigated maize.
2. To evaluate the response of plant height and SPAD units (in high yielding maize) to different N fertilizer application rates and their relationship with grain yield and biomass.
3. To evaluate the management of maize stover and its interaction with mineral N fertilization in irrigated, high-yielding, crop systems.
4. To examine the ability of the CSM-IXIM and CSM-CERES maize models included in DSSAT V4.5 to capture growth, production, and N uptake in high-yielding environments.

3. CHAPTER I. EFFECTS OF NITROGEN APPLICATION RATES ON HIGH YIELDING MAIZE PRODUCTION SYSTEMS

Abstract

Nitrogen (N) fertilizers are extensively used for maize (*Zea mays* L.) production in high-yielding irrigated Mediterranean areas. The present study was conducted over two years (2013 and 2014) in Lleida (North-East Spain) under sprinkler irrigated conditions. Five N rates (0, 100, 200, 300 and 400 kg N ha^{-1} year^{-1}) were compared in high maize production systems. N was applied in two side-dresses: the first at development stage V3–V4; and the second at V5–V6, for three different N rates (100, 200, and 300 kg N ha^{-1}); it was also applied in three other side-dresses of 400 kg N ha^{-1}. Grain yield, biomass, grain and plant N uptake and SPAD-unit values were greatly affected by N fertilization rates. Maximum yield values were achieved with N application rates of 198 and 192 kg ha^{-1}, in 2013 and 2014, respectively. The highest SPAD-unit values (58 and 59) were obtained at application rates of 190 and 180 kg N ha^{-1}, in 2013 and 2014, respectively. The optimal N rate varied depending on the year and was influenced by the soil NO_3^--N content before planting (Nini). The minimum quantities of N available (N_{av}) to the crop [N applied with fertilization plus Nini] necessary to achieve maximum grain yields (19.56 and 19.97 Mg ha^{-1}) were 339 and 315 kg N ha^{-1}, for N_{av} (0 – 90 cm) and N_{av} (0 – 30 cm), respectively. These values were close to plant N uptake (338 kg N ha^{-1}), suggesting that N_{av} at either of these soil depths (30 or 90 cm) was able to predict N maize requirements and could offer an interesting tool for managing N fertilization in high yielding maize.

3.1. Introduction

Maize (Zea mays L.) is one of the most important field crops in the irrigated areas of the Mediterranean part of the Ebro Valley (North-East Spain). In these areas nitrogen (N) is often applied at rates of more than 400 kg N ha^{-1} if organic fertilization is involved. However, surveys conducted in the area showed that when only mineral N was applied, fertilization rates ranged from 300 to 350 kg N ha^{-1} (Sisquella et al., 2004). These quantities of N are only based on possible N uptake and do not consider the high pre-planting levels of soil mineral N that are common in the area studied (Ballesta and Lloveras, 1996; Villar-Mir et al., 2002; Abad et al., 2004).

Nitrogen is normally considered the macronutrient that most limits maize grain yields (Uhart and Andrade, 1995; Varinderpal-Singh et al., 2011), so it is essential to ensure adequate N availability.

In crops with a high demand for N, such as maize, N fertilizer represents an important input cost, but yield increases are normally observed following N fertilizer applications (Ziadi et al., 2008; Nyiraneza et al., 2009; Gagnon and Ziadi, 2010; Gagnon et al., 2012; Lloveras and Cabases, 2014).

The rate of N application is an important management factor in maize production that is also related to increases in the quantity of nitrate reaching the soil surface and groundwater. N rates are also important with regard to the economics of maize production (Piekielek et al., 1995). Applications above crop needs, increase the pool of nitrates that remain in the soil after harvesting the crop and therefore the quantity of nitrate that could potentially move out of the soil profile (Berenguer et al., 2009). If the crop only receives the amount of N fertilizer required in a given year, this will not prevent nitrates from leaving maize fields or necessarily help to achieve the proposed water quality criteria; this can result in a reduction in the quantity of residual soil nitrate (Andraski et al., 2000).

Estimates of soil mineral N uptake by plants are important for understanding aspects of nitrogen dynamics under different agricultural conditions. Experiments and modelling have shown that total plant N uptake is controlled by plant N demand and the availability of N (von Wirén et al. 1997; Gastal and Lemaire 2002), which are driven by both plant growth and soil conditions (Eckersten and Jansson 1991; Hutson and Wanaget 1992).

The largest N effects are evident in crop growth, which is mainly measured using the leaf area index (LAI), biomass production (Lawlor, 1995) and grain yield. The effects of N on grain yield strongly correlate with the rate of crop growth during the critical period for kernel set, which occurs during or around the silking stage (Andrade et al., 2002).

A number of optical spectral indices and canopy characteristics have been widely applied to assist with N management. For example, the SPAD-502 chlorophyll meter is used to measure the relative chlorophyll (SPAD) content of the leaves (Piekielek, et al., 1995). Nitrogen is one of the enzymes associated with chlorophyll synthesis (Chapman and Barreto, 1997); chlorophyll concentration can therefore be used to predict the relative N status of the crop (Blackmer et al., 1994; Blackmer and Schepers, 1995).

Numerous researchers have correlated SPAD values with maize N status and various growth stages with grain yield (Piekielek et al., 1995; Varvel et al., 1997; Bullock and Anderson, 1998; Vetsch and Randall, 2004; Ma et al., 2005; Ma et al., 2007).

The main objective of this research was to evaluate the effects of applying high rates of mineral N fertilizer (up to 400 kg N ha^{-1}) on: grain yield; aboveground biomass; N uptake; soil NO_3^--N content before planting (Nini) and after harvest (Nresi); and SPAD-units in high-yielding irrigated maize in the Ebro Valley.

3.2. Materials and methods

3.2.1 Field experiments

Field experiments were conducted in Almacelles (NE Spain, 41°43’ N, 0°26’ E) over two consecutive years (2013 and 2014). The main soil characteristics for the experiment are presented in Table 3.1.

Five N fertilization rates: 0, 100, 200, 300 and 400 kg N ha^{-1} (N0, N100, N200, N300 and N400) were applied each year, to the same plots. The N fertilizer was applied as ammonium nitrate (34.5% N) in two side-dressings: 50% at development stage V3 – V4 and 50% at V5 – V6, for the N100, N200 and N300 treatments (Ritchie and Hanway, 1982), and in three equal side-dressing doses, at development stages V3 – V4, V5 – V6 and V7 – V8, for the N400 treatment. A zero N application rate was also included as a control (N0).

Table 3.1. Chemical and physical soil properties at the beginning of the study (2013).

Soil properties				
Depth, cm	0-22	23-45	46-110	>111
Sand (%)	42	43	17	17
Silt (%)	33	36	63	65
Clay (%)	25	21	20	18
pH	8.2	8.4	8.4	8.4
Organic matter (%)	2.87	-	-	-
Bulk density (g cm^{-3})	1.64	-	-	-
E.C., dS m^{-1}	0.19	0.17	0.22	0.22
P (Olsen), mg kg^{-1}	90	-	-	-
K (NH4Ac), mg kg^{-1}	383	-	-	-
Soil type†	Typic Calcixerept			
Precedent crop	maize			

†Soil Survey Staff (2003).

The statistical design consisted of a completely randomized block with three repetitions. The N treatments were randomized in the first year and thereafter they were applied to the same plots every year. The plot size was 17m x 8m.

The N0, N100 and N300 treatment plots had been under the same N treatments for the three previous years, whereas the N400 had been fertilized by applying pig manure (30 m^3 ha^{-1}) until 2012. As a result, in 2012, the initial soil N contents in all plots might not be the same (Biau et al, 2013a).

The plots were sprinkler-irrigated two to three times per week, with approximately 1000 mm of (nitrate free) water per season.

Maize was planted in the first week of April, at a rate of 95,000 plants ha^{-1} with a 71 cm space between rows in both years. Weed control was achieved by applying pre-emergent herbicides and hand weeding when necessary.

The maize hybrids used in the experiment belonged to the 700 FAO cycle (P1758Y in 2013, and PR33Y72 in 2014).

3.2.2 Analysis of plant and soil samples

SPAD-units were measured several days before silking, using a hand-held SPAD-502 Minolta SPAD-502.

SPAD meter readings were recorded by inserting a portion of a leaf ear into the slit of the SPAD meter. The leaf ear samples were taken from five randomly selected plants per plot and three measurements were performed on three different points of each leaf. The readings obtained were then averaged to obtain one SPAD reading per plot. Wet and widely spaced leaves and unusually tall or short plants were excluded from the analysis.

The aboveground biomass of the crop was estimated at physiological maturity by hand cutting maize plants of 4 m from a central row in each plot (to avoid any border effects) and then chopping three selected plants into pieces in order to determine the dry matter and plant N content. Total plant N content was determined by near infrared spectroscopy (NIRS), using a previously-calibrated 500 Infrared Analyzer (Bran Luebbe, Norderstedt, Germany). Total N uptake was calculated by multiplying the N content by the biomass at physiological maturity. The NIR device from our laboratory was adjusted every year since the year 2002. Biau (2013b) there is no statistically significant difference between in plant N content between our NIRs and the Dumas method.

The maize was harvested in the first week of October and its grain yield was measured by harvesting two complete central rows (1.42 m x 8 m). Grain moisture was determined in a 300 g sample from each plot (GAC II, Dickey-John, Auburn, IL. USA) and the grain yield was adjusted to 14% moisture. The grain N content was measured by NIRS as explained above.

The soil nitrate content (NO_3^--N) was determined before planting (initial NO_3^--N) and after harvesting (residual NO_3^--N). Five soil samples were taken from each plot (at a depth of 0 – 30 cm) and three samples per plot were taken at depths of from 30 cm to 90 cm, at 30 cm intervals.

Nitrate was extracted in deionized water and measured using Nitrachek (KPG Products Ltd., Hove, East Sussex, UK) test strips (Bischoff et al., 1996) calibrated according to the standard procedure (Bremner, 1965). Every year several groups of soil samples were sent to an official laboratory, every year, for checking the Nitracheck device. Several researchers have used similar methodology (Berenguer et al., 2008; Cela et al., 2011; Biau et al., 2013a) and the results were quite similar, for the values lower than 150 ppm(NO_3^-), and little higher (from -20 to 4 ppm of NO_3^-), for the values of 400 ppm of (NO_3^-).

Available N was calculated as the sum of NH_4^+–N and NO_3^--N, plus the amount of mineral N fertilizer applied. Previous studies had shown that the soil ammonium content (NH_4^+–N) in the study area could be considered negligible (Berenguer et al., 2009; Villar-Mir et al., 2002). The mean level of residual NH_4^+–N present in the soil was 15 kg ha^{-1} (at a depth of 0 – 30 cm) (Biau et al., 2013a).

3.2.3 Nitrogen balance and N-efficiency

The N balance was calculated for each plot in each year of the experiment. N mineralization (N_{min}) was estimated for the no fertilized plots, applying the equation $N_{min} = N_{fin} + N_{plant} - N_{ini}$ (Sexton et al., 1996). And assuming that nitrate leaching, ammonia losses and N from the rainfall water are negligible in unfertilized plots (Berenguer et al., 2009; Villar-Mir et al., 2002). N_{ini} was soil initial NO_3^--N content before sowing of each crop and N_{fin} was soil residual NO_3^--N content after harvesting the corn. N_{plant} was total N uptake by the corn at maturity. Nitrogen losses (N lost) were estimated from the N balance in the fertilized plots (Berenguer et al., 2009; Cela et al., 2011) following the equation:

N balance = $N_{fin} + N_{plant} - N_{ini} - N_{min} - N_{fert,}$

N_{fert} was the N applied by fertilization and considering. N lost as the sum of NO_3^--N leached, N lost by ammonia volatilization and denitrification and the N unaccounted. A negative value of N lost was interpreted as a net N loss from the soil-plant system; however a positive value could be interpreted as uncounted N inputs. The Nitrate content of the irrigation water was negligible, since the water come directly from the irrigation channel Aragón y Cataluña.

The following N-efficiency parameters (López-Bellido and López-Bellido, 2001) were calculated for each fertilized treatment:

(1) Apparent N recovery (ANR; kg kg^{-1}) as the ratio of (Plant N uptake in fertilized plots – Plant N uptake in unfertilized plots) to applied N in the fertilized plots.

(2) Agronomic N efficiency (ANE; kg kg^{-1}) as the ratio of (biomass yield in fertilized plots - biomass yield in unfertilized plots) to applied N in the fertilized plots.

3.2.4 Statistical analysis

The results were statistically analysed as split plots in time, using the Proc Mixed procedure in SAS (Littell et al., 1998), from the SAS statistical package (SAS Institute, 1999–2001). N rates and years were considered to be fixed factors.

In the cases of grain yield, plant and grain N uptake and SPAD-units, a bilinear model (linear-plus-plateau) was fitted to the N response data. The linear-plateau model, which is independent of the fertilizer-to-maize price ratio (Cerrato and Blackmer, 1990; Kyveryga et al., 2007) was used to relate the soil properties to N management practices.

The model was fitted using both the SAS NLIN (Ihnen and Goodnight, 1985) and GLM procedures (Spector, et al., 1985).

The term relative yield (expressed as a percentage) used in this paper refers to the ratio between the plateau yield from the linear-plus-plateau model and the yield for each N rate and year.

3.3. Results

3.3.1 Grain yield and above ground biomass

The N fertilization rate significantly affected the maize grain yield. Grain yield was also affected by year, but there was no significant effect on grain yield for the interaction (N rates × year) (Table 3.2).

The average grain yields for all the treatments applied in 2013 (18.02 Mg ha^{-1}) was higher than for those corresponding to 2014 (16.45 Mg ha^{-1}). However, based on the lineal-plus-plateau model, the optimal N application rates were very similar: 198 kg N ha^{-1} for 2013 and 192 kg N ha^{-1} for 2014 (Fig. 3.1).

The N fertilization rate had a significant influence on maize biomass. Aboveground biomass increased with increases in N fertilizer rates, with a significant linear relationship (R^2 = 89 for 2013 and R^2 = 92 for 2014) (Fig. 3.2). Biomass values ranged from 19.93 Mg ha^{-1} and 16.62 Mg ha^{-1} for 0 kg N ha^{-1}, to 33.48 Mg ha^{-1} and 33.26 Mg ha^{-1} for 400 kg N ha^{-1}, in 2013 and 2014, respectively (Table 3.2).

Yield and biomass responses to N fertilisation varied according to the year (Figs. 3.1 and 3.2, Table 3.2).

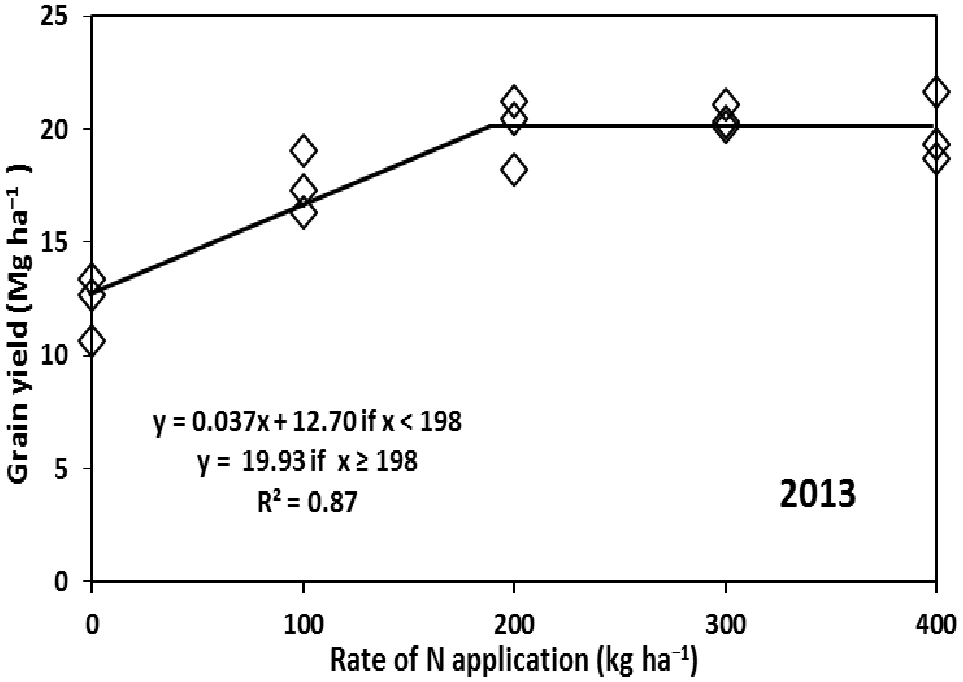
Table 3.2. Effect of N fertilization rates on grain yield, biomass at maturity, grain N uptake, plant N uptake and chlorophyll meter values for both study years.

N rate (kgha^{-1})	Grain yield (Mg ha^{-1})		Biomass (Mg ha^{-1})		Grain N uptake (kg ha^{-1})		Plant N uptake (kg ha^{-1})		Chlorophyll SPAD-units	
	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
0	12.22	8.65	19.93	16.62	124	86	179	171	44	42
100	17.55	15.59	25.76	23.44	180	165	238	244	54	56
200	19.97	18.74	28.87	29.07	222	200	295	325	59	61
300	20.48	19.44	30.24	31.34	242	216	329	338	59	60
400	19.87	19.85	33.48	33.26	240	220	337	347	59	62
N rate (N)	**		**		**		**		**	
Block	ns		ns		ns		ns		ns	
Error a	–		–		–		–		–	
Year (Y)	**		ns		**		ns		ns	
N×Y	ns		*		ns		ns		ns	

* Significant at the 0.05 level.

** Significant at the 0.01 level.

ns, not significant



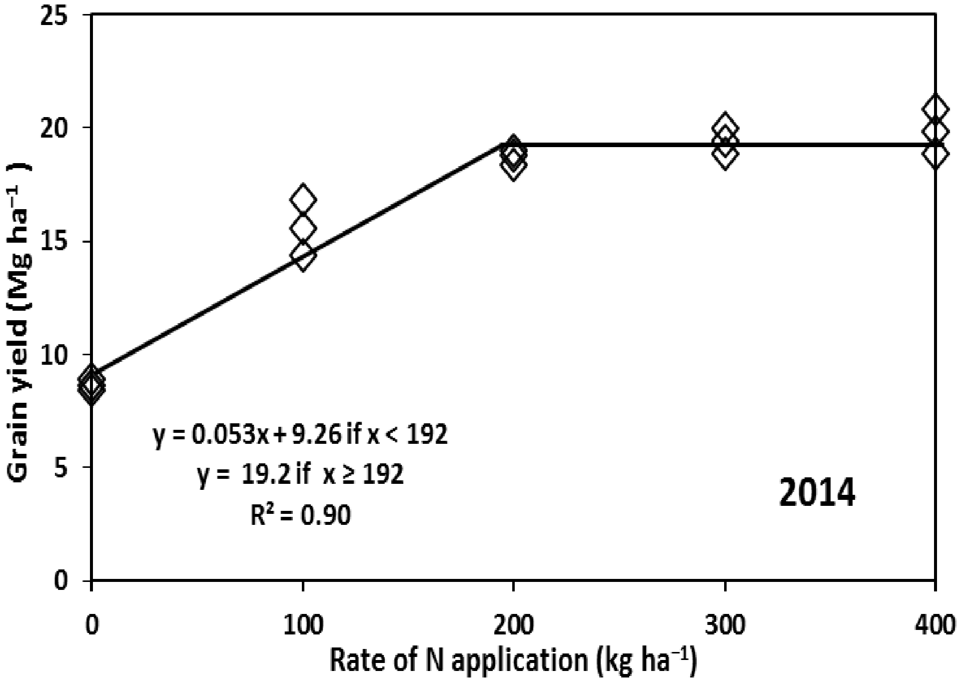
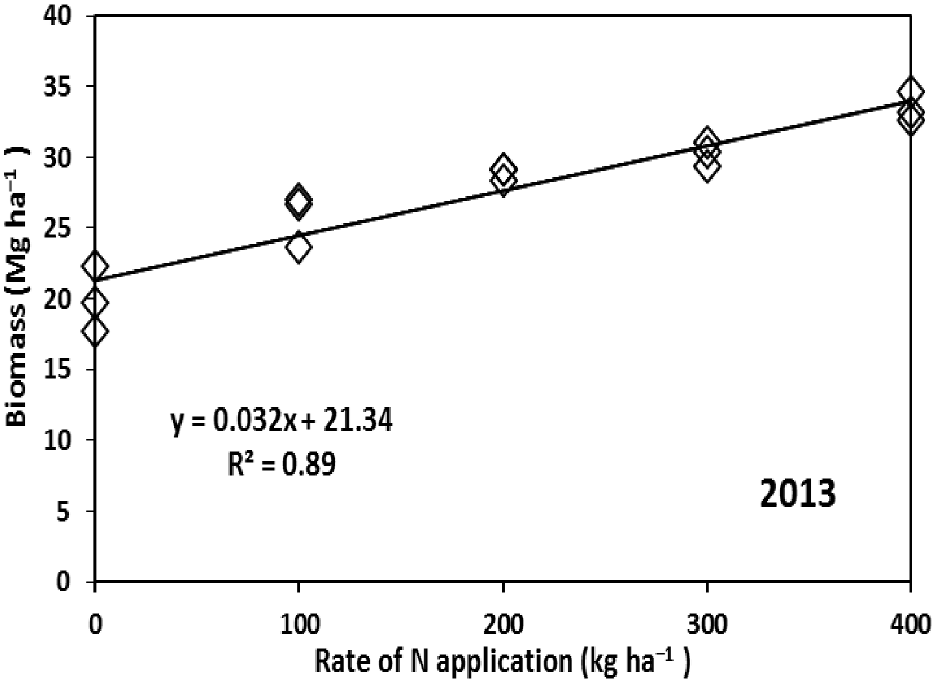


Figure 3.1. Effects of N fertilization on maize grain yield in 2013 and 2014.



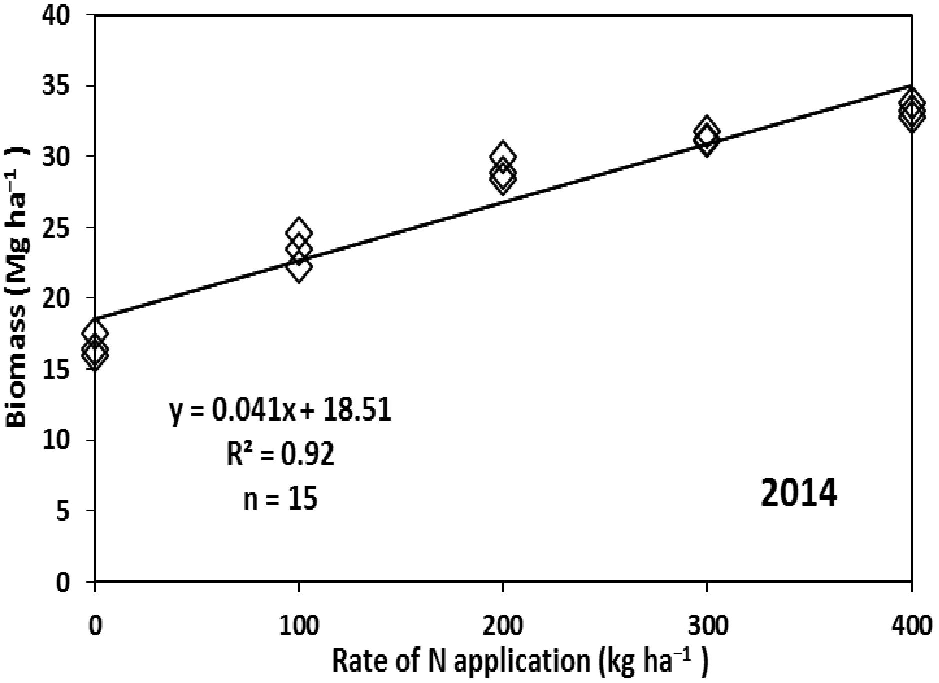


Figure 3.2. Effects of N fertilization on maize biomass at maturity in 2013 and 2014.

3.3.2 Plant and grain N uptake

Plant and grain N uptakes increased with increasing N application rates and varied from year to year (Figs. 3.3 and 3.4, Table 3.2).

Plant N uptake was significantly affected by N treatment, but not by year (Table 3.2, Fig. 3.5). The average plant N uptake ranged from 179 kg ha^{-1} in 2013 and 171 kg ha^{-1} in 2014 for N0 to 337 kg ha^{-1} in 2013 and 347 kg ha^{-1} in 2014 for N400 treatment.

Based on the lineal-plus-plateau model, the average plant N uptake of the highest yielding treatment was 338 kg ha^{-1} and the optimal N application rate during this 2-year study never exceeded 348 kg ha^{-1} (Fig. 3.3).

Grain N uptake was significantly affected by N rate and year (Table 3.2). The highest grain N uptakes (240 and 210 kg ha^{-1}) were recorded with N application rates of 230 and 225 kg N ha^{-1}, in 2013 and 2014, respectively (Fig. 3.4).

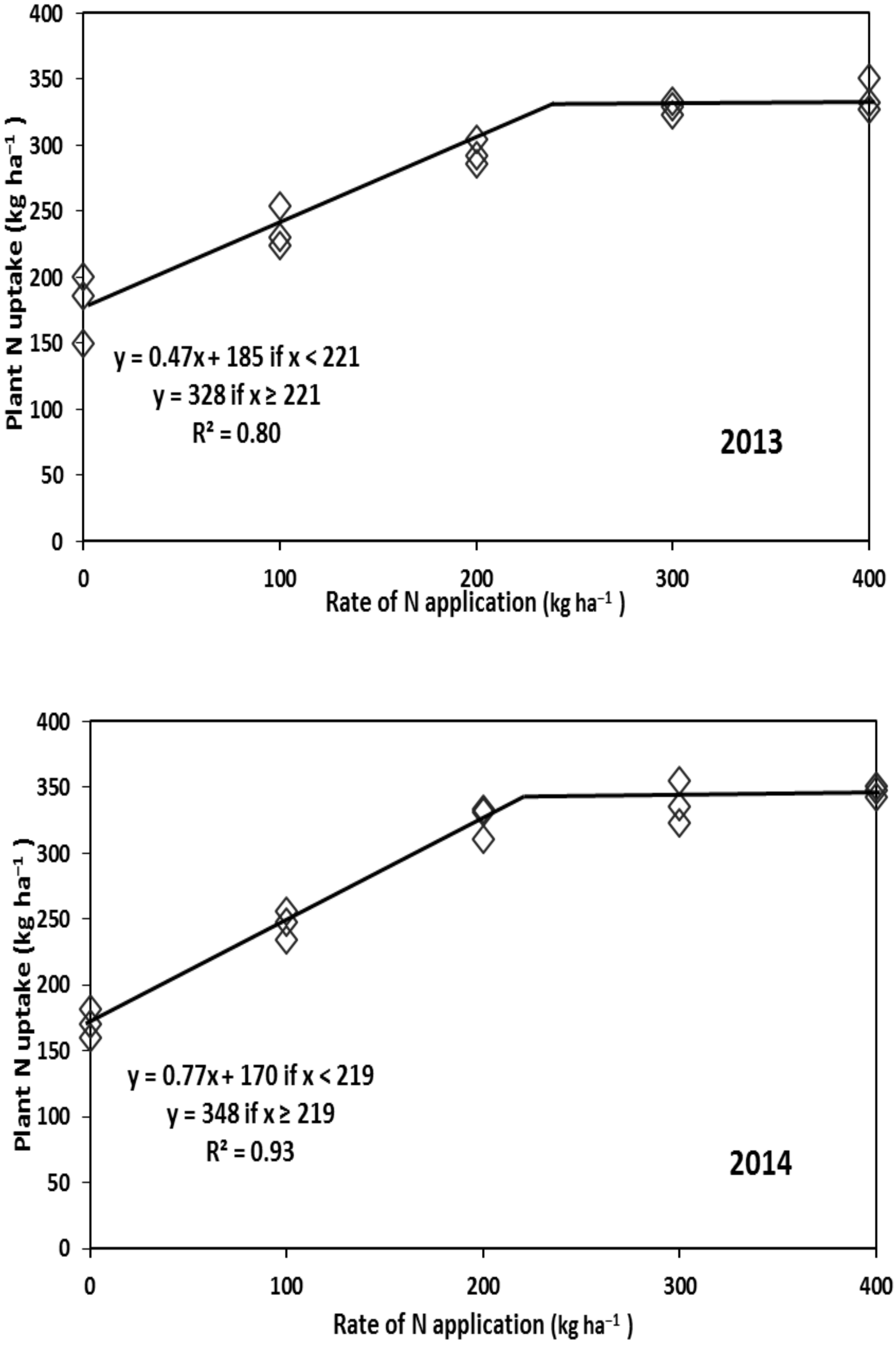
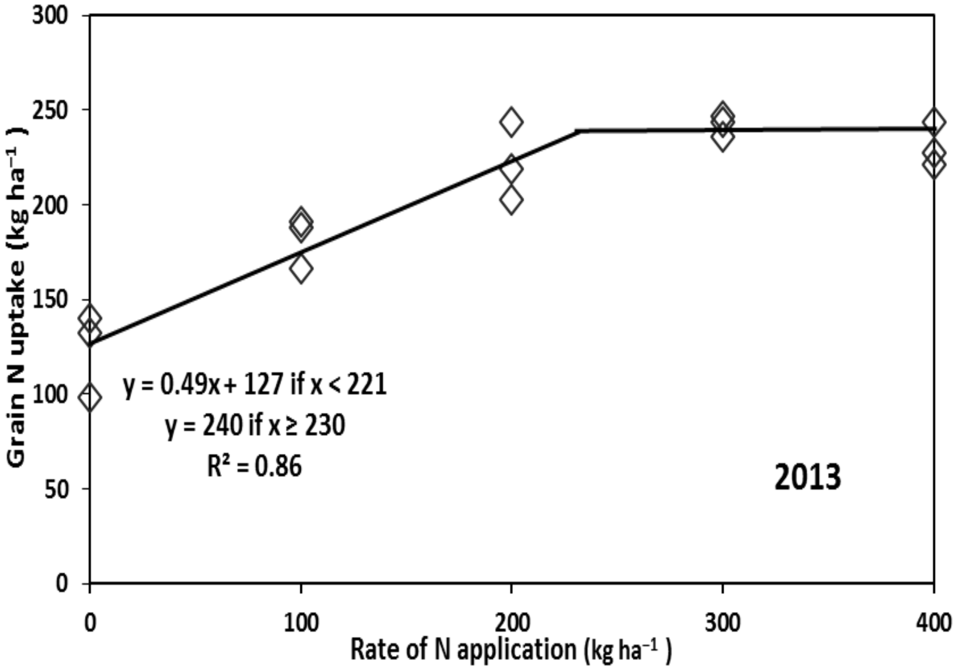


Figure 3.3. Effects of N fertilization on maize plant N uptake in 2013 and 2014.



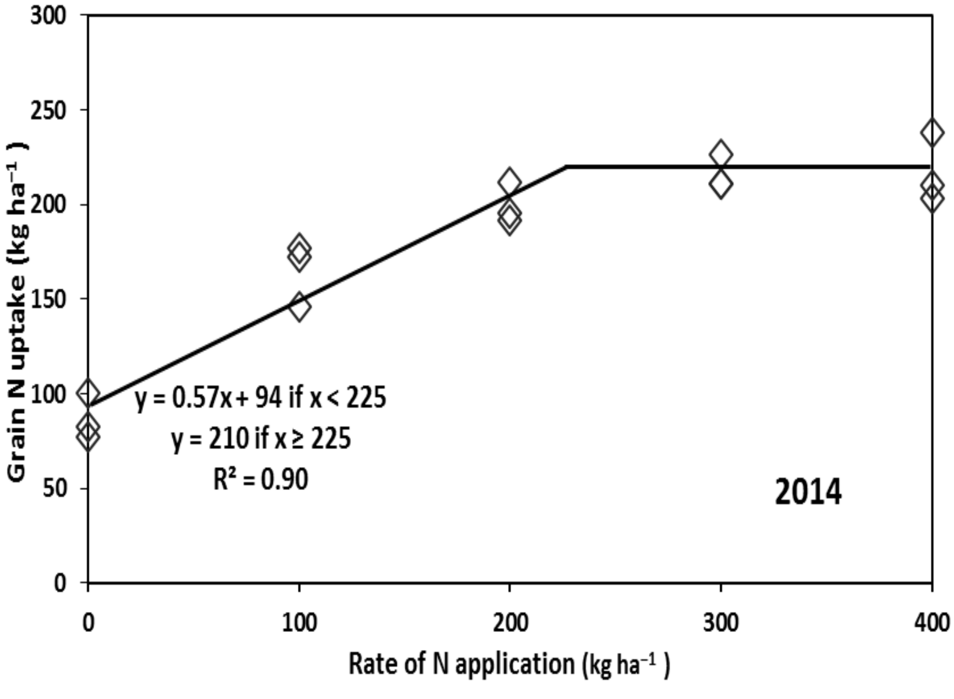


Figure 3.4. Effects of N fertilization on maize grain N uptake in 2013 and 2014.

3.3.3 Soil N content

At the beginning of the experiment, in 2013, the initial NO_3^--N content at a depth of 0 to 90 cm ranged from 49 kg ha^{-1} for the 0 kg N ha^{-1} treatment to 89 kg ha^{-1} for the 400 kg N ha^{-1} treatment (these plots had been treated with 30 m^3 ha^{-1} treatments of pig manure until 2012) (Table 3.3).

The soil NO_3^--N content (kg ha^{-1}) before planting (Nini) and after harvest (Nresi) in the different soil layers was significantly affected by the fertilizer treatment in 2014, while in 2013 only Nresi was significantly affected by fertilizer treatment. (Table 3.3, Fig. 3.5).

The Nresi in the different soil layers was quite similar to, or lower than, the Nini for the N0 and N100 application rates and greater than the Nini for N application rates of over 100 kg N ha^{-1}. It ranged from 25 for the 0 kg N ha^{-1} treatment to 210 kg N for the 400 kg N ha^{-1} treatment in 2013 and from 52 to 329 kg N ha^{-1} for the 0 and 400 kg N ha^{-1} treatments, respectively, in 2014.

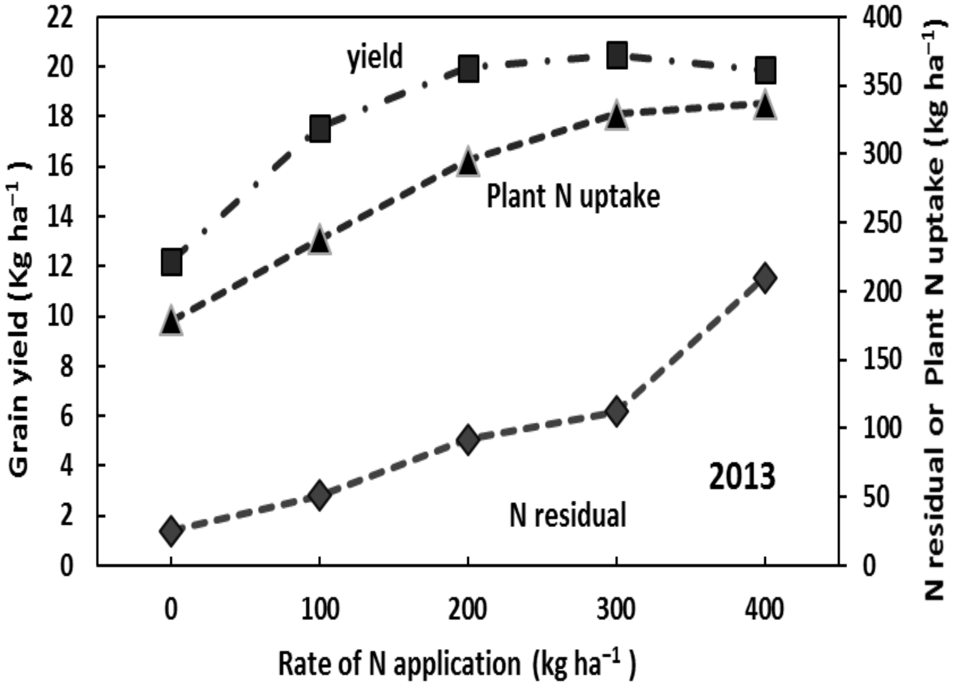
Table 3.3. Soil NO_3^--N content (kg ha^{-1}) before planting (Nini) and after harvest (Nresi) (depths: 0-30, 30-60 and 0-90 cm) for both study years.

Depth (cm)	0-30				30-60				60-90				0-90			
N rate (kgha^{-1})	Nini		Nresi		Nini		Nresi		Nini		Nresi		Nini		Nresi	
	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
0	16	28	9	17	16	28	10	24	17	14	6	11	49	70	25	52
100	25	39	22	37	26	33	19	32	17	16	10	15	67	89	51	83
200	24	47	34	88	24	34	33	53	21	17	25	29	69	107	92	170
300	25	58	41	115	23	58	39	105	20	29	33	55	68	134	112	275
400	16	98	96	169	24	63	51	102	25	45	63	58	89	206	210	329
Block	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
N rate (N)	ns	**	**	**	ns	*	**	**	ns	*	*	**	ns	**	**	**
N rate (N)	**		**		ns		**		**		**		**		**	
Block	ns		ns		ns		ns		ns		ns		ns		ns	
Error a	–		–		–		–		–		–		–		–	
N×Y	*		ns		ns		ns		ns		ns		*		ns	

* Significant at the 0.05 level.

** Significant at the 0.01 level.

ns, not significant



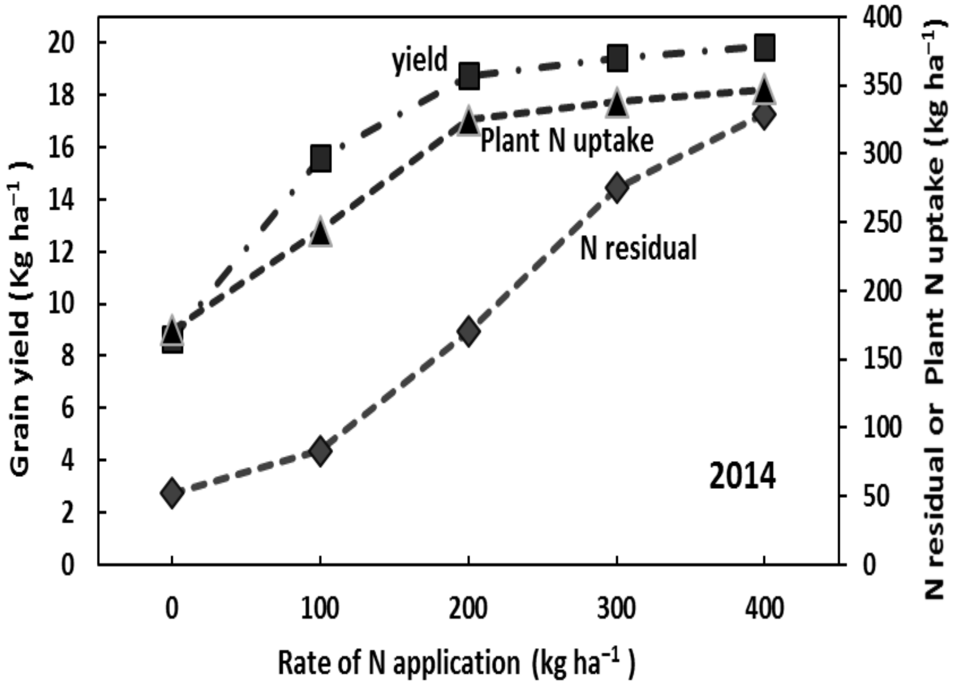


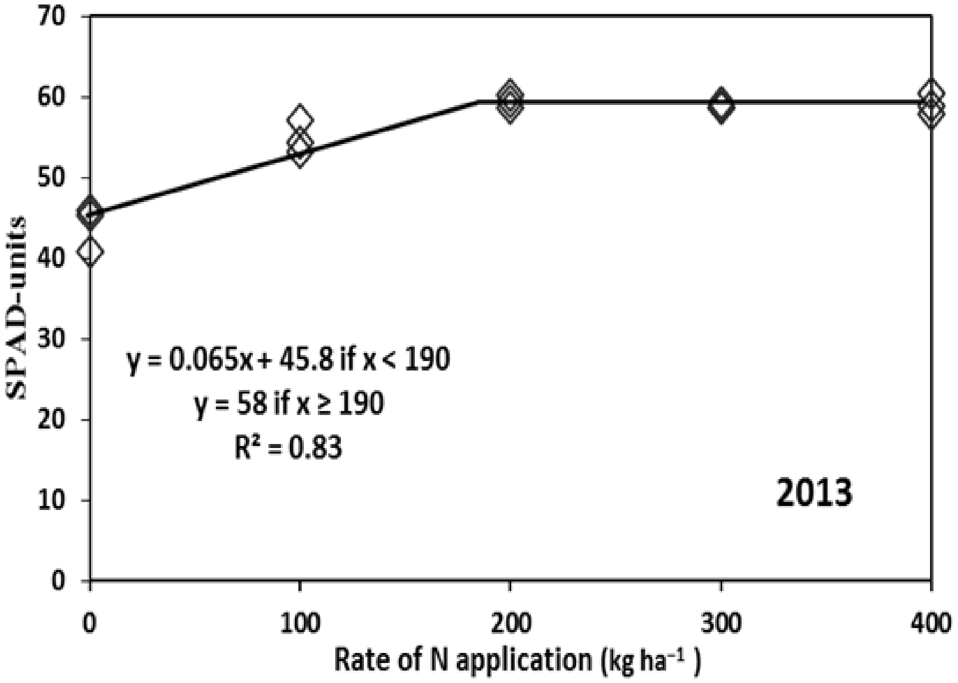
Figure 3.5. Effects of N fertilization on maize yield and plant N uptake and residual soil NO_3^--N (0 – 90 cm), in 2013 and 2014.

3.3.4 SPAD-units

The SPAD-units at silking were significantly affected by N rates and ranged from 44 to 59, in 2013, and from 42 to 62, in 2014 (Table 3.2).

Average SPAD-units at silking varied from year to year (Fig. 3.6, Table 3.2) and followed a similar trend to grain yields in almost every year; values increased from N0 to N200 in both years (Fig. 3.7).

SPAD-units were highly correlated with relative grain yield and reached a plateau value of 57 (Fig. 3.8).



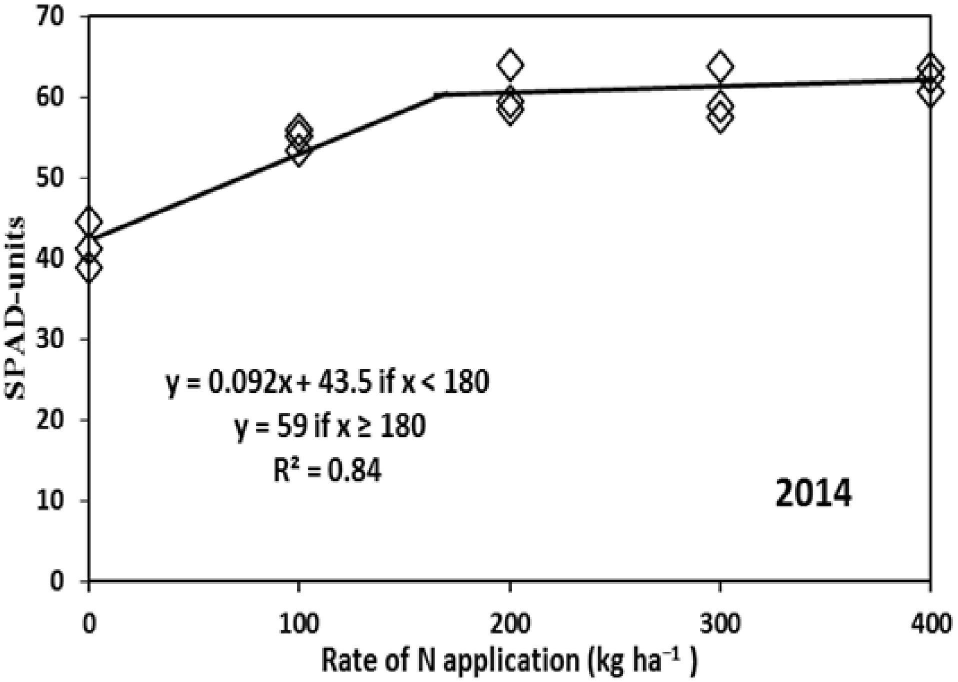


Figure 3.6. Effects of N fertilization on maize SPAD-units at silking, 2013 and 2014.

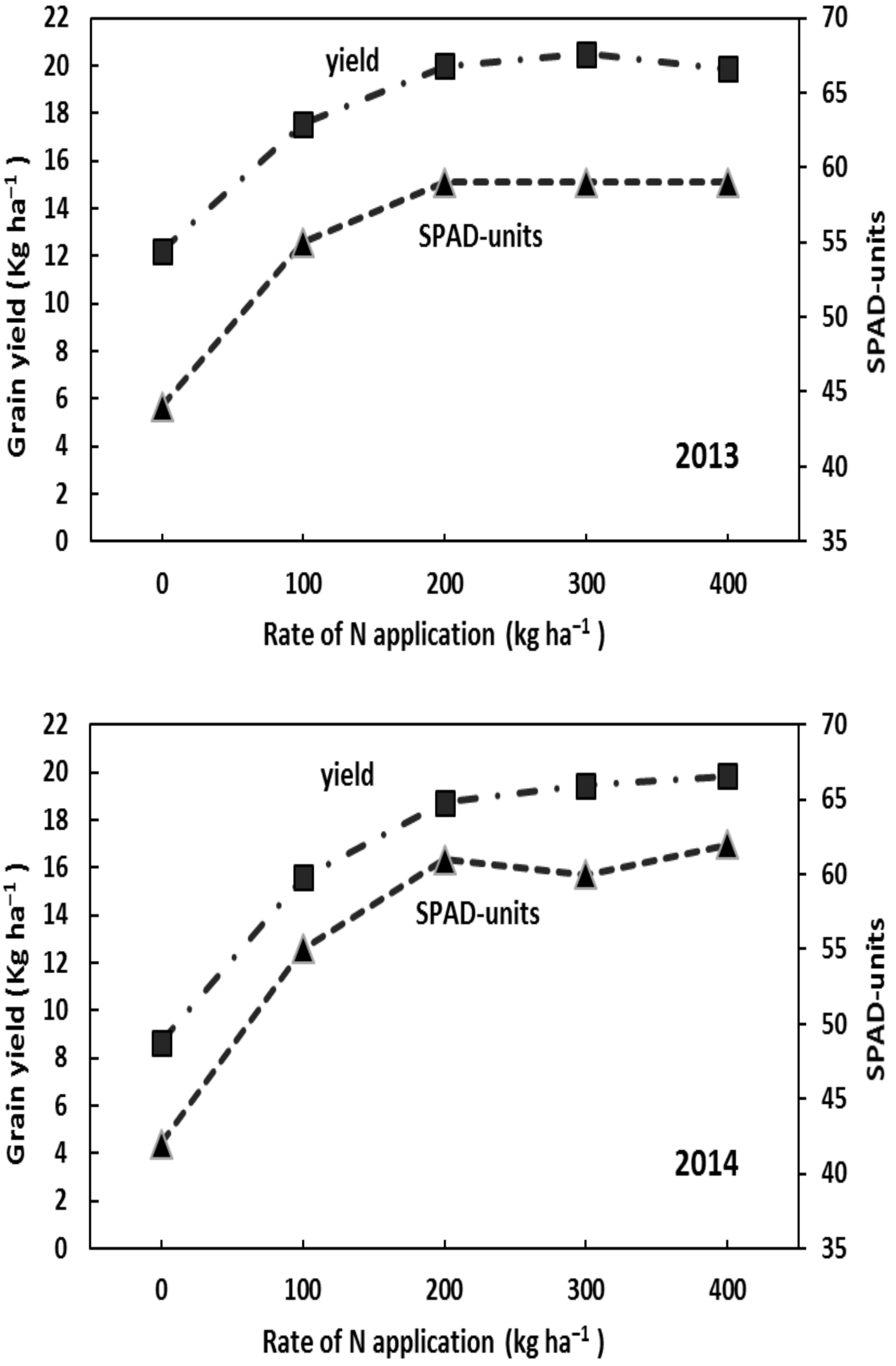


Figure 3.7. Effects of N fertilization on maize yield and SPAD-units at silking, in 2013 and 2014.

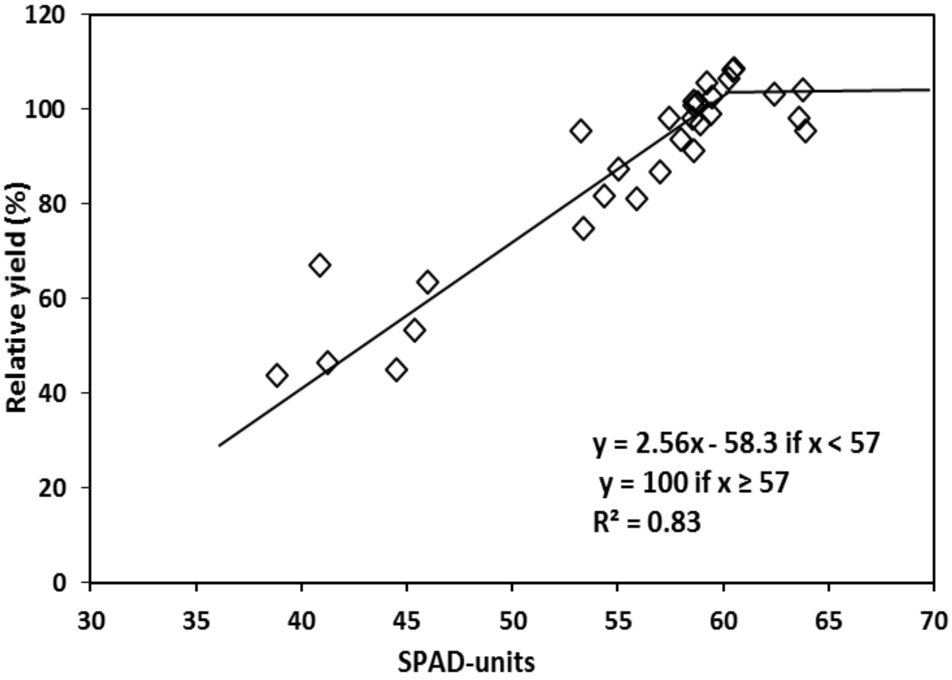


Figure 3.8. Relationship between relative grain yield and SPAD-units at silking (2013 and 2014).

3.3.5 Yield and available N

The grain yield was correlated with plant-available N (Nav) at the depths of 0 – 30 and 0 – 90 cm: $R^2 = 0.75$ for both depths (Fig. 3.9 and 3.10).

To achieve the highest grain yield (19.56 Mg ha^{-1}), it was necessary to have a Nav (0 – 90 cm) value of at least 339 kg N ha^{-1}.

When Nav (0 – 90 cm) was lower than 339 kg ha^{-1}, grain yields decreased, following a linear trend, whereas for Nav (0 – 30 cm), 315 kg N ha^{-1} was enough to achieve a maize grain yield of 19.97 Mg ha^{-1}.

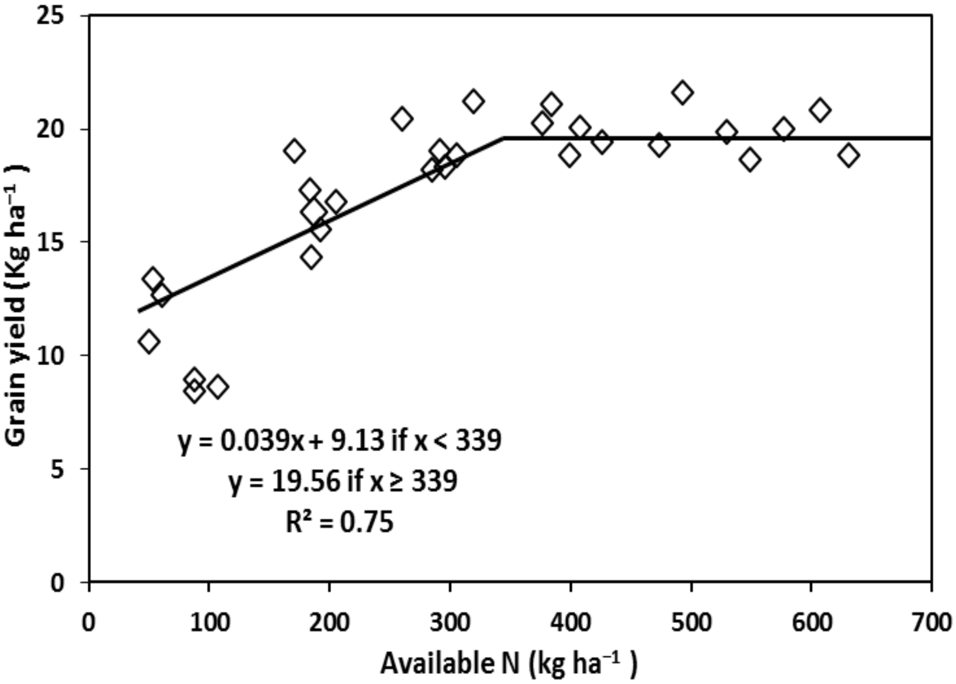


Figure 3.9. Grain yield as a function of plant-available N [initial soil NO_3^--N (0 – 90 cm) plus fertilizer N applied], in 2013 and 2014.

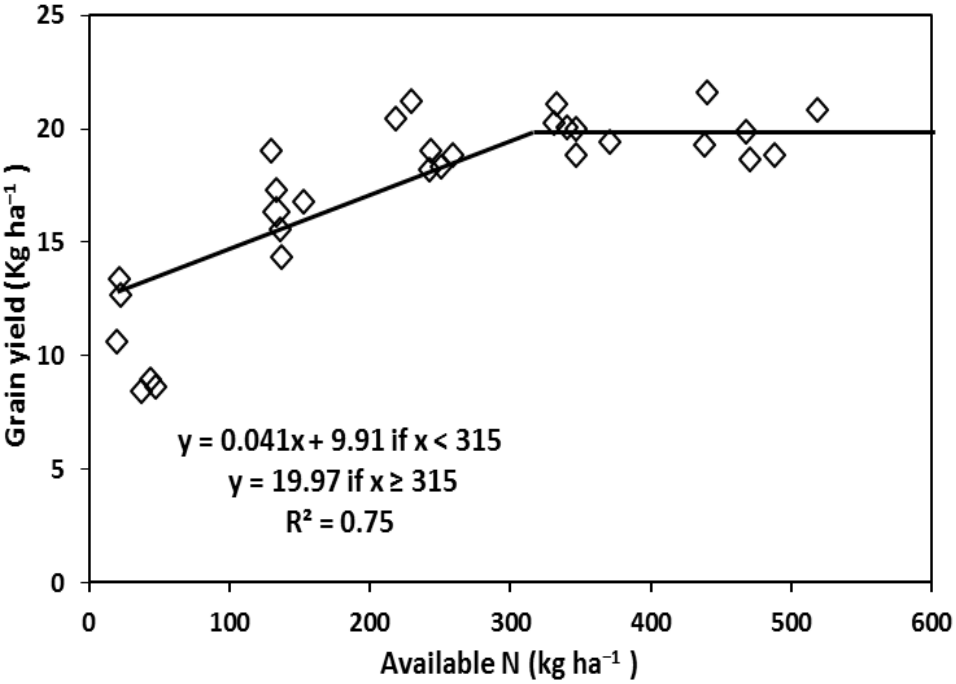


Figure 3.10. Grain yield as a function of plant-available N [initial soil NO_3^--N (0 – 30 cm) plus fertilizer N applied], in 2013 and 2014.

3.3.6 Nitrogen balance and N-efficiency

N lost was significantly affected by N fertilization rates and ranged from 64 Kg N ha^{-1} for the 100 kg N ha^{-1} treatment to 138 kg N ha^{-1} for the 400 kg N ha^{-1} treatment in 2013 and from 44 to 113 kg N ha^{-1} for the 100 and 400 kg N ha^{-1} treatments, respectively, in 2014 (Table 3.4).

Apparent N recovery and agronomic N efficiency were also influenced significantly by N rates (Table 3.4).

The maximum Apparent N recovery and agronomic N efficiency in our field trial were obtained at the N100 treatment (0.57, 58.33 kg kg^{-1} in 2013 and 0.75, 68.23 kg kg^{-1} in 2014, respectively) and the minimum were obtained at the N400 treatment (0.40, 33.87 kg kg^{-1} in 2013 and 0.44, 41.61 kg kg^{-1} in 2014, respectively (Table 3.4).

Table 3.4. N losses, apparent N recovery and agronomic N efficiency values for the study years.

N rate (kgha^{-1})	N lost (Kg N ha^{-1})		Apparent N recovery kg kg^{-1}		Agronomic N efficiency kg kg^{-1}	
	2013	2014	2013	2014	2013	2014
100	64	44	0.57	0.75	58.33	68.23
200	66	47	0.58	0.77	44.70	62.23
300	110	52	0.50	0.56	34.38	49.07
400	138	113	0.40	0.44	33.87	41.61
N rate (N)	**		**		**	
Block	ns		ns		ns	
Error a	–		–		–	
Year (Y)	ns		**		ns	
N×Y	ns		ns		*	

* Significant at the 0.05 level.

** Significant at the 0.01 level.

ns, not significant

3.4. Discussion

Maize grain yields increased when N fertilizer was applied in both of the years of the experiment. The relative increases in yield associated with increases in N fertilization compared with the control (0 kg N ha^{-1}) were: 44%, 63%, 68% and 63%, in 2013, and 80%, 117%, 125% and 129, in 2014, for applications of 100, 200, 300 and 400 kg N ha^{-1}, respectively. Previous studies conducted under similar conditions to ours (Berenguer et al., 2009) reported that the relative increases in yield associated with increases in N fertilization of up to 300 kg N ha^{-1} with respect to the control did not exceed 60%. This was probably due to either the high Nini reported in that study, with respect to the grain yields, which reduced the response of the grain yield to N fertilisation (Halvorson et al., 2005) or to the lower grain yields compared to our own.

However, in another study on high maize production in Pakistan, the grain yield increased by 88% when N fertilization increased from 0 to 210 kg N ha^{-1} (Abbasi et al., 2012).

The findings for our irrigated areas largely agree with those published by other authors, and particularly those from the USA (Onken et al., 1985; Vanotti and Bundy, 1994; Schmidt et al., 2002; Halvorson et al., 2005). These authors reported that the grain yield response to N fertiliser varied from year to year and was influenced by both the Nini and the rate of N fertilization.

The optimal N application rates for grain production in our study, according to the linear-plateau method, were: 198 kg N ha^{-1} in 2013 and 192 kg N ha^{-1} in 2014. Halvorson et al. (2006) [Colorado (USA)] also reported significant increases in grain yields with increasing N applications up to 224 kg N ha^{-1} in high-yielding irrigated maize crops (up to 14 Mg ha^{-1}). Berenguer et al. (2008), who conducted their study in a similar area to ours, and under the same climatic conditions, found that the maximum grain yield (14.17 Mg ha^{-1}) was achieved with a N application of only 153 kg N ha^{-1}. This was probably due to the high levels of mineral N already present in the soil at pre-planting in their study (172 kg N ha^{-1} on average), which compared to an average of 95 kg N ha^{-1} in our study, and also to the lower grain yields obtained in their study (an average of 12.74 Mg ha^{-1} vs 17.23 Mg ha^{-1}).

Biomass production was high, with average dry matter yields of 27.2 Mg ha^{-1} ranging from 18.27 for the N0 treatment to 33.37 for the N400 treatment, with an average harvest index of 0.65 for the N300 treatment and 0.59 for the N400 treatment. The maximum value for aboveground biomass recorded in this study was close to the potential biomass values for maize reported under field (de Ruiter et al., 2009) and modelled (Fletcher et al., 2011) conditions.

Plant and grain N uptake were both significantly influenced by N fertiliser rates, as also reported by other researchers (Cox and Cherney, 2001; Derby et al., 2005; Shapiro and Wortmann, 2006; Halvorson et al., 2006; Berenguer et al., 2009). In our study, the highest N uptakes for grain production were achieved at 300 kg N ha^{-1}, whereas the highest plant N uptakes were achieved with 400 kg N ha^{-1}. Even so, it should be underlined that many of the pieces of research reported above referred to similar plant and grain N uptake responses to N fertilisation.

The average plant N uptake ranged from 175 to 342 kg ha^{-1} for the N0 and N400 treatments, respectively (Table 3.2). These levels could be considered to be in line with previous studies conducted in the same area (Daudén and Quílez, 2004; Berenguer et al., 2009; Biau et al., 2013a).

Increased plant N uptake with increased N fertilization could perhaps be attributed to increased aboveground biomass yields and plant N concentrations, as N-uptake followed a similar pattern to plant biomass.

The significant increase in maize plant N uptake with N fertilizer applications was consistent with reports from other studies, most of which were carried out under Mediterranean conditions (Vanotti and Bundy, 1994; Schmidt et al., 2002; Berenguer et al., 2008; Nyiraneza et al., 2010; Messiga et al., 2012).

Grain N uptake followed a similar trend to grain yield. However, the minimum N application rates necessary to obtain the highest values of grain N uptake (230 kg N ha^{-1} in 2013 and 225 kg N ha^{-1} in 2014) were slightly higher than those necessary to obtain the maximum yield (221 kg N ha^{-1} in 2013 and 219 kg N ha^{-1} in 2014). The grain N uptake was higher in 2013 than in 2014 due to the fact that the grain yield in 2013 was higher than in 2014 (Table 3.2).

In 2014, the initial soil NO_3^--N content was influenced by N fertilisation in the previous year. The results obtained show that the N fertilization rate significantly affected the Nresi. Our results were in agreement with those reported by several other authors who reported NO_3^--N content remaining in the soil after maize harvests increased following increases in N application rates during the growing season (Berenguer et al., 2009; Gagnon and Ziadi, 2010; Ziadi et al., 2012) (Fig. 3.5).

Sió et al. (2000) and Cela et al. (2011) suggested that under Mediterranean conditions (low winter rainfall), and depending on the year, the residual NO_3^--N content in the soil after harvest could persist until at least the seeding of the next crop and could therefore affect N fertilization recommendations.

In our unfertilised plots and those that received little fertilisation (100 kg N ha^{-1}), there was an evident reduction and depletion of soil Nini and Nresi over time. This reduction was less noticeable with medium and highly N fertilised treatments, which still presented high NO_3^--N soil contents at the end of the study.

Our results showed an increase in soil NO_3^--N content in the period from harvest to the seeding of the following year's crop, even at the application rate of 0 kg N ha^{-1}; this suggested that N mineralization during this period could have been important and may have supplied part of the N needed by the crop, even in soils with low initial N contents (Abad et al., 2004).

For N application rates of 300 and 400 kg N ha^{-1}, the level of soil NO_3^--N depletion (at a depth of 0 - 90 cm) during the growing season (with considerable differences between Nini and Nresi) was greater than the differences between plant N uptake and the rate of N applied during the growing season. This suggested high N losses, which increased with increasing N application rates. Similar losses have also been reported by other authors (Brye et al., 2003; Berenguer et al., 2009).

As reported in previous research (Piekielek et al., 1995; Schröder et al., 2000; Berenguer et al., 2009), the SPAD values reflected the maize N deficiency stress level, but they did not differentiate between adequate and excess N. According to our study, the critical level beyond which maize could be considered non-responsive to N application was 58 SPAD-units; this value was a little higher than that the values reported by Piekielek et al. (1995) (52–56 SPAD-units) and was possibly due to the high grain yields obtained in our experiments. However, in another study conducted in our area, Berenguer et al. (2009) reported a lack of responsive to N application, with SPAD values of 53 units, for average grain yields of 12.74 Mg ha^{-1}.

The data obtained from our study revealed that the highest Nav was found in the 0 – 30 cm soil layer, followed by a lower level in the 30 – 60 cm soil layer and the lowest in the 60 – 90 cm soil layer. These findings agree with those of other authors (Weber et al., 1995; Arbačiauskas et al., 2014).

As reported in other studies, grain yield was highly correlated with soil available N (Nav) (0- 90 cm) (Berenguer et al., 2009; Halvorson et al., 2005). However, previous studies conducted in our area (Villar-Mir et al., 2002) did not find any relationship between Nav (0 – 90 cm) and grain yield. This was probably due to the range of N fertilization rates that they used in their study (250 – 340 kg N ha^{-1}) and also to the irrigation system that they used (flood irrigation, instead of sprinkler irrigation) (Villar-Mir et al., 2002).

The minimum Nav (0 - 90 cm) required to achieve maximum grain yields in our experiment was 339 kg N ha^{-1}. Lower values (258 –265 kg Nav ha^{-1}) were obtained by Berenguer et al. (2009) in the same study area, although their grain yields (14-15 Mg ha^{-1}) were lower than ours, and by Halvorson et al. (2005), whose study was based on irrigated high-production maize (up to 14 Mg ha^{-1}) in Colorado (USA). Dara et al. (1992) also reported that a Nav of 247 kg ha^{-1} was required for a grain yield of 11.86 Mg ha^{-1} [under irrigated conditions in North Dakota (USA)]. The high Nav value required to obtain maximum grain yields in our study may have been due to the high grain productions obtained in our study (up to 20 Mg ha^{-1}).

The highest yielding treatments in our study (19.57 Mg ha^{-1} on average) presented very similar plant N uptake values (338 kg N ha^{-1} on average) to the minimum Nav (0-90 cm) value required to achieve maximum yields (339 kg N ha^{-1}). This suggests that Nav (0 -90 cm) was able to predict maize N requirements and could be considered a good tool for improving N fertilisation recommendations. Under similar conditions to ours, Halvorson et al. (2005) [Colorado (USA) high-yielding irrigated maize] also found that Nav (0-90 cm) was a good predictor of yield response.

Grain yield was also correlated with Nav (0 – 30 cm) (Fig. 3.10). The R^2 for the segmented model between grain yield and Nav (0 – 30 cm) was highly significant (R^2 = 0.75), indicating that 75% of the variability in grain yield could be accounted for by Nav (0 - 30cm).

The minimum Nav (0 - 30 cm) value required to achieve maximum grain yields (315 kg N ha^{-1}) was close to the minimum Nav (0 - 90 cm) value required to achieve maximum yields (339 kg N ha^{-1}) and plant N uptake values (338 kg N ha^{-1} on average). This suggests that Nav (0-30 cm) was also able to predict maize N requirements. Mtambanengwe and Mapfumo (2006) also found that Nav (0 - 30 cm) was a good predictor of yield response.

The calculated N balance in this experiment indicated that the highest N fertilization rates caused the highest N losses, as presented by others (Liu et al., 2003; Brye et al., 2003; Isla et al., 2006; Berenguer et al., 2009). N lost in our study ranged from 44 Kg N ha^{-1} for the 100 kg N ha^{-1} treatment to 138 kg N ha^{-1} for the 400 kg N ha^{-1} treatment. Our findings agreed with many other studies, in Castilla-La Mancha (Spain) De Juan Valero et al. (2005), calculated N losses for maize under optimized irrigation treatments, ranging between 43 to 165 kg N ha^{-1}. Isidoro et al. (2006), in the irrigated maize area of Ebro valley estimated an N lost up to 68 kg N ha^{-1} with 150 kg N ha^{-1} treatment. Also in the Ebro Valley, Isla et al. (2006), reported that in a liximeter study, that the N lost by lixiviation varied depending on the year, and reported values between 10 kg N ha^{-1} the 0 N fertilization, to 150 kg N ha^{-1} kg/ha for the N fertilization with 300 kg N ha^{-1}. In a different growing conditions, in an area of Illinois mainly cultivated with maize and soybean David et al. (1997) calculated a yearly N losses from 59 to 117 kg ha^{-1}.

In our study, apparent N recovery varied from 0.40 to 0.77 kg kg^{-1}. These values agree with the values reported by other researchers (Legg et al., 1979; Meisinger et al., 1985; Fox & Piekielek, 1993; Staley & Perry, 1995; Berenguer et al., 2009) which varied from 0.34 to 0.76 kg kg^{-1}. A review of worldwide data on N use efficiency from re-search-managed experimental plots reported that fertilizer N recovery efficiencies averaged 0.65 kg kg^{-1} for maize (Ladha et al., 2005).

Our results showed that, the largest Agronomic N efficiency (ANE) (68.23 kg kg^{-1}) was recorded with N100. There was a decreasing pattern in (ANE) values with increasing fertilizer rates, indicating that maximum crop efficiency was attained with lower fertilizer applications. Our results are in agreement with another study conducted in our study area, Berenguer et al. (2009) who reported values of ANE ranged from 39 kg kg^{-1} for N300 to 55 kg kg^{-1} for N100. Results of this study also correspond with the findings of Bock (1984) and Simonis (1988) who reported a higher ANE for maize at low than at high N application.

3.5. Conclusions

Under our high yielding irrigated maize conditions (about 20 Mg ha^{-1} on average), grain yield, biomass, plant and grain N uptake and SPAD-units showed a significant response to N fertilization rates.

Maximum yield values (19.93 and 19.20 Mg ha^{-1} in 2013 and 2014, respectively) were achieved with N application rates of 198 and 192 kg N ha^{-1}, in 2013 and 2014, respectively.

Soil Nini and Nresi were influenced by rates of N fertilizer application and varied from year to year. Maize responses to N fertilization clearly depended on the initial soil NO_3^--N content. In our study, excellent yields (19.93 and 19.20 Mg ha^{-1}) were achieved with N fertilization rates close to 200 kg N ha^{-1} (198 and 192 kg N ha^{-1}, in 2013 and 2014, respectively) and with initially moderate soil NO_3^--N contents (68 kg N ha^{-1} in 2013 and 121 kg N ha^{-1} in 2014, at an average at depth 0 - 90 cm). Even so, plant and grain N uptake were highest in the most fertilized plots.

According to our results, N fertilization recommendations should not be based on fixed rates of N application. Testing initial soil NO_3^--N levels before applying N mineral fertilisation as a sidedress could help to achieve more accurate N fertilizer recommendations. Moreover, the annual optimal N application rate, of about 200 kg N ha^{-1}, gave almost the lowest soil NO_3^--N content after harvest and probably the lowest N losses; as a result, this could also be considered the most environmentally friendly N application rate.

For the climatic conditions of the Ebro Valley, with low summer and winter rainfall, soils with high NO_3^--N contents after harvest can supply part of the nitrogen needed by maize for the following year’s crop.

The minimum Nav values required to obtain maximum grain yields were 339 kg N ha^{-1} for Nav (0 - 90 cm) and 315 kg N ha^{-1} for (0 - 30 cm): these values were close to that of maize N uptake (338 kg ha^{-1}). As it seems able to predict maize N requirements, Nav could be considered a good tool on which to base N fertilization recommendations for Mediterranean conditions.

N lost was significantly affected by N rates and ranged from 44 Kg N ha^{-1} for the 100 kg N ha^{-1} treatment to 138 kg N ha^{-1} for the 400 kg N ha^{-1} treatment.

Apparent N recovery and agronomic N efficiency were significantly affected by N rates and ranged from 0.40, 33.87 kg kg^{-1} for N400 to 0.57, 68.23 kg kg^{-1} for N100, respectively.

3.6. References

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4. CHAPTER II. RESPONSE OF LEAF COLOR (SPAD READINGS) AND PLANT HEIGHT TO N FERTILIZATION RATES IN HIGH-YIELDING IRRIGATED MAIZE ENVIRONMENTS

Abstract

SPAD readings and plant height are parameters that represent aspects of plant status and response to N nutrition during the development of maize (*Zea mays* L.). This study was conducted to evaluate the response of maize SPAD units and plant height to different N fertilization rates (0, 100, 200, and 300 kg N ha^{-1}) in areas of high maize production and to assess the relationships between SPAD units and plant height and maize grain yield and biomass. Field experiments were performed over a continuous 5-year period (2010-2014) under sprinkler irrigation conditions. SPAD units significantly increased with N application rates of up to 190 kg N ha^{-1}. The highest SPAD-units were obtained with application rates of 125, 188, 181, 190 and 180 kg N ha^{-1} in the years 2010, 2011, 2012, 2013 and 2014, respectively. The linear correlation between SPAD-units at silking and the grain yield and between the SPAD-units and biomass was strongly positive (R^2 = 0.76 and 0.71 respectively) under our conditions. Plant height responded to the N rate treatments and varied from year to year. In general, maize yield and biomass at maturity were strongly related to plant height at silking (R^2 = 0.61 and 0.72, respectively). In conclusion, maize SPAD-units and plant height at silking can help to predict yield and biomass for maize under high-yielding irrigated, conditions.

4.1. Introduction

Chlorophyll content, which is one of the most important physiological parameters related to plant photosynthesis, is usually used to predict yield potential through comparisons with well-fertilized plants. Instruments for measuring chlorophyll content, such as the SPAD-502 device, offer a simple, inexpensive and rapid way to estimate the foliar chlorophyll content. A chlorophyll meter can also be useful for predicting crop production (Piekielek, and Fox. 1992; Le Bail et al., 2005).

SPAD meter readings have been found to be related to plant nutrition status (Piekielek, and Fox. 1992; Piekielek, et al. 1995; Arregui et al. 2006;Wu et al. 2007; Pagola et al. 2009), seed protein content (Poblaciones et al. 2009), types of nodulation (Gwata et al. 2004), and the photosynthetic rates of plant leaves (Ma et al. 1995).

The majority of leaf N is accumulated in the chloroplast, which is where photosynthesis takes place; this results in a strong association between plant photosynthesis and leaf N status (Evans, 1989). This association facilitates the modeling of plant growth and yield via leaf N assessment because the latter can be rapidly estimated using a SPAD chlorophyll meter. Several authors have reported a strong linear relationship between SPAD values and leaf nitrogen concentration, but this relationship varies with crop growth stage and variety (Takebe and Yoneyama, 1989; Turner and Jund, 1994), mainly as a result of leaf thickness and/or specific leaf weight (Peng et al., 1993). The linear relationship between leaf nitrogen and SPAD values has led to the SPAD meter being adapted to assess crop N status and to determine plant requirements for additional N fertilizer (Piekielek, and R.H. Fox. 1992; Peng et al., 1995 and 1996; Balasubramanian et al., 1999).

Even so, other authors have reported that the SPAD meter cannot be used to make accurate predictions concerning the N fertilizer requirements of a crop during a future growing season (Bullock and Anderson, 1998).

Significant correlations have been observed between chlorophyll content values obtained with a chlorophyll meter and whole plant N in maize (Bullock and Anderson, 1998). Several researchers have also reported significant coefficients of correlation between grain yield and N concentration in leaves and SPAD values recorded at critical physiological growth stages in rice, wheat and maize (Turner and Jund, 1991; Peng et al., 1993; Murdock et al., 1997; Yang et al., 2003; Shukla et al., 2004).

The SPAD-502 chlorophyll meter, which was developed in the early 1960's (Inada, 1963), provides a rapid and non-destructive estimation of leaf chlorophyll density. Its output is presented in arbitrary units and has been shown to be strongly related to leaf chlorophyll concentration and therefore photosynthetic capacity (Ma et al., 1995; Markwell et al., 1995).

Plant height provides a good measure of maize growth during vegetative development. It is affected by both crop and soil management factors and is a key parameter that describes plant growth status and its response to N nutrition during the vegetative development of maize (Yin et al., 2011 b).

As N fertilizer recommendations for maize are based on yield goals in many areas, more research is needed to assess the relationship between maize yield and plant height, in order to make plant height a reliable tool for predicting maize yield and thereby assessing the N fertilizer requirements(Yin et al., 2011 a).

Some authors have reported that plant height offer the most accessible method for predicting maize yield (Vyn and Raimbault, 1993; Moreno et al., 1997; Vetsch and Randall, 2004); however, assessments of the spatial variability of maize responses to N fertilization have yet to be adequately documented (Katsvairo et al., 2003; Yin et al., 2011 b).

The objectives of this study were:

- To evaluate the response of plant height and SPAD units in high yielding maize to different N fertilizer application rates.
- To study the relationship between SPAD values at silking and plant height and grain yield and biomass, in high-yielding irrigated maize environments.

4.2. Materials and methods

4.2.1 Field experiments

Field experiments were conducted in Almacelles (NE Spain, 41°43’ N, 0°26’ E) for five consecutive years (2010 – 2014). The main soil characteristics are presented in Table 4.1.

The experiment treatments consisted of applying N fertilizer at four different rates: 0, 100, 200, and 300 kg N ha^{-1}, henceforth referred to as: N0, N100, N200, and N300, respectively. The N fertilizer was applied as ammonium nitrate (34.5% N) in two side-dress doses, with 50% applied at V3 – V4 and 50% at V5 – V6 (Ritchie et al., 1989).

Maize was planted in the first week of April at a rate of 90,000-95,000 plants ha^{-1} with a space of 71 cm between rows in all five experiments. The maize hybrids used in the experiment belonged to the 700 FAO cycle. The hybrids used were: PR33P67 in 2010; PR32G49 in 2011 and 2012; P1758Y in 2013; and PR33Y72 in 2014.

Weed control was achieved through the application of pre-emergent herbicides and hand weeding, undertaken when necessary.

Table 4.1. Chemical and physical soil properties at the beginning of the study (2010).

Soil properties				
Depth, cm	0-22	23-45	46-110	>111
Sand (%)	42	43	17	17
Silt (%)	33	36	63	65
Clay (%)	25	21	20	18
pH	8.2	8.4	8.4	8.4
Organic matter (%)	3.30	-	-	-
Bulk density (g cm^{-3})	1.64	-	-	-
E.C., dS m^{-1}	0.19	0.17	0.22	0.22
P (Olsen), mg kg^{-1}	90	-	-	-
K (NH4Ac), mg kg^{-1}	383	-	-	-
Soil type†	Typic Calcixerept			
Precedent crop	maize			
Previous mineral N application	~300 kg N ha^{-1} yr^{-1}			

† Soil Survey Staff (2003)

The plots were sprinkler-irrigated two to three times per week, with the application of approximately 1000 mm of water per season.

The dimensions of the experimental plot were 8 m by 17 m. In the first year of the experiment, they were randomized in a complete block design, with three replications. The N treatments applied were randomized in the first year; thereafter, the N treatments were applied in the same plots, every year.

4.2.2 Plant measurements and analysis

SPAD-units were measured in maize close to silking using a hand-held Minolta SPAD-502. The SPAD readings were recorded at three points on each selected maize leaf in there points of the maize leaf, by inserting part of the leaf ear into the slit of the SPAD meter.

The readings were taken from maize ear leave from five randomly selected plants per plot and three measurements were performed on each leaf. The readings were then averaged to give one SPAD reading per plot. Wet leaves and widely spaced and unusually tall or short plants were excluded from the study.

Plant height was measured using a meterstick; this was done at silking and measured as the distance from the base of the plant to the base of the last leaf (cm): the leaf closest to the tassel. Plant height was calculated as the average height of seven plants from each plot.

Crop biomass was estimated at physiological maturity. This was done by hand cutting a 4 m plant sample from the central row of each plot (this was done to avoid border effects) and then chopping up three plants in order to determine their dry matter content. The maize was harvested in the last week of September and the grain yield was measured by harvesting two complete central rows (1.42 by 8 m) with a small plot combine. Grain moisture was determined from a 300-g sample taken from each plot using a Dickey-John® GAC grain analysis computer (GAC II, Dickey-John, Auburn, IL). The grain weight was adjusted to 14% moisture and scaled to express the yield in Mg ha^{-1}.

4.2.3 Statistical Analysis

The statistical analyses were performed using the SAS statistical package (SAS Institute, 1999–2001). The effects of the N fertilization rate on maize plant height and SPAD-units was statistically analyzed as a split-plot in time using the PROC MIXED procedure of SAS (Littell et al., 2006). Year and N rate were considered fixed variables, while replication was considered a random effect.

A bilinear model (linear-plus-plateau) was used to describe the effects of N fertilization on maize SPAD-units at silking. The model was fitted using both SAS NLIN (Ihnen and Goodnight, 1985) and GLM procedures (Spector, et al., 1985).

A linear model was also used to describe the effects of N fertilization on maize plant height at silking and the relationship between: SPAD-units and grain yield; SPAD-units and biomass; plant height and grain yield; and plant height and biomass.

Yin et al. (2011a), suggested that several different mathematical models could be used to describe the relationship between maize yield and plant height under different cropping systems and weather conditions, but of these, the linear model may be preferable because of its simplicity.

4.3. Results

4.3.1 SPAD-units

Average SPAD-units at silking were significantly affected by the N application rate and varied from year to year; even so, the year × N fertilization effect factor did not have a significant influence on the SPAD-units (Table 4.2, Fig. 4.1).

The highest SPAD-units (56, 58, 61, 58 and 59) were achieved with application rates of 125, 188, 181, 190 and 180 kg N ha^{-1} in 2010, 2011, 2012, 2013 and 2014, respectively (Fig. 4.1).

Analyzing the data for the whole five-year period (2010 -2014), the highest SPAD-units (58) was achieved with the application rate of 173 kg N ha^{-1} (Fig. 4.1).

The average number of SPAD-units at silking followed a similar trend to the average grain yield in all five years of the study (Fig. 4.2).

The linear correlation between SPAD measurements and grain yield was strongly positive (R^2 = 0.76) (Fig. 4.3). Biomass was also significantly correlated with SPAD readings (R^2 = 0.71) (Fig. 4.4).

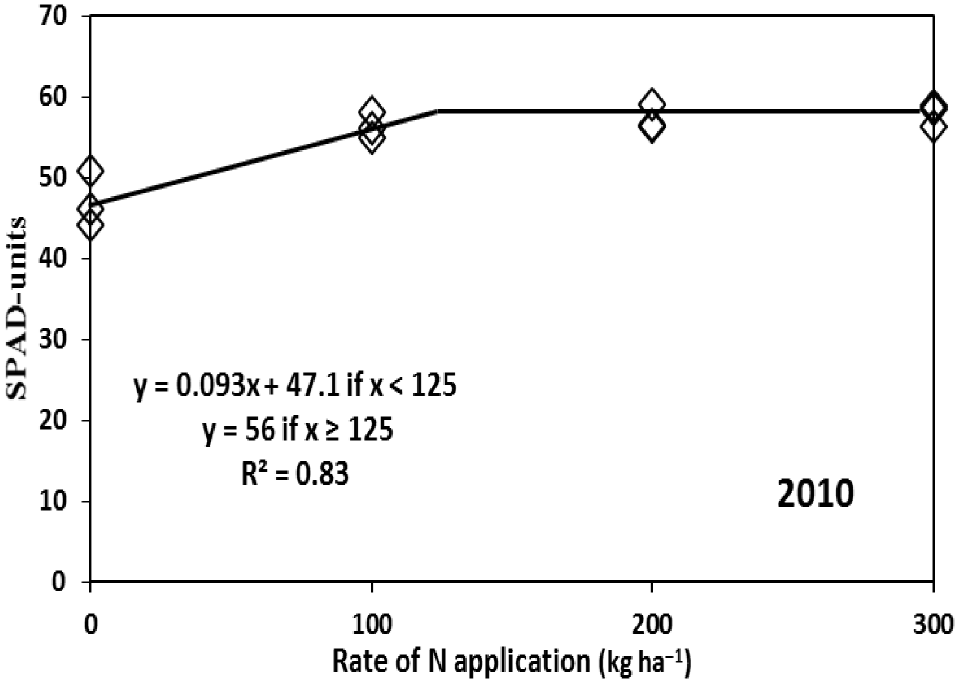
Table 4.2. Effect of N fertilization rates on chlorophyll meter values and plant height (cm) for the whole study period (2010 – 2014).

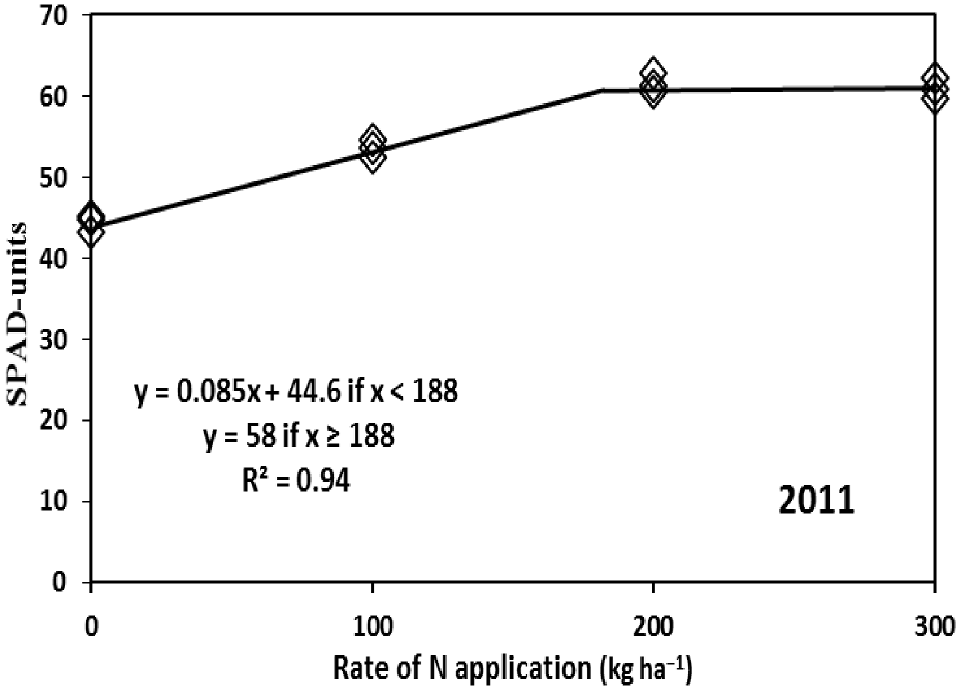
N rate (kgha^{-1})	SPAD-units	Plant height (cm)
0	45	239
100	55	259
200	60	265
300	60	270
	ANOVA	
Block	ns	ns
N rate (N)	**	**
Error a	–	–
Year (Y)	**	**
N×Y	ns	*
Error b	–	–

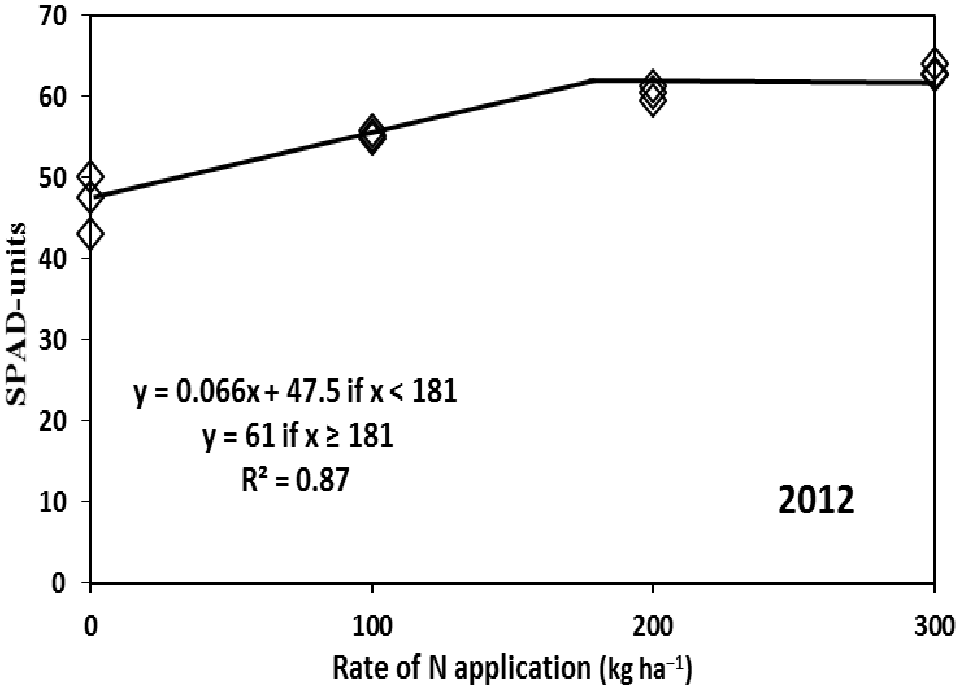
* Significant at the 0.05 level.

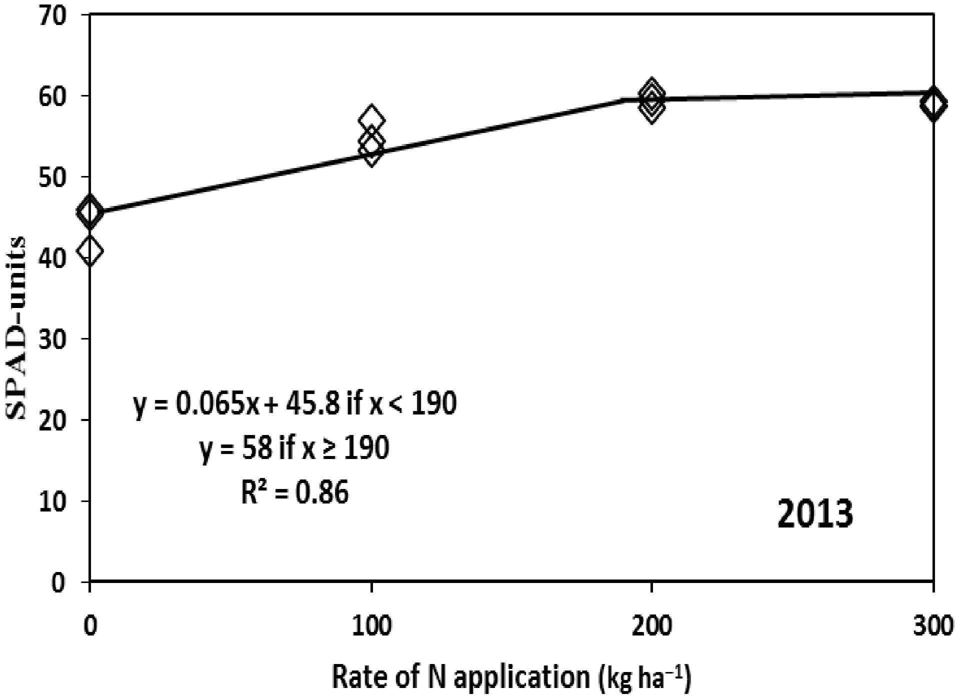
** Significant at the 0.01 level.

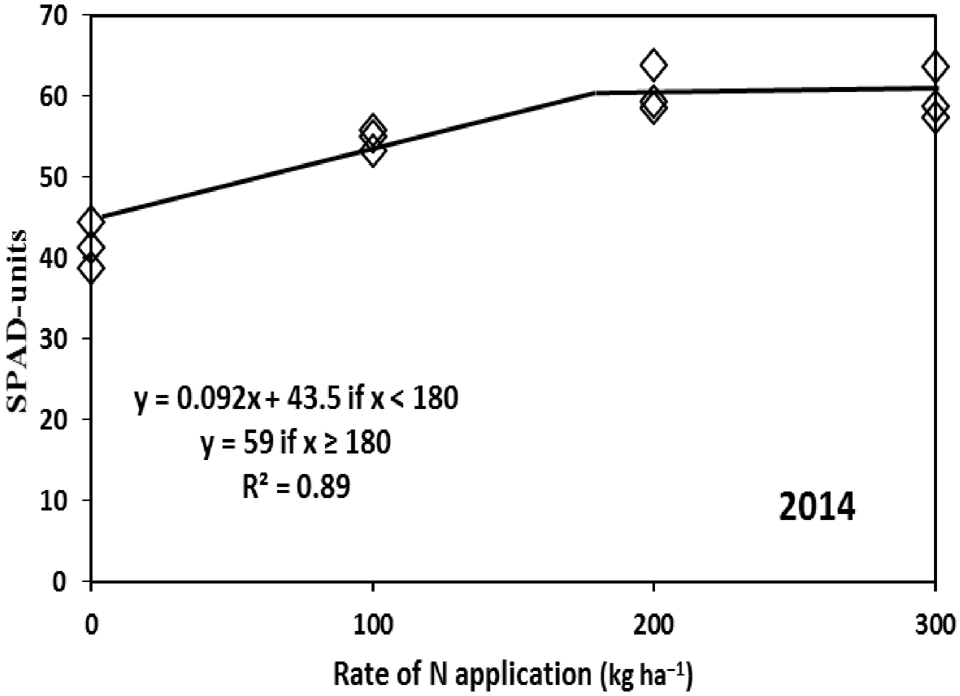
ns, not significant


70
60
50
40
30
20
10
0
SPAD-units
0
100
200
300
Rate of N application (kg ha⁻¹)
y = 0.093x + 47.1 if x < 125
y = 56 if x ≥ 125
R² = 0.83
2010


70
60
50
40
30
20
10
0
SPAD-units
0
100
200
300
Rate of N application (kg ha⁻¹)
y = 0.085x + 44.6 if x < 188
y = 58 if x ≥ 188
R² = 0.94
2011


70
60
50
40
30
20
10
0
SPAD-units
0
100
200
300
Rate of N application (kg ha⁻¹)
y = 0.066x + 47.5 if x < 181
y = 61 if x ≥ 181
R² = 0.87
2012


70
60
50
40
30
20
10
0
SPAD-units
0
100
200
300
Rate of N application (kg ha⁻¹)
y = 0.065x + 45.8 if x < 190
y = 58 if x ≥ 190
R² = 0.86
2013



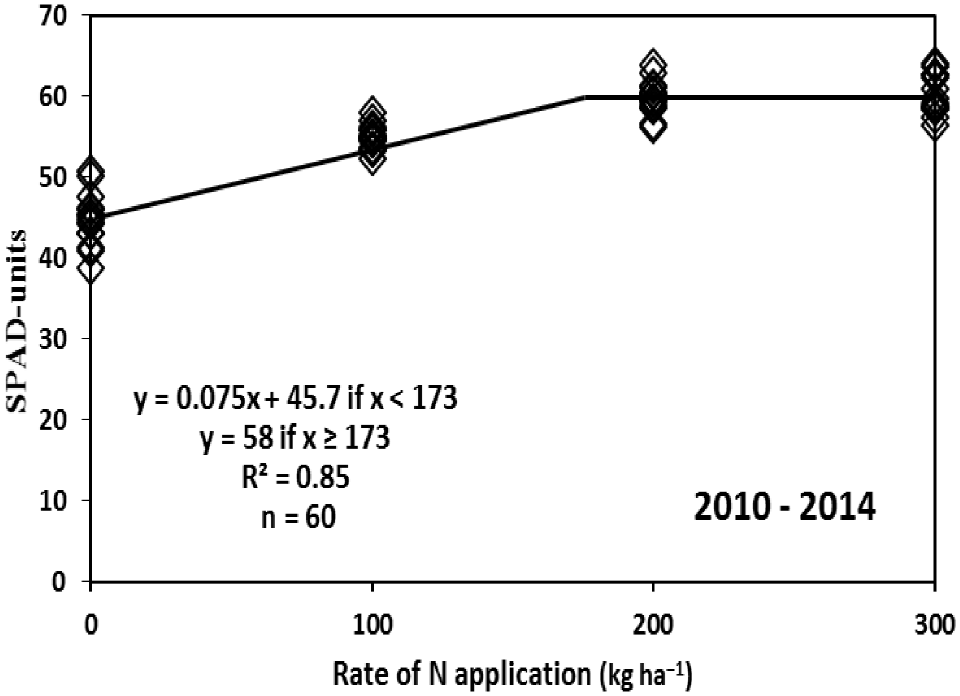


Figure 4.1. Effects of N fertilization on maize SPAD-units at silking (2010 – 2014).

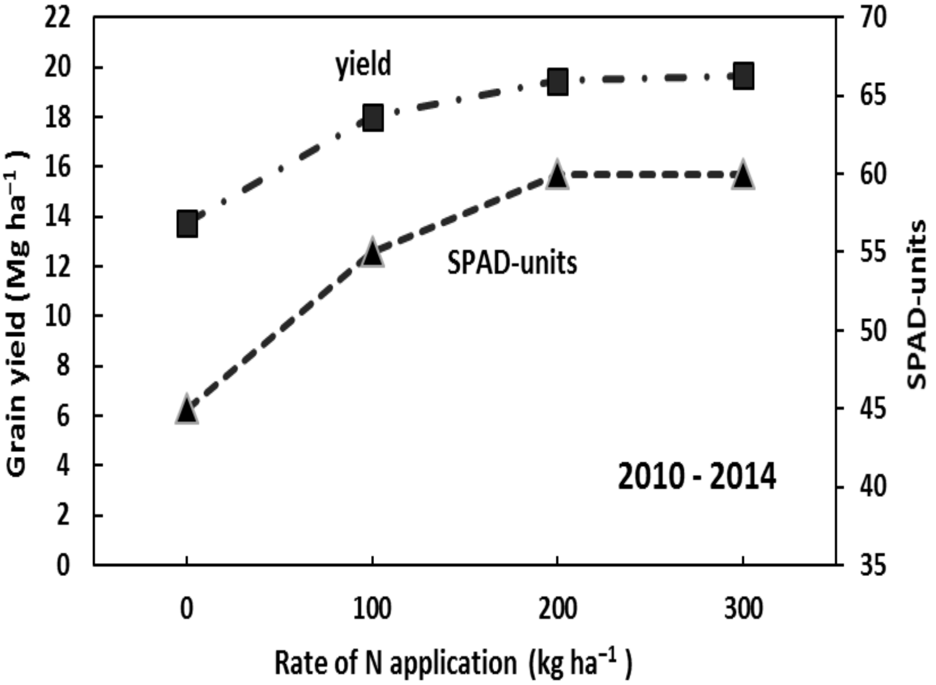


Figure 4.2. Effects of N fertilization on maize yield and SPAD-units at silking: average values for the 2010 – 2014 period.

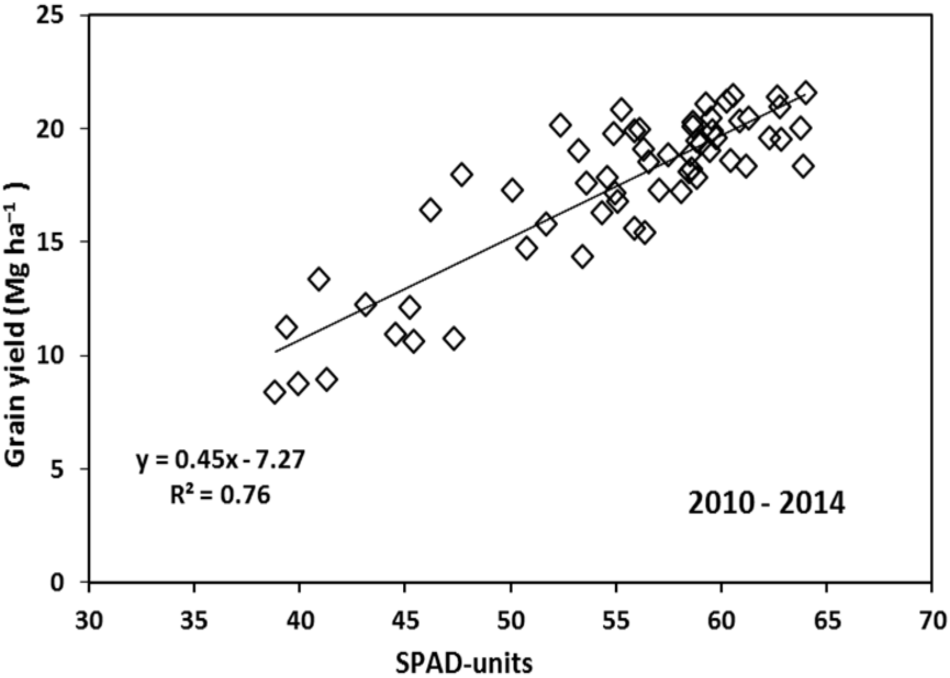


Figure 4.3. Relationship between grain yield and SPAD-units at silking (2010 – 2014).

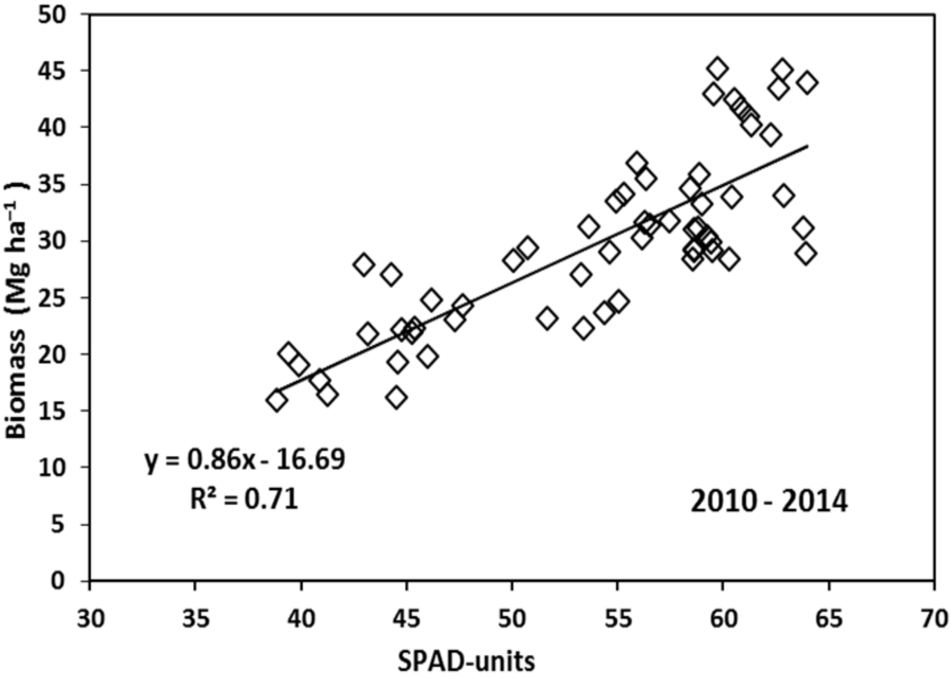


Figure 4.4. Relationship between biomass and SPAD-units at silking (2010 – 2014).

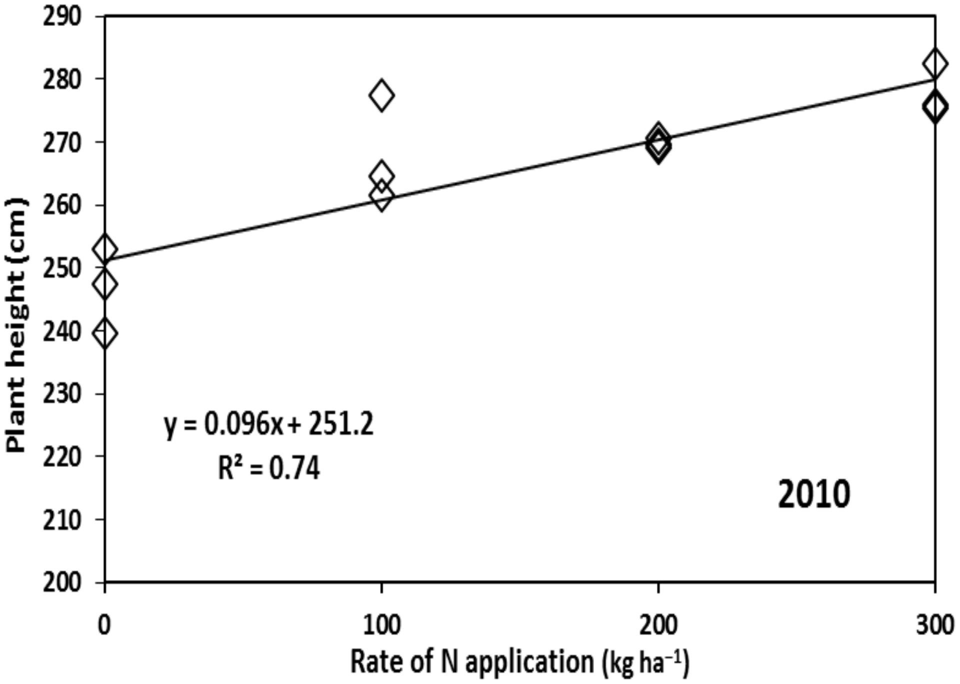
4.3.2 Plant height

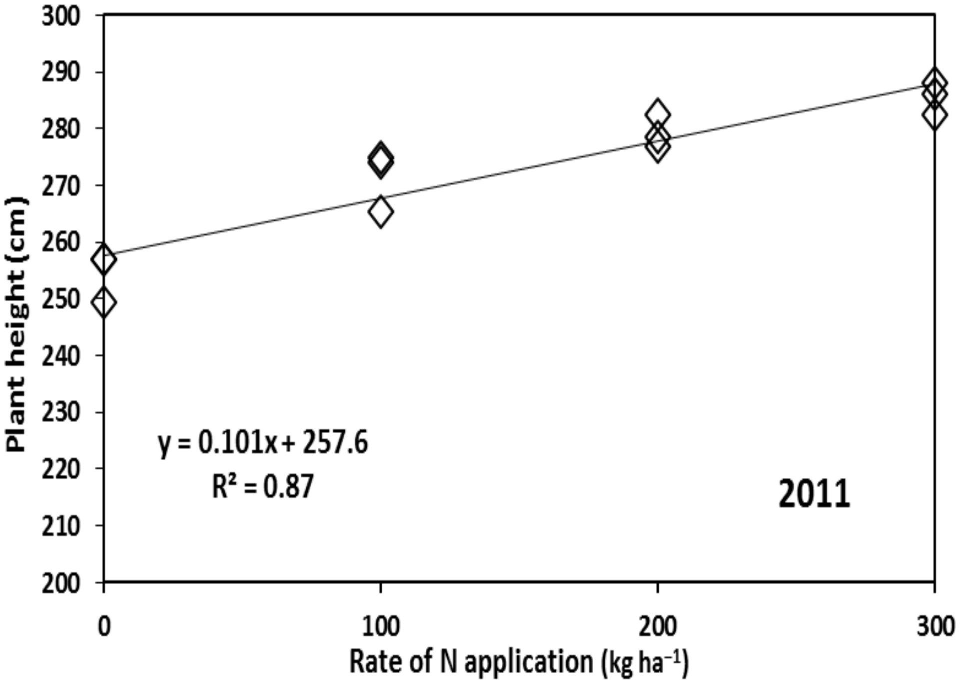
Plant height showed a significant response to the N rates applied in the different treatments and varied from year to year (Table 4.2, Fig. 4.5).

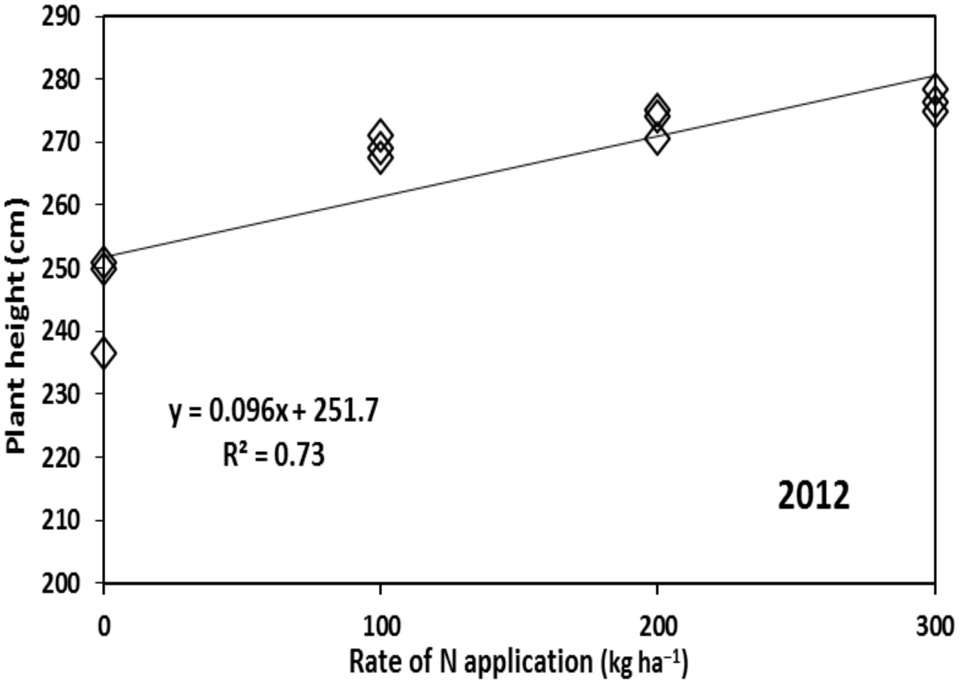
The average maize plant heights ranged from 247, 254, 246, 226 and 224 cm for the 0 kg N ha^{-1} application rate to 278, 285, 277, 266 and 245 cm for the 300 kg N ha^{-1}, for the years 2010, 2011, 2012, 2013 and 2014, respectively (Table 4.2).

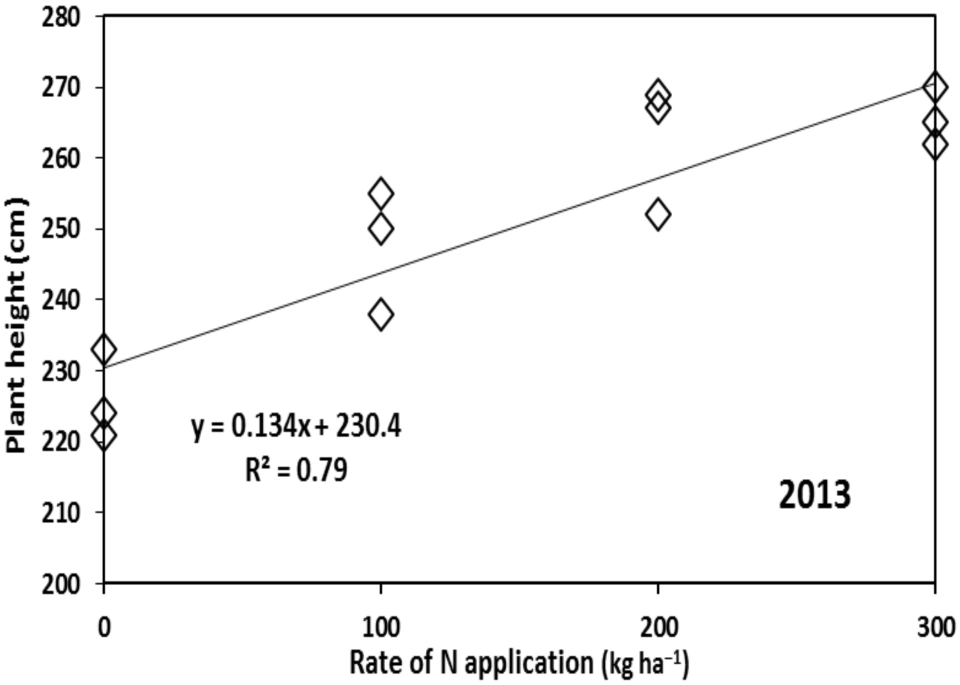
Increasing the rate of nitrogen application from 0 to 300 kg N ha^{-1} resulted in increases in plant height by 31, 31, 31, 40 and 21 cm, in the years 2010, 2011, 2012, 2013 and 2014, respectively.

The relationship between grain yield and biomass and plant height measured at silking was significant and positive under a linear model (R^2 = 0.61 for grain yield and 0.72 for biomass) (Figs. 4.6 and 4.7).


290
280
270
260
250
240
230
220
210
200
Plant height (cm)
y = 0.096x + 251.2
R² = 0.74
2010
0
100
200
300
Rate of N application (kg ha⁻¹)


300
290
280
270
260
250
240
230
220
210
200
Plant height (cm)
y = 0.101x + 257.6
R² = 0.87
2011
0
100
200
300
Rate of N application (kg ha⁻¹)


290
280
270
260
250
240
230
220
210
200
Plant height (cm)
0
100
200
300
Rate of N application (kg ha^{-1})
y = 0.096x + 251.7
R² = 0.73
2012


280
270
260
250
240
230
220
210
200
Plant height (cm)
0
100
200
300
Rate of N application (kg ha^{-1})
y = 0.134x + 230.4
R² = 0.79
2013

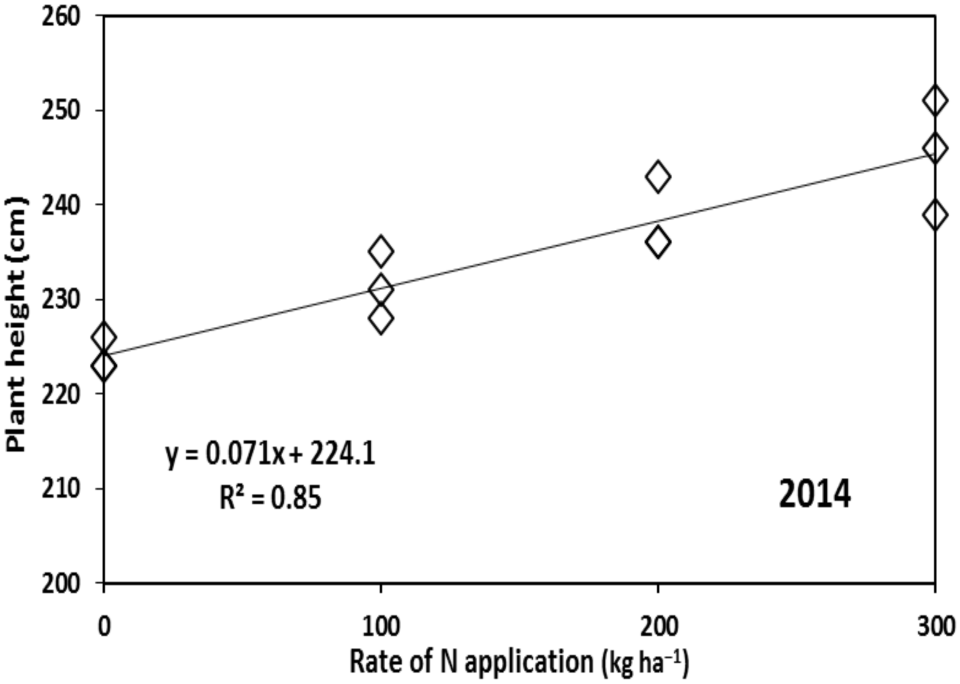


Figure 4.5. Effects of N fertilization on maize plant height at silking, based on five years of continuous maize production (2010–2014).

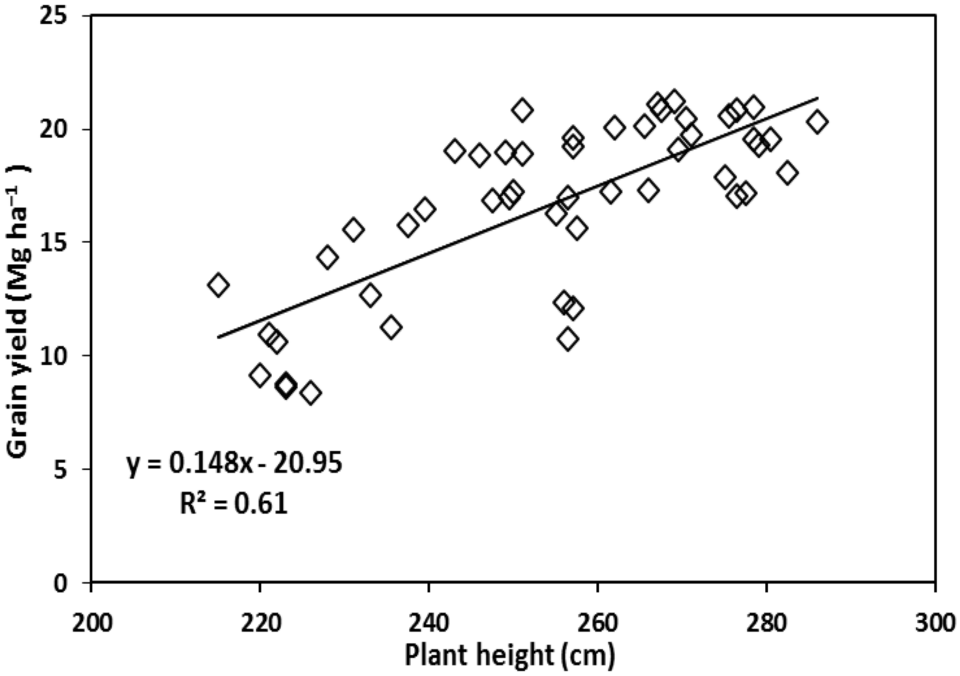


Figure 4.6. Relationship between grain yield and plant height at silking. Five years of continuous maize production (2010–2014).

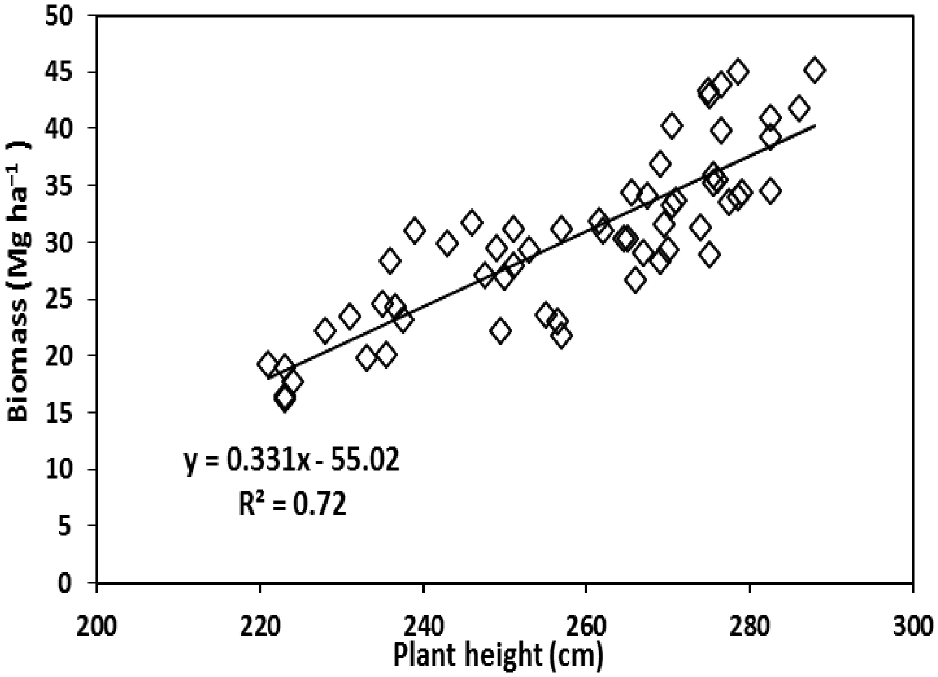


Figure 4.7. Relationship of biomass and plant height at silking, based on five years of continuous maize production (2010 – 2014).

4.4. Discussion

SPAD readings varied from year to year. In this respect, our results coincided with those of Waskom et al. (1996) who reported that the variability of the SPAD readings across different environments was also related to factors such as the hybrids used.

Numerous researchers have correlated SPAD values with maize N status (Varvel et al., 1997; Bullock and Anderson, 1998; Vetsch and Randall, 2004; Ma et al., 2005; Ma et al., 2007; Liu and Wiatrak, 2011). In our study, the SPAD readings at the silking stage significantly increased (up to 61) with increasing N application rates, up to 190 kg N ha^{-1}. In this respect, our findings agreed with many other studies that have shown good relationships between SPAD readings and grain yield (Fig. 4.3) (Waskom et al., 1996;

Fox et al., 2001; Boomsma et al., 2009). This suggests that the chlorophyll (SPAD) content at the silking stage may be a good predictor for estimating plant N status for N application rates of below 190 kg N ha^{-1}.

In our results, N application rates of above 190 kg N ha^{-1} maintained the SPAD-unit levels, but reduced the predicting ability of SPAD for plant N status. This was due to the fact that not all the N is converted into chlorophyll when N availability is high (Varvel et al., 1997). Several authors (Schepers et al., 1992; Dwyer et al., 1995) have reported that excessive applications of nitrogen did not increase chlorophyll meter values.

In our study, the critical level beyond which maize could be considered non-responsive to further N application was, on average, 58 SPAD-units; this is slightly higher than the values recommended by Piekielek et al. (1995) (52–56 SPAD-units). This may have been due to the high productivity of our hybrids (up to 20 Mg ha^{-1}) and the high N application rates used in the current study (up to 300 kg ha^{-1})**.** Nevertheless, in another study conducted in our study area, Berenguer et al. (2009) reported non-responsive reactions to N application SPAD values ranging from 52 to 61. In another chapter (Chapter I) in this document, we reported that when applying N to maize at up to 400 kg ha^{-1} the non-response SPAD values ranged from 58 to 59 units; these values coincide with those reported in this chapter.

Maize yield and biomass were strongly correlated with SPAD-units at silking ($R^2 = 0.76$ and 0.71 respectively) (Figures 4.3, 4.4). Similar linear relationships between chlorophyll meter readings and grain yields were observed in maize experiments conducted in the USA, with yields of up to 12 Mg ha^{-1} being obtained with a wide range of N fertilization application rates (Zhang et al., 2008). These significant linear relationships indicate that chlorophyll (SPAD) content offers quite good potential for predicting maize grain yield and biomass.

Piekielek and Fox, (1992) reported that chlorophyll meter readings at the V6 growth stage of maize could also be used to predict yield response to fertilizer N applied as sidedress, while Wood et al. (1992) found that chlorophyll meter readings at the V10 growth stage generally correlated with maize yields. We measured SPAD units at silking and we could not exactly compare our results with theirs. Even so, quite similar findings were reported by other authors. Vetsch and Randall (2004) reported that chlorophyll content (SPAD-units) began to show a close relationship with maize grain yield from the V6 growth stage ($R^2 > 0.77$). Blackmer et al. (1993) observed a better relationship ($R^2 = 0.81$) between SPAD meter readings and maize yield in the later growth stages.

In wheat, Girma et al. (2006) reported that chlorophyll content was a good predictor of final grain yield, whereas Ma et al. (1996) also observed that SPAD measurements were closely correlated with irrigated maize grain yields in Canada.

Plant height at silking was significantly affected by the N application rate and varied from year to year. Plant height changed every year because of the different hybrids used and because of the different temperatures during plant growth. Even so, the plant heights were quite similar as all of the hybrids were obtained from the same seed company (Pioneer Hybrid). The differences between years may also have been related to the initial N soil fertility and to the weather condition; this was in line with Yin et al. (2012) who obtained similar results.

When we compared the plant height of the non-fertilized treatment with those associated with the 100, 200 and 300 kg N ha^{-1} N application rates, we found that in those that were fertilized, there were increases in plant height of 8.4, 10.9 and 13%, respectively (Table 4.2). These values are quite similar to the findings of Zhang et al. (2013), who reported that, under their conditions, applying 100 kg N ha^{-1} resulted in an increase in maize plant height of 11.5% compared to the non-fertilized control treatment.

The N0 treatment produced a significantly lower plant height than the other N application rates; the differences in plant height were mainly between the N0 and the (200 and 300 kg N ha^{-1}) N treatments. Bocchi and Tano (1994) and Berenguer et al. (2008) reported similar results in their studies.

The linear correlations between plant height and grain yield and between plant height and biomass were significant and positive (R^2 = 61 for grain yield 0.72 for biomass) (Figs. 4.6 and 4.**7**). This good relationship is an indicator that plant height, in our irrigated areas, without any water or N restrictions, could probably be used to estimate the grain yield and biomass production of maize.

As maize yield normally increases with plant biomass, and as plant biomass is positively related to plant height, it can be assumed that when working with the hybrids used in our study, maize yield should increase as plant height increases, within a certain range of plant height (Yin et al., 2011 a).

Investigations into the relationship between maize yield and plant height have so far been relatively limited (Katsvairo et al., 2003; Machado et al., 2002; Mallarino et al., 1999). These studies have largely focused on the linear correlation between maize yield and plant height and have shown that plant height is often spatially variable and tends to correlate with maize yield. Plant height was used by Katsvairo et al. (2003), Freeman et al. (2007), Yin et al. (2011a, b) and Martin et al. (2012) to estimate maize grain yield and biomass.

Machado et al. (2002) observed that plant height explained 61% of the variation in maize grain yields.

Katsvairo et al. (2003) [working with irrigated and non-irrigated maize in the USA] and Machado et al. (2002) [working with unirrigated maize in Texas (USA)] both reported that plant height correlated with maize yields, but this correlation varied with the location and year.

4.5. Conclusions

SPAD-units and plant height at silking were significantly affected by the N application rate, although they varied from year to year; this was possibly because of the different hybrids used.

Our results suggest that during the 5 years of continuous maize cultivation corresponding to our study, the minimum N application rates required to obtain maximum SPAD readings (56, 58, 61, 58 and 59) varied from year to year, but never exceeded 190 kg Nha^{-1}.

Maize grain yield and biomass significantly correlated with plant height (R^2 = 0.61 and 0.72 respectively) and chlorophyll (SPAD) content at the silking stage (R^2 = 0.76 and 0.71 respectively). This suggests that, at this stage, plant height and chlorophyll (SPAD) offer good potential for predicting maize grain yields and biomass under our high yielding irrigated conditions.

This relationship between yield and biomass involving SPAD values and the height of maize plants should be further evaluated under different soil conditions in order to make these reliable tools for predicting maize yields.

The prediction of maize yields based on SPAD and plant height may enable maize producers to estimate their maize grain yields at an earlier stage of crop development.

The response of SPAD-units and plant height to N application rates and their correlation with N application rates is a subject that still requires further research.

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5. CHAPTER III. EFFECTS OF STOVER MANAGEMENT AND ITS INTERACTION WITH NITROGEN FERTILIZATION ON IRRIGATED MAIZE PRODUCTION

Abstract

Maize (*Zea mays* L.) grown for grain returns large amounts of crop residues (stover) to the soil at harvest. A study of stover management and its interaction with N fertilization was conducted in Lleida (north-east Spain) under sprinkler irrigation over a period of five years (2010 - 2014). The objective of this study was to evaluate the effects of incorporating maize stover into the soil after harvest or removing it. The trial was run in areas with high maize yields for different N fertilization rates (0, 100, 200, and 300 kg N ha^{-1}), monitoring maize production, soil mineral nitrogen and soil organic carbon (SOC) levels. Stover management (incorporation or removal) did not affect maize production or soil mineral nitrogen levels, but the SOC level was significantly affected and increased from an average of 19.1 g C kg $^{-1}$ in 2010 to 20.3 in 2013 and 19.6 in 2014, when the stover was incorporated, but declined from 19.4 g C kg $^{-1}$ in 2010 to 16.9 in 2013 and 17.0 in 2014, when the stover was removed.

5.1. Introduction

Stover is the non-grain part of a maize plant which is left on the soil surface after the grain has been harvested; it consists of the stalks, husks, leaves, and cobs of maize plants (Wilhelm et al., 2004).

Maize for grain production returns large amounts of crop residue to the soil at harvest, with the “normal” harvest index being about 0.5 (Burgess et al. 2002). In the long term, maize stover retention is indispensable for achieving effective soil and water conservation (Lal, 2004). Crop residues are also an important source of nutrients and are known to improve the physical and biological properties of soils (Venkateswarlu and Hegde, 1992).

Maize stover is also a potential feedstock and biofuel and can be used in biomass production as an alternative to conventional fuels (Pacala and Socolow, 2004; Joshi et al., 2005; Service, 2007; Sassner et al., 2008). On the other hand, the collection and transportation of maize residues from the field normally involves the use of wheeled vehicles, which can increase soil compaction, surface runoff and soil erosion and may contribute to a reduction in dry matter production in subsequent years (Wilhelm et al., 2004; Lal et al., 2004).

Lal (2009) discourages the use of crop residues for energy production. He cites several reasons for returning crop residues to the land, including: (i) recycling plant nutrients, (ii) carbon sequestration, (iii) improving the physical properties of the soil, such as its structure and water retention and transmission potentials, (iv) promoting soil fauna, (v) improving water infiltration, (vi) controlling water runoff, (vii) conserving water in the root zone, and (viii) fostering more sustainable agronomic productivity.

The importance of maintaining and/or incorporating crop residues in the soil surface to control soil erosion and improve soil organic matter (SOM) dynamics has been widely recognized in different countries and cropping systems (Mann et al., 2002; Oelbermann et al. 2004; Johnson et al., 2006; Wilhelm et al., 2007). SOM is important to soil quality, productivity and sustainability, as it provides and stores nutrients for plants, retains air and water, reduces soil erosion, and controls the movement of pesticides (Gregorich et al. 1994; He et al. 2008).

The removal of crop residues from the fields is known to hasten soil organic carbon (SOC) decline, especially when coupled with conventional tillage (Yang and Wander 1999; Mann et al. 2002; Biau et al, 2013). Inorganic N fertilizer can also enhance the efficiency of the use of microbial C (Kirkby et al., 2013). In contrast, N fertilizer can increase C mineralization (Salinas-Garcia et al., 1997) and reduce aggregate-protected C by increasing the aggregate turnover rate (Fonte et al., 2009; Chivenge et al., 2011; Plaza et al., 2013). Soil organic carbon is also considered a key component in removing CO_2 from the atmosphere (Carbon sequestration) and helping to reduce greenhouse gas emissions and thereby mitigating global climate change (Christopher et al., 2009).

Nitrogen is one of the main nutrients recycled through the incorporation of crop residues. However, most of the N found in crop residues is present in its organic form and is not directly available for plant growth. During decomposition, this organically bound N is gradually made available for crop or microbial growth through N mineralization (Lupwayi et al., 2006; Van Den Bossche et al., 2009). The C:N ratio of maize residues is rather high and would therefore be expected to result in N immobilization at some point in the decomposition process (Barraco et al., 2007; Burgess et al., 2002). For this reason, some kind of interaction between stover management and N fertilization would be expected.

The objective of this study was to evaluate the effects of applying two different maize stover management practices (incorporation and removal) in combination with several different N fertilization rates (0, 100, 200, and 300 kg N ha^{-1}) on: maize production (grain yield, biomass at maturity, grain and plant N uptake), soil mineral nitrogen, and soil organic carbon (SOC), under conventional tillage practices.

5.2. Materials and methods

5.2.1 Field experiments

Field experiments were conducted in Almacelles (NE Spain, 41°43’ N, 0°26’ E) over five consecutive years (2010 – 2014). The main soil characteristics of the field (soil texture, pH, electrical conductivity (EC), bulk density, P and K content and the percentage of organic matter) are presented in Table 5.1.

The location is characterized by a semiarid climate with low precipitation (192 mm) and high temperatures (19.1°C) during the growing period of maize (Fig. 5.1).

Experimental treatments consisted of maize stover management and four N fertilization rates. The stover management practices were:

1- Stover removal from the field after each year’s maize harvest, using commercial machinery.

2- Stover incorporation through conventional tillage (by disk plowing) to a depth of 25 to 30 cm.

The amount of maize stover incorporated into the soil was calculated as whole plant aboveground biomass minus grain biomass.

It should be noted that at the end of the 2013 season, the stover was incorporated in all plots, including those from which it should have been removed, due to a misunderstanding with the farmer.

Table 5.1. Chemical and physical soil properties at the beginning of the study (2010).

Soil properties				
Depth, cm	0-22	23-45	46-110	>111
Sand (%)	42	43	17	17
Silt (%)	33	36	63	65
Clay (%)	25	21	20	18
pH	8.2	8.4	8.4	8.4
Organic matter (%)	3.30	-	-	-
Bulk density (g cm^{-3})	1.64	-	-	-
E.C., dS m$^{–1}$	0.19	0.17	0.22	0.22
P (Olsen), mg kg$^{–1}$	90	-	-	-
K (NH4Ac), mg kg$^{–1}$	383	-	-	-
Soil type†	Typic Calcixerept			
Precedent crop	maize			
Previous mineral N	~300 kg N ha$^{–1}$ yr$^{–1}$			

† Soil Survey Staff (2003).

The different stover management treatments were combined with four N fertilization rates: 0, 100, 200, and 300 kg N ha$^{–1}$, henceforth referred to as: N0, N100, N200, and N300, respectively. The N fertilizer was applied as ammonium nitrate (34.5% N) in two side-dressing applications 50% at V3–V4 and 50% at V5–V6 (Ritchie et al., 1989).

Maize was planted in the first week of April at a rate of 85,000 to 95,000 plants ha$^{–1}$ with 71 cm between rows. The maize hybrids used in the experiment were of the 700 FAO cycle. The hybrids planted were PR33P67 in 2010, PR32G49 in 2011 and 2012, P1758Y in 2013 and PR33Y72 in 2014.

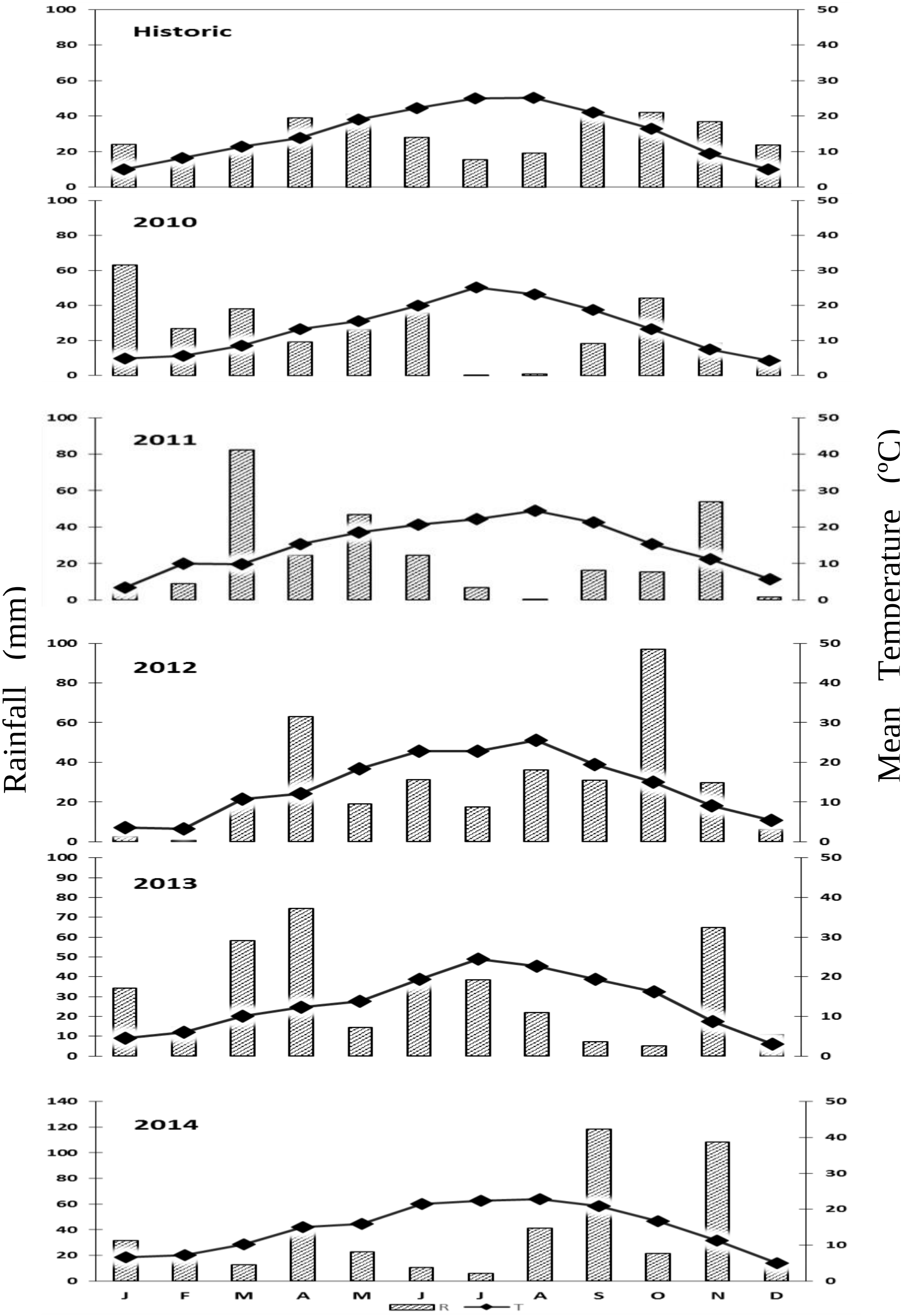

Figure 5.1. Monthly precipitation and mean temperature for the historic period (1989 – 2014) and for the experimental period (2010 – 2014).

The plots were sprinkler-irrigated two to three times per week, with approximately 1000 mm of water per season. The experimental design was a randomized split-plot, with three replications. The treatments were randomized in the first year and the same treatments were applied to the same plots thereafter. The stover management practices were the main plots and the N fertilization rates the subplots. The experimental plot dimensions were 8 by 17 m.

5.2.2 Analysis of plant and soil samples

The crop aboveground biomass was estimated at physiological maturity by hand cutting 4 m from a central row of each plot (to avoid border effects) and then chopping three plants into pieces in order to determine their dry matter and N contents. Aboveground plant N content was determined by near infrared spectroscopy (NIRS) (InfraAlyzer 2000 spectrometer, Bran+Luebbe, Norderstedt, Germany). Total N uptake was calculated by multiplying the N content by the biomass at physiological maturity.

Maize for grain was harvested in the last week of September and grain yield was measured by harvesting two complete central rows (1.42 by 8 m). Grain moisture was determined from a 300 g sample taken from each plot using a Dickey-John® GAC grain analysis (GAC II, Dickey-John, Auburn, IL). The grain weight was adjusted to 14% moisture and scaled to Mg ha^{-1} yield. The grain N content was measured by NIRS, as above.

Soil nitrate content (NO_3^-–N) was determined before planting (initial NO_3^-–N) and after harvesting (residual NO_3^-–N). Five soil samples were taken from each plot (0 – 30 cm depth) and three samples per plot were taken from depths of 30 cm to 90 cm, at 30 cm intervals. The nitrate was extracted in deionized water and measured using Nitrachek (KPG Products Ltd., Hove, East Sussex, UK) test strips (Bischoff et al., 1996) calibrated according to the standard procedure (Bremner, 1965).

The SOC in the top layer of the soil (0 – 30 cm) was determined by measuring organic C using the dichromate oxidation procedure in which residual dichromate is titrated against ferrous sulfate (Walkley and Black, 1934).

5.2.3 Statistical Analysis

The statistical analysis was performed using the SAS statistical package (SAS Institute, 1999 –2001).

All of the parameters studied were statistically analyzed as a split-plot in time using the PROC MIXED procedure of SAS (Littell et al., 1998). In the mixed model, stover, N dose, and years were considered as fixed variables, while replication was considered a random effect. The different treatments were then compared using Tukey's mean separation procedure ($p < 0.05$).

5.3. Results

5.3.1 Grain yields and biomass

Grain yield was not significantly influenced by the stover management treatment in any of the five years of the study: the grain yields were similar whether the stover was removed or incorporated into the soil (Table 5.2 and 5.3, Fig. 5.2).

N fertilization significantly affected maize production. An increase in grain yield was observed when the N application rate increased from N0 to N300. For N0, the grain yields for 2010, 2011, 2012, 2013 and 2014 were 14.98, 12.06, 16.87, 12.23 and 8.72 Mg ha^{-1} respectively, whereas for the 300 N treatment, the corresponding grain yields were 17.94, 19.91, 21.6, 20.12 and 19.76 Mg ha^{-1}, respectively.

Table 5.2. Maize yield (14% moisture content), aboveground biomass (dry matter), grain and plant N content at maturity for the different stover management practices and N fertilizer application rates in 2010, 2011, 2012, 2013 and 2014†.

Stover management	N rate kg ha^{-1}	Yield Mg ha^{-1}					Biomass Mg ha^{-1}					Plant N uptake (kg ha^{-1})					Gain N uptake (kg ha^{-1})				
		2010	2011	2012	2013	2014	2010	2011	2012	2013	2014	2010	2011	2012	2013	2014	2010	2011	2012	2013	2014
Incorporated	0	13.9	11.0	16.1	12.2	8.81	26.1	21.5	26.7	19.6	18.1	251	178	254	165	188	134	90	148	113	85
	100	18.5	17.0	18.3	17.0	15.6	35.1	32.2	38.3	27.8	22.9	392	284	407	269	245	200	165	190	173	157
	200	18.9	20.0	20.5	19.3	19.8	31.0	37.8	37.1	28.9	27.8	360	366	418	314	297	210	203	190	218	190
	300	18.7	19.9	20.8	19.7	20.0	33.0	38.4	35.8	30.8	29.1	391	392	375	369	322	202	214	232	231	218
Mean		17.5	17.0	18.9	17.1	16.0	31.3	32.5	34.5	26.7	24.5	349	305	363	279	263	187	168	190	184	221
Removed	0	16.0	13.0	17.6	12.2	8.62	28.4	26.3	35.8	19.9	16.1	302	253	331	181	163	163	119	172	124	172
	100	18.1	18.5	20.1	17.5	15.5	37.2	31.5	42.7	25.7	23.4	403	307	438	239	170	199	188	199	182	86
	200	19.0	18.8	20.6	19.9	18.7	30.4	35.6	41.2	28.8	29.0	354	349	423	275	246	207	206	217	222	165
	300	17.1	19.8	21.3	20.4	19.4	35.7	42.1	41.4	30.2	31.3	412	435	439	316	325	187	221	224	242	199
Mean		17.5	17.5	19.9	17.5	15.6	32.9	33.9	40.3	26.2	25.0	368	336	408	253	338	189	183	203	192	216
Block		ns	ns	ns	ns	ns	ns	**	ns	ns	*	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
Stover (S)		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns
Error a		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
N rate (N)		**	**	**	**	**	**	**	ns	**	**	**	**	**	**	**	**	**	**	**	**
S×N		ns	ns	*	ns	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	*	ns	ns	ns	ns	ns

† stover was incorporated in all of the treatments before planting.

* Significant at the 0.05 level.

** Significant at the 0.01 level. ns - not significant.

Table 5.3. Maize grain yield (14% moisture content), aboveground biomass (dry matter), grain and plant N content at maturity for the different stover management practices and N fertilizer application rates. Average for the period 2010-2014.

Stover management	N rate kg ha⁻¹	Yield Mg ha⁻¹	Biomass Mg ha⁻¹	Plant N uptake (kg ha⁻¹)	Gain N uptake (kg ha⁻¹)
Incorporated	**0**	12.44	22.43	207	114
	100	17.34	30.81	319	177
	200	19.73	32.73	351	208
	300	19.94	33.58	370	223
Mean		**17.35**	**29.76**	**312**	**180**
Removed	**0**	13.74	25.33	252	133
	100	18.00	30.55	335	187
	200	19.44	33.31	345	210
	300	19.65	36.24	388	218
Mean		**17.70**	**31.35**	**330**	**187**
			ANOVA		
Block		ns	ns	ns	*
Stover (S)		ns	ns	ns	ns
Error a		–	–	–	–
Nrate (N)		**	*	ns	**
SxN		ns	ns	ns	ns
Error b		–	–	–	–
Year (Y)		**	**	**	*
Y × S		ns	ns	ns	ns
Y × N		**	ns	ns	**
Y × S × N		ns	ns	ns	ns

* Significant at the 0.05 level.

** Significant at the 0.01 level.

ns - not significant.

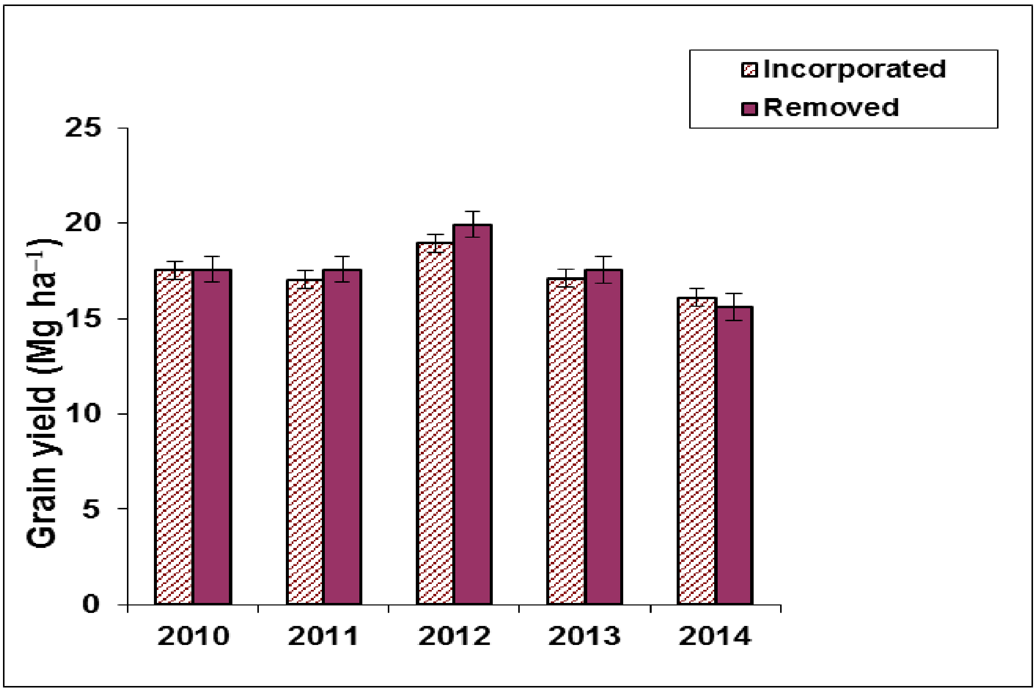

Figure 5.2. Effects of stover management on average grain yields for all of the treatments and years of study (2010 - 2014). No significant stover management effects were observed.

Stover management and different N fertilization rates had no significant influence on grain yields, except in 2012 (Table 5.2).

Stover management did not affect biomass yields at maturity in any of five years of the study (Tables 5.2 and 5.3). The average biomass yields over the five years of study were 29.76 Mg ha^{-1} when the stover was removed and 31.35 Mg ha^{-1} when the stover was incorporated (Table 5.3).

Increasing N fertilization rates significantly increased biomass, except in 2012. The average biomass yields were 27.29, 23.91, 19.77 and 17.16 Mg ha^{-1} for 0 kg N ha^{-1} and 34.36, 40.28, 30.53 and 30.25 Mg ha^{-1} for 300 kg N ha^{-1}, in 2010, 2011, 2013 and 2014 respectively.

There were no significant effects the interaction between stover management and N fertilization rates except for with biomass production in 2014 (Table 5.2).

5.3.2 Plant and grain N uptake

Nitrogen fertilization rates significantly affected plant N uptake in all of the years of the study (Table 5.2).

Only in 2013 did stover management have a significant influence on plant N uptake. The average plant N uptake in that year was 253 kg ha^{-1} when the stover was removed and 279 kg ha^{-1} when it was incorporated (Table 5.2).

Grain N uptake was significantly affected by N treatments but not by stover management or by the interaction between stover management and N fertilization rates (Table 5.2 and 5.3).

5.3.3 Soil mineral nitrogen content

At the beginning of the experiment, in 2010, the initial NO_3^-–N at a depth of 0 to 90 cm was 167 kg ha^{-1} (Table 5.4).

Soil N content before planting (Nini) and residual nitrogen after harvest (Nresi) varied from year to year and were both influenced by the N rates applied in previous seasons (Table 5.4).

Average Nini ranged from 157, 139, 139, 38 and 75 kg ha^{-1} for 0 kg N ha^{-1} to 162, 216, 273, 82 and 177 kg ha^{-1} for 300 kg N ha^{-1}, in 2010, 2011, 2012, 2013 and 2014, respectively. The average Nresi ranged from 105, 120, 80, 54 and 66 kg ha^{-1} for 0 kg N ha^{-1} to 300, 196, 229, 103 and 266 kg ha^{-1} for 300 kg N ha^{-1}, in 2010, 2011, 2012, 2013 and 2014, respectively. Incorporating or removing maize stover had no significant impact on either (Nini) or (Nresi) (Table 5.4).

Table 5.4. Soil mineral N (kg ha^{-1}) before planting and applied nitrogen fertilizer (Nini), and residual nitrogen after harvest (Nresi) (depth 0 – 90 cm) for 2010 -2014.

Stover management	**N rate kg ha^{-1}**	**2010**		**2011**		**2012**		**2013**		**2014**	
		Nini	**Nresi**	**Nini**	**Nresi**	**Nini**	**Nresi**	**Nini**	**Nresi**	**Nini**	**Nresi**
Incorporated	**0**	189	135	131	143	118	92	42	52	76	68
	100	150	83	121	80	177	75	49	51	84	115
	200	155	203	157	116	219	125	57	59	112	203
	300	159	225	194	237	309	281	94	76	216	256
Mean		**163**	**161**	**151**	**144**	**230**	**143**	**61**	**60**	**122**	**186**
Removed	**0**	126	76	148	97	160	69	34	56	75	65
	100	223	122	156	85	155	76	60	65	89	113
	200	175	176	219	116	152	103	68	60	84	161
	300	165	344	237	249	237	177	69	130	138	275
Mean		**172**	**179**	**190**	**137**	**176**	**106**	**58**	**78**	**96**	**154**

ANOVA

	2010-2013		**2010-2014**	
	Nini	**Nresi**	**Nini**	**Nresi**
Block	ns	ns	ns	ns
Stover (S)	ns	ns	ns	ns
Error a	–	–	–	–
Nrate (N)	*	**	**	**
SxN	ns	ns	ns	ns
Error b	–	–	–	–
Year (Y)	**	**	**	ns
Y × S	ns	ns	ns	ns
Y × N	ns	ns	ns	ns
Y × S × N	ns	ns	ns	ns

* Significant at the 0.05 level.

** Significant at the 0.01 level.

ns - not significant.

5.3.4 Soil Organic Carbon

SOC was significantly affected by stover management, year and the management x year interaction; it was not, however, significantly affected by the different N treatments (Table 5.5).

From 2010 to 2013, SOC levels increased from an average (for all the experimental plots) of 19.1 in 2010 to 20.3 g C kg $^{-1}$ in 2013. It was 19.6 g C kg $^{-1}$ in 2014, when the stover was incorporated. However, these values declined from 19.4 g C kg^{-1} in 2010 to 16.9 g C kg^{-1} in 2013 and 17.0 g C kg $^{-1}$ in 2014 when the stover was removed (remember that in 2013, the stover was incorporated in all of the plots) (Fig. 5.3, Table 5.5). A significant interaction was therefore observed (year × stover).

Two “Anova” are presented for SOC and for soil mineral N, in Tables 5.4 and 5.5. This has been done in order to provide added precision; in 2013, all the maize stover was incorporated and for this reason, the most correct Anova is that for the first four years (2010-2013) and not for 2010-2014. The two Anova were quite similar, except for soil mineral N, which exhibited a significant year effect for the period 2010 to 2013. However, when the same analysis was used for the period 2010 to 2014, no significant differences were observed.

Table 5.5. Soil organic C (g kg^{-1}) after harvest, following different stover management practices and N fertilizer application rates, in 2010, 2011, 2012, 2013 and 2014.

Stover management	**N rate kg N ha^{-1}**	**2010**	**2011**	**2012**	**2013**	**2014**
Incorporated	0	19.9	19.8	19.1	20.0	18.8
	100	19.4	19.7	17.9	19.4	18.9
	200	18.6	19.0	20.0	20.2	20.8
	300	18.4	17.9	19.5	21.4	19.8
Mean		**19.1**	**19.1**	**19.1**	**20.3**	**19.6**
Removed	0	18.9	17.3	17.0	16.3	16.1
	100	20.2	19.8	19.5	16.8	17.3
	200	19.9	18.5	18.4	17.3	17.4
	300	18.7	18.1	17.4	17.1	17.3
Mean		**19.4**	**18.4**	**18.1**	**16.9**	**17.0**

ANOVA

	2010 - 2013	**2010 - 2014**
Block	ns	*
Stover (S)	**	**
Error a	–	–
Nrate (N)	ns	ns
SxN	ns	ns
Error b	–	–
Year (Y)	**	**
Y × S	**	**
Y × N	ns	ns
Y × S × N	ns	ns

* Significant at the 0.05 level.

** Significant at the 0.01 level.

ns - not significant.

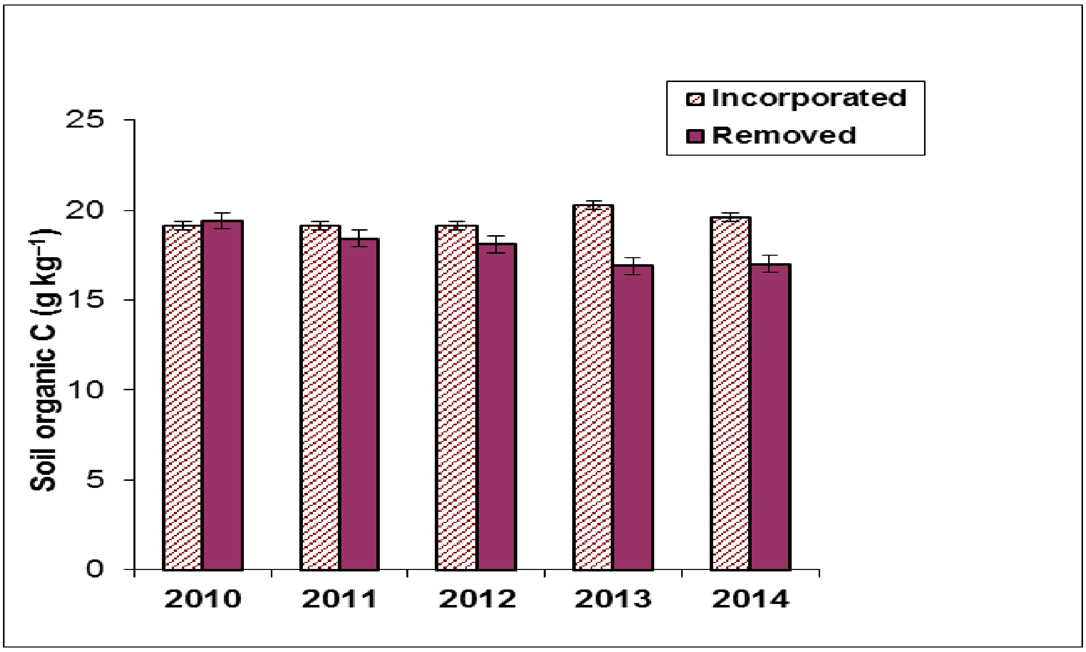

Figure 5.3. Effects of stover management on SOC contents for all the study years (2010 - 2014).

5.4. Discussion

Maize stover management did not significantly affect maize yields in our study. Several short-term and long-term studies had previously been conducted to assess the impact of residue management on crop yields (Morachan et al., 1972; Wilhelm et al., 1986; Karlen et al., 1994; Linden et al., 2000; Biau et al., 2013). Most of these studies had shown that incorporating maize stover into soils at rates of more than 16 Mg ha^{-1} yr^{-1} had no effect on maize yields. One possible reason for the lack of yield response to stover management could have been already high levels of SOC (Biau et al., 2013).

In our study, significant interactions between stover and N rates were only observed in 2012 and 2014, after 3 and 5 years of trials. These results from our study showed stover incorporation reducing grain yields at the lowest N rates; this could possibly have been due to N immobilization (Biau et al., 2013).

In our experiment, biomass production was high, with average yields of 31.29 Mg ha^{-1} when stover was incorporated and of 33.35 Mg ha^{-1} when it was removed; there were no significant differences between the two treatments, with a harvest index of about 0.55. As a result of the high grain yields obtained in our study, biomass production was also high.

In our trial, the average level of whole plant N uptake ranged from 173 to 292 kg ha^{-1} for 0 kg N ha^{-1} and from 324 to 414 kg ha^{-1} for 300 kg N ha^{-1} (Table 5.2). These N uptake levels, which were mainly associated with the N300 treatment, were high, but could be considered in line with previous studies conducted in similar areas (Daudén and Quílez, 2004; Berenguer et al., 2009; Biau et al., 2013).

NO_3^-–N levels before planting were affected by the fertilizer treatments applied in previous years (Table 4). After 5 years of fertilizer application, it was possible to observe a decline in residual soil NO_3^-–N levels, for the N0 treatment, with plot-associated levels falling from 189 and 126 kg N ha^{-1} to 68 and 65 kg N ha^{-1} when stover was respectively incorporated and removed. These results are in-line with previous reports of extensive N mineralization associated with the use of mineral fertilizers under the same climatic conditions (Villar-Mir et al., 2002; Biau et al., 2012).

When the stover was removed, the SOC content decreased over the experimental period, falling from an average value of 19.4 in 2010 to 16.9 in 2013 g C kg^{-1} and 17.0 g C kg^{-1} in 2014 (note that stover was mistakenly incorporated in 2013), representing a decrease of 12.4 %. In contrast, when the stover was incorporated, the SOC content increased very little or remained at or near its original level, with an average values of

19.1 in 2010, 20.3 g C kg $^{-1}$ in 2013 and 19.6 g C kg $^{-1}$ in 2014: a fall of 2.6 % (Table 5.5).

Several studies have also shown how stover removal over four years reduced grain and stover yields in subsequent (maize and soybean) crops (Wilhelm et al., 1986) and further reduced SOC levels (Clapp et al., 2000; Maskina et al., 1993). Others, however, have shown either no effect or even increases in subsequent maize grain yields (Karlen et al., 2011). However, in our study no changes in grain yields were observed when the stover was either removed or incorporated, although SOC levels fell by an average of 12.4 % over the study period when stover was removed. This could have possibly been due to the already high SOC levels in our experiment; as a result, removing the stover did not have much effect on soil quality.

Lal (2004) and Wilhelm et al.**,** (2004, 2007) concluded that returning a portion of the crop residue to the soil was crucial for replenishing SOC and that doing so was a fundamental requirement for sustainable soil and crop management; this was in line with our result.

Nitrogen fertilizer can increase the SOC level by increasing crop residue (organic matter) inputs to the soil or reduce the SOC level by increasing C mineralization (Russell et al., 2009). Although the net effect of inorganic N fertilization on SOC levels remains open to debate (Roberston et al., 2013), the application of inorganic N fertilizer typically has a positive effect on SOC when it is not applied far in excess of crop demand (Alvarez, 2005; Russell et al., 2009). In our study, the N fertilization rates did not affect the SOC content. On average, these ranged from 17.1 to 19.5 g C kg $^{-1}$ for 0 kg N ha^{-1} and from 17.7 to 19.4 g C kg $^{-1}$ for 300 kg N ha^{-1} when stover was respectively removed and incorporated.

Soil organic matter, which is a critical factor for soil crop production functions, either slowly increased, or did not increase, under our conditions, when stover was incorporated into the soil. However, SOC levels decreased quite rapidly (12.4%) within a period of only 5 years when stover was removed. Given this slow response and the variable nature of SOC measurements, time is required to measure the direction of changes in SOC levels in response to soil and crop management practices (Wilhelm et al., 2007).

5.5. Conclusions

Our study, which involved highly productive maize grain with yields of up to 20 Mg ha^{-1}, suggests that, in the short term (5 years), crop residue management (incorporated or removed) had no significant effect on either maize grain yield or biomass.

However, particularly when the stover was removed, stover management caused significant changes in SOC levels. In only five years, they increased or remained stable when stover was incorporated (increasing from 19.1 to 20.3 g C kg $^{-1}$ in 2013 and to 19.6 g C kg $^{-1}$ in 2014) and decreased quite rapidly (12.4%) when stover was removed (from 19.4 g C kg^{-1} in 2010 to 16.9 g C kg^{-1} in 2013 and to 17.0 g C kg $^{-1}$ in 2014).

No significant interactions were observed between stover management and N fertilization rates except for grain yield in 2012 and biomass in 2014.

The results of this study showed that the incorporation of maize residues is recommended for maintaining SOC levels in soils with high initial SOC levels. Even so, further long term research is needed to determine the influence of stover management on soil properties and crop yields.

5.6. References

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6. CHAPTER IV. EVALUATION OF DSSAT MAIZE MODELS: CSM-CERES AND CSM-IXIM FOR SIMULATING GRAIN YIELD, BIOMASS AND CROP N UPTAKE IN HIGH YIELDING CONDITIONS

Abstract

The DSSAT (Decision Support System for Agrotechnology Transfer) is the most widely used model package to characterize crops growth, development, yield, and N uptake. The objectives of this study were twofold: 1) to evaluate the performance of the maize (Zea mays L.) models CSM–CERES and CSM-IXIM available in DSSAT version 4.5, when simulating high yielding conditions, and 2) to test the IXIM model with an alternative approach to estimate crop N demand, based on Plénet and Lemaire (2000). The two models were evaluated with data collected from experimental field, in Almacelles, Spain during three consecutive years under various N management treatments, combining fertilization and residue handling. Fertilization treatments included two doses of mineral fertilizer: 300 kg N ha^{-1} (N300), along with a N-free fertilized control (N0). Crop residues were either removed (R) or incorporated (I). The grain yields obtained in the fields varied, depending on the N fertilization from 11 to 20 Mg ha^{-1}. In our high yielding irrigated maize conditions the CSM–CERES and CSM-IXIM models were able to simulate phenology, grain yield, and biomass accurately, while they were less efficient estimating crop N uptake. CSM-IXIM model was able to simulate the total aboveground biomass, and crop N uptake better than CSM–CERES. The IXIM model with the alternative approach to estimate crop N demand based on Plénet and Lemaire (2000), simulated grain yield and crop N uptake better than the IXIM with the current approach based on Jones (1983).

6.1. Introduction

Maize (*Zea mays* L.) is the most produced cereal in the world. Over the last five years, maize farmers have harvested over 852 million Mg of grain per year (FAO, 2014). Although world maize yields have been increasing up to more than 5 Mg ha^{-1}, the current population of 7.2 billion is expected to reach more than 9.5 billion by 2050. Therefore, a sustained effort to continue rising yields should provide the basis to maintain hunger reduction and assure food security worldwide (UN, 2013).

Dynamic crop models, such as those in the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 2010), can be used as a multipurpose tool for various applications, ranging from decision support for crop management at a farm level to advancing understanding of agricultural research (Hoogenboom, 2000; Jones et al., 2003).

Modularizing the model structure to facilitate information exchange among system components and model improvements led to the development of a uniform model structure within DSSAT, the Cropping System Model (CSM; Jones et al., 2003), which is now implemented for most crop models.

The CSM-CERES Maize model is one of the most popular and highly reliable maize model and has been evaluated in many sites across the world. The results indicated its capability to simulate the development of roots and shoots, growth and senescence of leaves and stems, biomass accumulation and partitioning between roots and shoots, leaf area index, root, stem, leaf, and grain growth under different climatic conditions (Jones and Kiniry 1986; Quiring and Legates 2008).

The model has been found to be able to accurately predict yield variability, N uptake and maize growth response to nitrogen (Pang et al. 1997; Bert et al. 2007) and to assess site-specific nitrogen management to maximize field level net return and minimize environmental impact by using spatially variable management practices (Paz et al. 1999; Batchelor et al. 2002; Link et al. 2006; Miao et al. 2006; Thorp et al. 2008). Though it has been widely used, the application of CERES-Maize model to solve problems in the real world depends on the availability of information that makes it both possible to run the model for particular scenarios and to specify the accuracy of the models for target regions (Hunt and Boote, 1998).

CERES-Maize has been widely used to investigate various aspects of maize growth, including leaf area calculation (Ben Nouna, et al., 2003), leaf expansion and senescence (Lizaso, et al., 2003a), leaf level canopy assimilation (Lizaso et al., 2005), light capture (Lizaso, et al., 2003b), kernel number (Ritchie, et al., 2003; Lizaso, et al., 2007), and silage (Braga et al., 2008).

CSM-IXIM is a new maize simulation model, based on CSM-CERES-Maize. Code from CERES-Maize version 4.5 was modified to include a number of improvements and new modules (Lizaso, et al., 2011). It incorporates improvements in the simulation of leaf area, C assimilation and partitioning, ear growth, kernel number, grain yield, and plant N acquisition and distribution. Both models are available in DSSAT v4.5.

In this study, we focus on the simulation of crop N dynamics by CERES and IXIM with two objectives: 1) Examine the ability of the models to capture growth, production, and N uptake in high-yielding environments; 2) Compare the current approach to estimate crop N demand, based on Jones (1983) which uses phenology as the driving variable, with an alternative approach based on Plénet and Lemaire (2000) using growth as the driving variable.

6.2. Materials and Methods

6.2.1 Field experiments

Data were collected from two experimental maize fields (Ap, Ac) in Almacelles, Lleida, (NE Spain, 41°43' N, 0°26' E, altitude: 286 m) during 2010, 2011 and 2012, (Biau et al., 2013). In both fields, the combination of residue management and N fertilizer was examined.

Plots were arranged in a randomized block split-plot design with 3 replications at both locations with population densities ranging within 84,000 to 90,000 seeds ha^{-1} depending on the year and field. The main plot was the harvested residue management with two levels: 1) Stover removal from the field (R) after maize harvest each year using commercial machinery and the rest of the residues were removed manually; 2) Stover incorporation (I) with conventional tillage (by disk plowing) to a depth of 25 to 30 cm.

The subplots were nitrogen fertilization consisting of 2 levels, 0, 300 kg N ha^{-1} from ammonium nitrate (34.5% N) in two side-dressing doses applied, 50% at V3–V4 and 50% at V5–V6 (Ritchie and Hanway, 1982).

The cultivars used were genetically modified hybrids of FAO 700 cycle. Hybrids included in the field Ac were PR33P67, PR33Y72 and Lerma, in 2010, 2011 and 2012, respectively. In the Ap field, hybrids were PR33P67 in 2010, and PR32G49 in 2011 and 2012. Both fields were irrigated by sprinkler irrigation systems. Irrigation amounts were recorded and used as inputs in the experimental simulation.

Crop aboveground biomass was estimated at physiological maturity by hand cutting 4 m from a central row of each plot (to avoid border effects) then chopping three plants in order to determine the dry matter and plant N content. Total plant N content was determined by near infrared spectroscopy (NIRS), using a previously-calibrated 500

Infrared Analyzer (Bran Luebbe, Norderstedt, Germany). Total N uptake was calculated by multiplying the N content by the biomass at physiological maturity.

Grain yield was measured by harvesting two complete central rows (1.42 m x 8 m). Grain moisture was determined in a 300 g sample from each plot (GAC II, Dickey-John, Auburn, IL) and the grain yield was adjusted to 14% moisture .The grain N content was measured by NIRS as above.

Soil nitrate content (NO_3^--N) was determined before planting (initial NO_3^--N) and after harvesting (residual NO_3^--N). Five soil samples were taken from each plot (0 – 30 cm depth) and three samples per plot were taken from 30 cm to 90 cm at 30 cm intervals. The nitrate was extracted in deionized water and measured using Nitrachek (KPG Products Ltd., Hove, East Sussex, UK) test strips (Bischoff et al., 1996) calibrated according to the standard procedure (Bremner, 1965).

Additional crop data collected included phenology (emergence, silking, and maturity dates) and leaf number. Further field information was previously reported by Biau et al. (2013).

6.2.2 Models description

CSM-CERES-Maize, from now on simply CERES, and CSM-IXIM, from now on IXIM, as distributed with DSSAT V4.5, were used in this work. CERES calculates daily growth rate using the PAR use efficiency (RUE) approach, estimating canopy leaf area and PAR interception (Jones and Kiniry, 1986). IXIM describes per-leaf light capture, instantaneous leaf CO_2 assimilation, and canopy respiration (Lizaso et al., 2011). Major differences in grain yield are associated to kernel number calculation. Both models assume kernel set is source limited. CERES estimates the average daily photosynthesis during the lag phase after silking, and calculates kernel number per plant as a capped linear function of such an average. IXIM calculates an average growth rate during a critical thermal time window around silking, and uses this average rate with a double-curve function to compute kernel number per ear (Lizaso, et al., 2011).

N uptake is simulated by both models contrasting potential soil N supply with crop N demand. Main differences are in the calculation of crop demand. To estimate crop N demand the models compare the daily concentration of N in plant tissues with a target concentration called critical N. Models assume that if the concentration of N is greater than the critical, it does not result in further growth. But if the concentration of N falls below the critical, then the crop experiences N deficit and growth is reduced accordingly.

Important differences between the two models are in the calculation of crop demand. CERES estimates shoot N demand from a modified Phenology-N critical relationship by Jones (1983):

$$Shoot\ N_C = EXP\ (1.52 - 0.16 \times Phen) \qquad (1)$$

where *Shoot* N_C is the target N concentration (%) in aboveground tissues and *Phen* is a relative (0-10) phenology scale (Fig. 6.1).

IXIM uses a similar approach but separating demands from leaf (Lindquist and Mortensen, 1999) and stem (Fig.6.1):

$$Leaf\ N_C = 5.06 \times EXP\ (-0.11 \times Phen) \qquad (2)$$

$$Stem\ N_C = 4.7 \times Phen^{-1.13} \qquad (3)$$

where *Leaf* N_C and *Stem* N_C are leaf and stem target N concentrations (%). *Stem* N_C is confined at a maximum of 4%. During the time period of ear growth, ear demand is computed as:

$$Ear\ N_C = (4.0 - 0.0086 \times TTEg) \qquad (4)$$

where $Ear\ N_C$ is ear target N concentration (%), and *TTEg* is thermal time since the beginning of ear growth. Grain N is remobilized from shoot tissues by both models during grain filling.

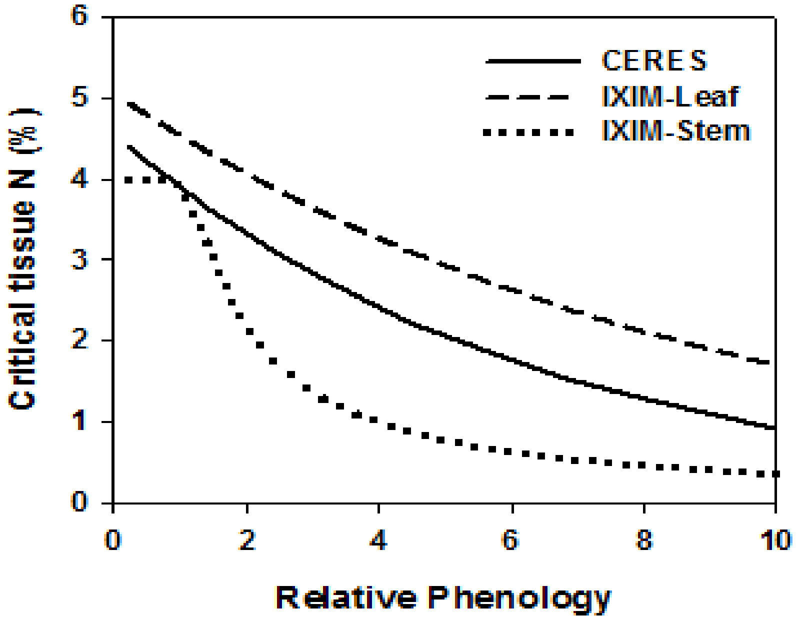


Figure 6.1. Critical tissue N concentration used by CERES (Eq. 1, shoot) and IXIM (Eq. 2, leaf, Eq. 3, stem) to estimate crop N demand. Both models distributed with DSSAT v4.5.

In our study we compare two approaches to calculate the critical N concentration (i.e. estimate crop N demand): the Jones (1983) approach based on phenology (Eq. 1 for CERES; Eqs. 2, 3, and 4 for IXIM), and the Plénet and Lemaire (2000) function, investigated for IXIM, based on biomass accumulation originally proposed as:

$$Shoot\ NC = 3.4 \times B^{-0.37} \qquad (5)$$

where B is aboveground biomass (Mg ha^{-1}). Since model calculations are on a per-plant basis, Eq. 5 was reworked using the population densities in Plénet and Lemaire (2000) study:

$$Shoot\ N_C = 8.29 \times b^{-0.37} \qquad (6)$$

where b is aboveground biomass in g plant^{-1}. Once taken-up, N is partitioned among plant organs. Target N concentrations for leaves ($Leaf\ N_C$) and stems ($Stem\ N_C$) were derived from data collected in Nebraska by Lindquist et al. (2005):

$$Leaf\ N_C = 8.35 \times b^{-0.23} \qquad (7)$$

$$Stem\ N_C = 18.56 \times b^{-0.54} \qquad (8)$$

Maximum concentrations for leaves and stems were set at 5% and 4% respectively (Lindquist and Mortensen, 1998; Lindquist et al., 2007). In addition, a target N concentration for ears ($Ear\ N_C$) was adapted from Plénet and Lemaire (2000) using ear biomass (be, g plant^{-1}):

$$Ear\ N_C = 4.2 \times be^{-0.25} \qquad (9)$$

Maximum N concentration in ears was set to 3.3% (Plénet and Lemaire, 2000). Fig. 6.2 shows the shape of Eqs. 7-9.

The IXIM model limits daily N uptake to account for the cost of N assimilation.

Maximum N uptake (XNU) is limited by a curvilinear function of the daily plant growth rate (PGR, g plant^{-1} d^{-1}):

$$XNU = Nx\ (1 - \exp(-0.8 \times PGR)) \qquad (10)$$

where Nx is the maximum rate of N uptake (0.06 g plant^{-1} d^{-1}) observed under unrestrictive growing conditions (Lizaso, et al., 2011).

Eq. 1 will be referred to as Jones – XNU, when added the constraint on maximum N uptake and Jones – woXNU otherwise.

Eq. 5 will be referred to as P&L – XNU, when the constraint on maximum N uptake was included, and P&L – woXNU without this constraint.

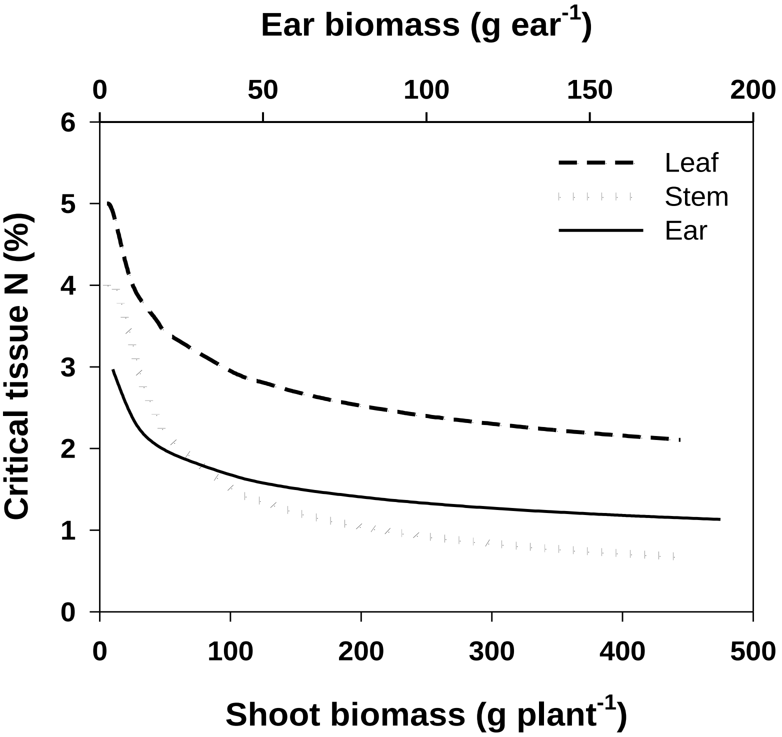


Figure 6.2. Proposed critical tissue N concentration to be used by IXIM (Eq. 7, leaf; Eq. 8, stem; Eq. 9, ear) to estimate crop N demand as a function of shoot or ear biomass.

6.2.3 Models input parameters

The main model inputs are: daily weather data, hydraulic characteristics of the soil profile, cultivar characteristics, field management, and initial conditions of the soil profile (moisture content, crop residues, mineral nitrogen and organic matter).

The daily weather data, i.e. maximum and minimum temperature (ºC), precipitation (mm), and solar radiation (MJ m^{-2}), were obtained from the Raimat weather station, near Almacelles (RuralCat, 2013), located within 10 km of the experimental fields. Soil characteristics for the two fields were measured in site and are given in Table 6.1.

Table 6.1. Soil characteristics used in the simulations

	AC field			AP field			
Depth	0-30	31-102	103-130	0-22	23-45	46-110	>111
Sand (%)	28	30	32	42	43	17	17
Silt (%)	42	46	47	33	36	63	65
Clay (%)	30	24	21	25	21	20	18
pH	8.4	8.2	8.3	8.2	8.4	8.4	8.4
Organic matter (%)	3.47	-	-	3.30	-	-	-
Bulk density (g cm^{-3})	1.40	-	-	1.64	-	-	-
E.C., dS m^{-1}	0.21	1.57	1.73	0.19	0.17	0.22	0.22
K (NH4Ac), mg kg^{-1}	420	-	-	383	-	-	-
Soil type†	Gypsic Haploxerept			Typic Calcixerept			

† Soil Survey Staff (2003).

6.2.4 Model calibration

The calibration procedure minimizes the difference between measured and corresponding simulated data by tuning the cultivar parameters of the models. Field data was split into calibration data (Table 5.2) and evaluation data. Cultivar coefficients (Table 5.3) were calibrated sequentially. First, those coefficients controlling phenology (P1, P2, P5 and PHINT) were modified to match silking and maturity dates, and leaf number. Later, G2 and G3 parameters were changed until biomass and yield simulations were close to observed values. In the case of IXIM, once the phenology parameters were calibrated, the coefficients controlling leaf expansion and senescence (Ax, Lx) were adjusted to reproduce seasonal leaf area.

To calibrate the hybrid Lerma, data from 2013 field experiments conducted at Gimenells Research Station (GM) (15 km from Almacelles) in north-east Spain (41°65' N, 0°39' E) were used.

Table 6.2. Data used for cultivar coefficient calibration

Cultivar	Year	Field	Treatment
PR33P67	2010	AP	R1-N300
PR33Y72	2011	AC	R1-N300
PR32G49	2011	AP	R1-N300
Lerma	2013	GM	R0-N300

Table 6.3. Definition and units of the cultivar coefficients for the models CERES and IXIM. AX and LX are used only by IXIM.

Coefficient	Definition	Unit
P1	Thermal time from emergence to the end of the juvenile phase	degree-days
P2	Photoperiod sensitivity, expressed as additional duration of flower induction for each hour increase above the critical photoperiod (12.5 h)	days
P5	Thermal time from silking to physiological maturity	degree-days
G2	Maximum number of kernels per plant	kernels plant^{-1}
G3	Potential kernel filling rate during the linear grain filling stage	mg day^{-1}
PHINT	Thermal time interval between successive leaf tip appearances	degree-days
AX	One-side surface area of the largest leaf	cm^2 leaf^{-1}
LX	longevity of the most long-lived leaf in thermal time	°C d

6.2.5 Model evaluation

The accuracy of model simulations was evaluated by testing the significance of linear regression coefficient using the determination coefficient (R^2) between simulated and observed values.

The root mean-squared error (RMSE) was computed to measure the coincidence between measured and simulated values and it was calculated as

$$\text{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(Si - Oi)^2\right]^{0.5} \tag{11}$$

where Si and Oi are a corresponding pair of simulated and observed values, respectively, and n is the number of observations included in the evaluation.

The parameter d or Willmott's index of agreement (Willmott, 1982) was calculated as

$$d = 1- \left[\frac{\sum_{i=1}^{n}(Si-Oi)^2}{\sum_{i=1}^{n}(|Si'|+|Oi'|)^2}\right] \tag{12}$$

where $Si' = Si - \bar{O}$ and $Oi' = Oi - \bar{O}$

Finally, predicted values of biomass, grain and N uptake were also compared graphically with field measurements to assess accuracy of models performance.

6.3. Results

6.3.1. Evaluating current CERES and IXIM maize models

6.3.1.1 Phenology

After calibrating the cultivar coefficients (Table 6.4) both models correctly simulated maize phenology. The difference between simulated and observed days to flowering and physiological maturity of different varieties over the 3 years ranged from 0 to 4 and from 0 to 5 days respectively.

Table 6.4. Calibrated genetic coefficients for maize hybrids used in this study

Variable	PR32G49			PR33P67			Lerma			PR33Y72		
	CERES	IXIM Jones	IXIM P&L	CERES	IXIM Jones	IXIM P&L	CERES	IXIM Jones	IXIM P&L	CERES	IXIM Jones	IXIM P&L
P1	220	280	280	300	330	330	328	322	322	280	280	280
P2	0.80	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P5	1015	1010	1010	830	810	810	890	1030	1030	950	970	970
G2	700	700	700	750	680	670	800	860	820	700	600	650
G3	8.00	6.80	6.80	8.80	7.60	6.80	9.00	9.30	8.50	8.10	7.00	6.70
PHINT	42.0	36.0	36.0	52.0	51.0	51.0	43.0	41.0	41.0	40.0	40.0	40.0
AX	-	800	650	-	1000	860	-	750	600	-	700	700
LX	-	700	620	-	1500	860	-	850	680	-	720	580

6.3.1.2 Yield evaluation

In our fields, maize scored elevated productions (14% moisture) within 11 (for the N0) to 20 Mg ha^{-1} (for the N300). The statistical coefficients indicated the close proximity between observed and simulated grain yield values (Table 6.5).

Grain yield was well simulated by CERES and IXIM $_{\text{(Jones – XNU)}}$ included in DSSAT V4.5 (Fig. 6.3) with determination coefficients (R^2) ranging within 0.644 to 0.993 for CERES, and 0.724 to 0.996 for IXIM $_{\text{(Jones – XNU)}}$ (Table 6.5).

Corresponding ranges for Willmott's *d* statistic were 0.65 to 0.97 for CERES, and 0.65 to 0.98 for IXIM $_{\text{(Jones – XNU)}}$.

In general the various statistical indicators did not suggest differences between both models when simulating grain yield, yet IXIM $_{\text{(Jones – XNU)}}$ was usually a little better than CERES.

Table 6.5. Statistical indices to assess the results from the simulations by CERES, IXIM $_{\text{(Jones – XNU)}}$ and IXIM $_{\text{(Jones – woXNU)}}$.

Variable			N	O_{avg} (kg ha^{-1})	S_{avg} (kg ha^{-1})	RMSE	*d*	r^2
Ac$_0$	Biomass	CERES	6	28051	29358	3618	0.16	0.364
		IXIM $_{\text{(Jones – XNU)}}$	6	28051	29240	1879	0. 76	0.707
		IXIM $_{\text{(Jones – woXNU)}}$	6	28051	29625	2166	0. 72	0.680
	Yield	CERES	6	13327	14679	1465	0.70	0.909
		IXIM $_{\text{(Jones – XNU)}}$	6	13327	14390	1199	0.77	0.889
		IXIM $_{\text{(Jones – woXNU)}}$	6	13327	14492	1338	0.75	0.861
	N uptake	CERES	6	330	309	38	0.80	0.711
		IXIM $_{\text{(Jones – XNU)}}$	6	330	334	23	0.90	0.849
		IXIM $_{\text{(Jones – woXNU)}}$	6	330	342	29	0.87	0.790
Ac$_{300}$	Biomass	CERES	5	31891	31947	3840	0.20	0.687
		IXIM $_{\text{(Jones – XNU)}}$	5	31891	32552	1079	0.93	0.921
		IXIM $_{\text{(Jones – woXNU)}}$	5	31891	34516	3715	0.39	0.841
	Yield	CERES	5	15176	15365	1034	0.73	0.746
		IXIM $_{\text{(Jones – XNU)}}$	5	15176	15737	602	0.95	0.996
		IXIM $_{\text{(Jones – woXNU)}}$	5	15176	16959	2199	0.75	0.976
	N uptake	CERES	5	397	374	30	0.68	0.614
		IXIM $_{\text{(Jones – XNU)}}$	5	397	436	46	0.46	0.380
		IXIM $_{\text{(Jones – woXNU)}}$	5	397	474	84	0.25	0.395
Ap$_0$	Biomass	CERES	6	25655	26058	2165	0.74	0.561
		IXIM $_{\text{(Jones – XNU)}}$	6	25655	26605	1196	0.94	0.969
		IXIM $_{\text{(Jones – woXNU)}}$	6	25655	26166	1886	0.90	0.911
	Yield	CERES	6	12432	13616	1692	0.65	0.644
		IXIM $_{\text{(Jones – XNU)}}$	6	12432	13425	1528	0.65	0.724
		IXIM $_{\text{(Jones – woXNU)}}$	6	12432	12477	762	0.94	0.881
	N uptake	CERES	6	282	257	44	0.70	0.592
		IXIM $_{\text{(Jones – XNU)}}$	6	282	285	27	0.88	0.765
		IXIM $_{\text{(Jones – woXNU)}}$	6	282	297	37	0.81	0.713
Ap$_{300}$	Biomass	CERES	4	32555	30968	3593	0.64	0.583
		IXIM $_{\text{(Jones – XNU)}}$	4	32555	32170	794	0.99	0.988
		IXIM $_{\text{(Jones – woXNU)}}$	4	32555	31683	2771	0.79	0.782
	Yield	CERES	4	14945	15303	452	0.97	0.993
		IXIM $_{\text{(Jones – XNU)}}$	4	14945	15204	324	0.98	0.993
		IXIM $_{\text{(Jones – woXNU)}}$	4	14945	16009	1336	0.71	0.874
	N uptake	CERES	4	415	362	54	0.39	0.931
		IXIM $_{\text{(Jones – XNU)}}$	4	415	426	29	0.75	0.942
		IXIM $_{\text{(Jones – woXNU)}}$	4	415	472	61	0.33	0.533

N: number of observations; O_{avg}: average observed value; S_{avg}: average simulated value; RMSE: root mean square error; d: index of concordance (Willmott, 1982) and determination coefficient (R^2).

Where Ac$_0$, Ap$_0$ and Ac$_{300}$, Ap$_{300}$ referred to the fields Ac, Ap with 0, 300 kg N ha^{-1}, respectively.

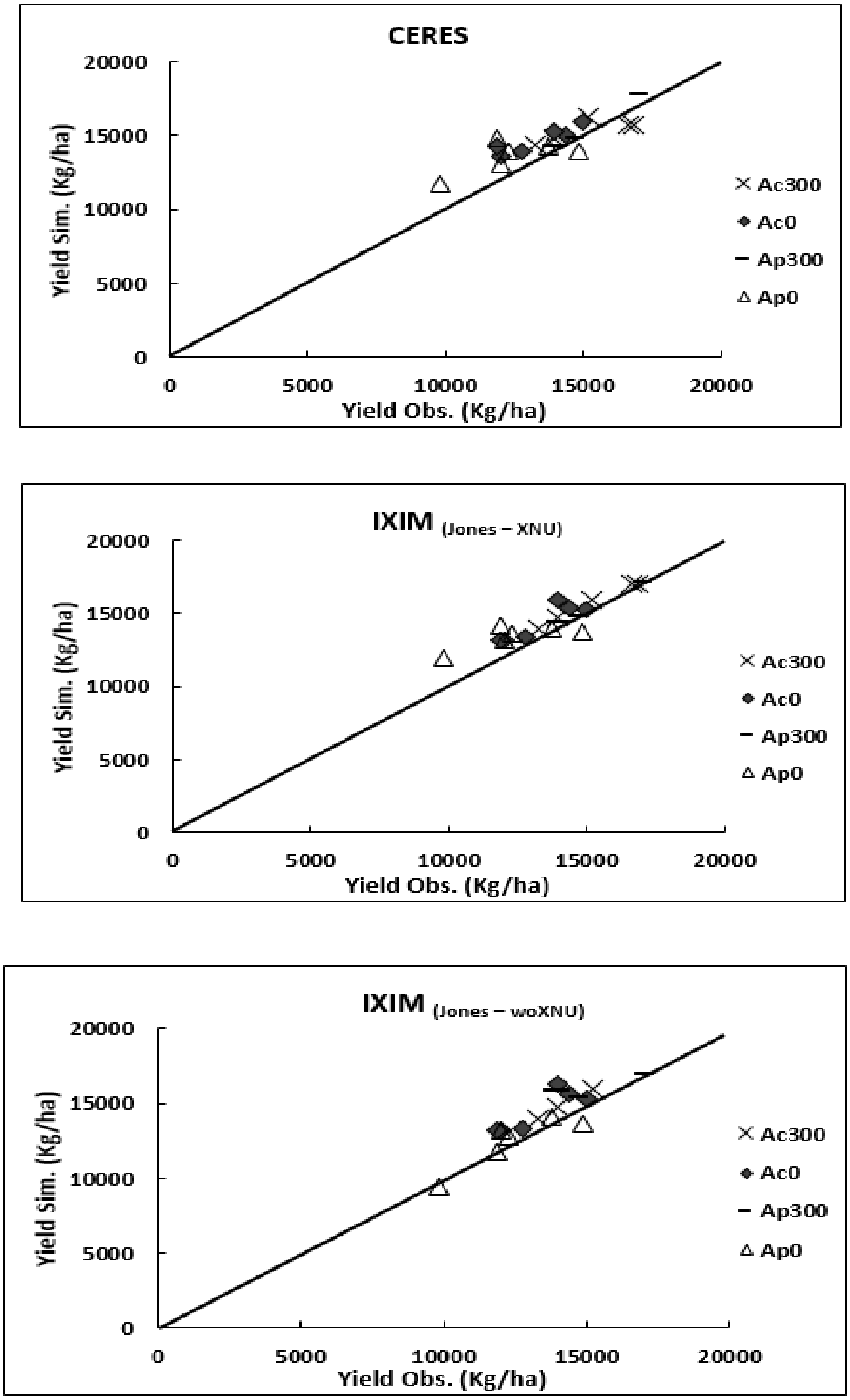


Figure 6.3. Simulated and observed values of grain yield expressed on a dry mass basis by CERES, IXIM $_{(\text{Jones – XNU})}$ and IXIM $_{(\text{Jones – woXNU})}$.

Where Ac_{0}, Ap_{0} and Ac_{300}, Ap_{300} referred to the fields Ac, Ap with 0, 300 kg N ha^{-1}, respectively.

6.3.1.3 Total aboveground biomass evaluation

CERES and IXIM models were able to correctly capture seasonal field crop growth in spite of the large variation observed in our fields, within 26 and higher than 35 Mg ha^{-1}.

Figure 6.4 and Table 6.5 show that in general, IXIM model was able to simulate total aboveground biomass better than CERES.

The *d* values for IXIM $_{\text{(Jones – XNU)}}$ were lower when no N was applied (0. 76 and 0.94) than when N was applied (0.93 and 0.99), suggesting more accurate growth simulation under elevated soil N availability.

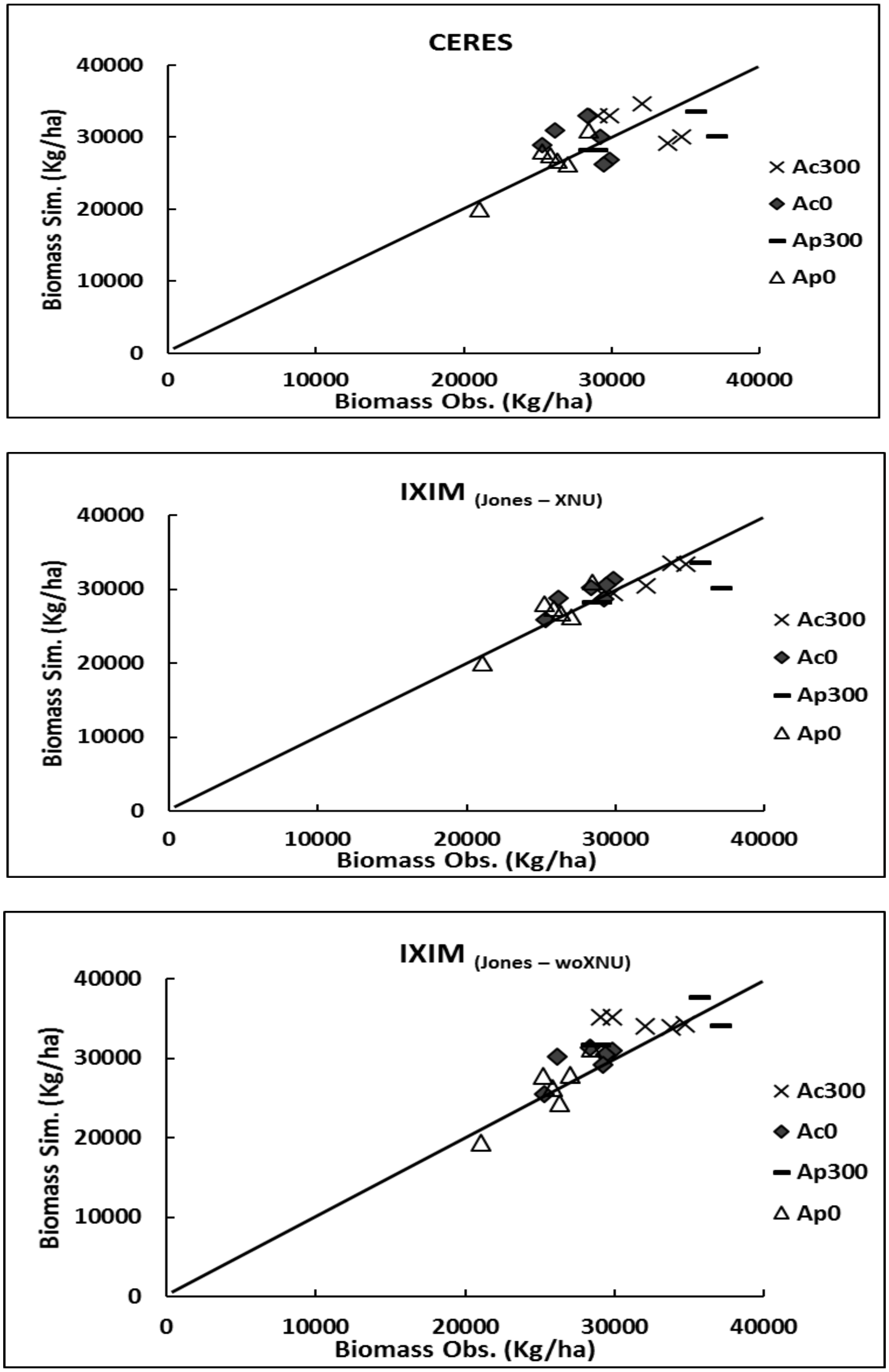


Figure 6.4. Simulated and observed values of Biomass by CERES, IXIM $_{\text{(Jones – XNU)}}$ and IXIM $_{\text{(Jones – woXNU)}}$.

Where Ac_{0}, Ap_{0} and Ac_{300}, Ap_{300} referred to the fields Ac, Ap with 0, 300 kg N ha^{-1}, respectively.

6.3.1.4 Crop N uptake evaluation

The N uptake, as simulated with CERES and IXIM models, are depicted in Fig. 6.5. Accurate forecast of plant N content depends on the correct calculation of biomass and N concentrations in tissues. Statistical indices presented in Table 6.5 show that simulation of plant N dynamics was not as satisfactory as the estimates of growth and grain yield.

Willmott's *d* values were 0.39 to 0.80 for CERES and 0.25 to 0.90 for IXIM. When IXIM was equipped with the maximum N uptake limitation (XNU), always yielded results closer to measured. These values and the Figure 5 show that the IXIM $_{\text{(Jones – XNU)}}$ model simulated crop N uptake better than CERES.

Values of RMSE for IXIM $_{\text{(Jones – XNU)}}$ were within the range of 23 to 46 kg ha^{-1}, and 29 to 84 kg ha^{-1} for IXIM $_{\text{(Jones – woXNU)}}$. As a result, the model simulated crop N uptake better when Eq. 10 was used to limit maximum uptake calculated by IXIM (IXIM $_{\text{(Jones – XNU)}}$).

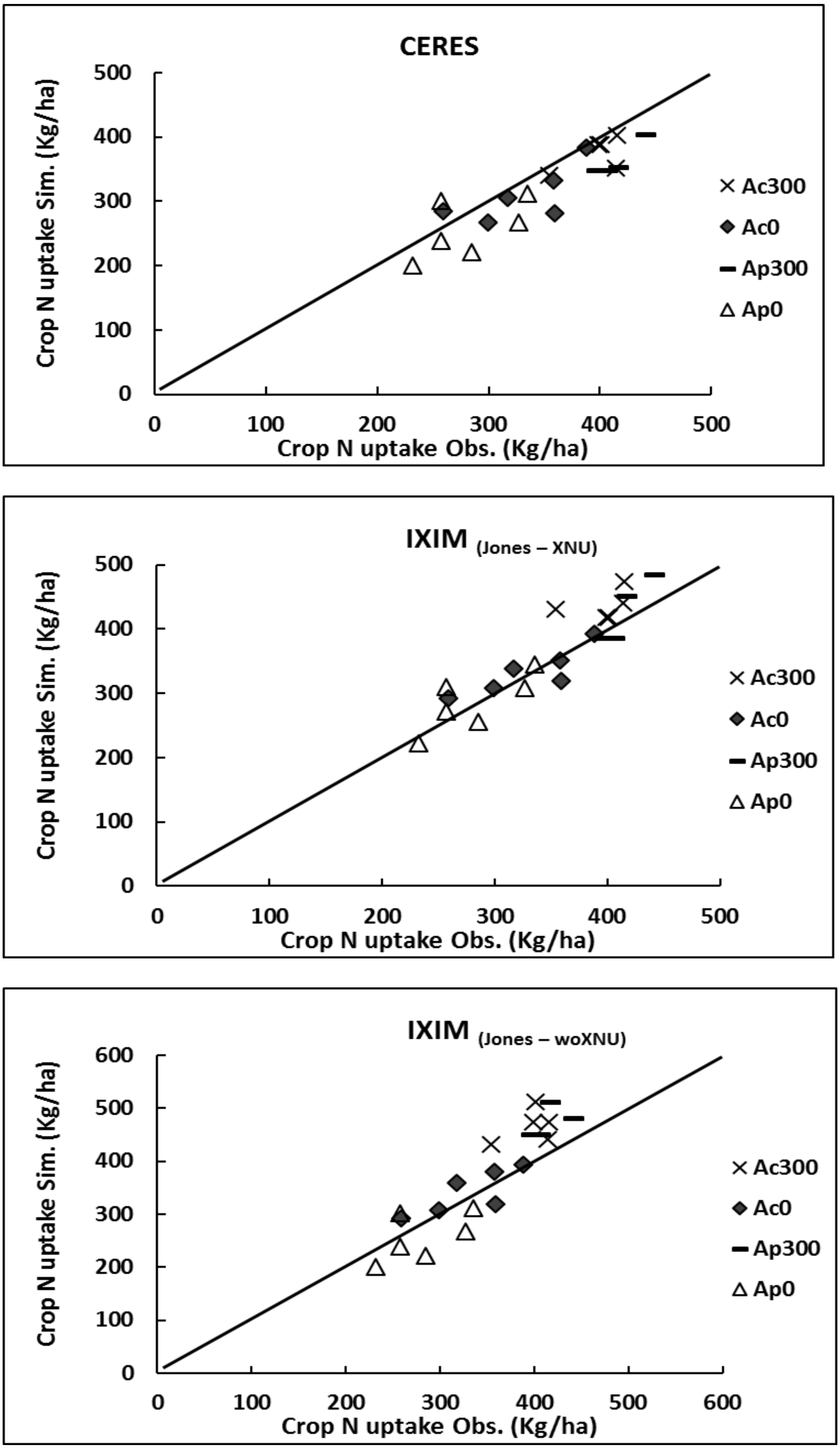


Figure 6.5. Simulated and observed values of crop N uptake by CERES, IXIM $_{\text{(Jones – XNU)}}$ and IXIM $_{\text{(Jones – woXNU)}}$.

Where Ac_0, Ap_0 and Ac_{300}, Ap_{300} referred to the fields Ac, Ap with 0, 300 kg N ha^{-1}, respectively.

6.3.2 Testing an alternative approach to estimate crop N demand

6.3.2.1 Yield evaluation

The IXIM model furnished with the alternative approach to estimate crop N demand, based on Plénet and Lemaire (2000) simulated well grain yield (Table 6.6 and Fig. 6.6). Corresponding ranges for Willmott’s *d* statistic were 0.84 to 0.93 for IXIM $_{\text{(P\&L – XNU)}}$, and 0.86 to 0.94 for IXIM $_{\text{(P\&L – woXNU)}}$. In general, simulated grain yield data were slightly lower than the observed grain yield data.

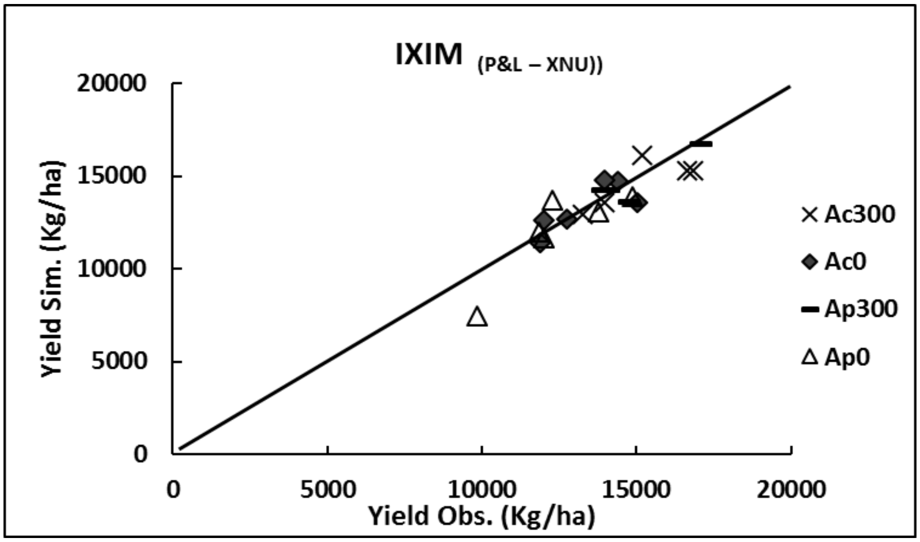
Values of RMSE were within the range of 324 to 1528 kg ha^{-1} for IXIM $_{\text{(Jones – XNU)}}$, 762 to 2199 kg ha^{-1} for IXIM $_{\text{(Jones – woXNU)}}$, 637 to 1226 kg ha^{-1} for IXIM $_{\text{(P\&L – XNU)}}$, and 607 to 1040 kg ha^{-1} for IXIM $_{\text{(P\&L – woXNU)}}$ (Table 6.5 and 6.6). These vales show that the IXIM with the approach based on Plénet and Lemaire (2000) simulated grain yield better than the IXIM with the approach to estimate crop N demand, based on Jones (1983).

Table 6.6. Statistical indices to assess the results from the simulations by IXIM $_{\text{(P\&L – XNU)}}$ and IXIM $_{\text{(P\&L – woXNU)}}$.

Variable			N	O_{avg} (kg ha^{-1})	S_{avg} (kg ha^{-1})	RMSE	*d*	r^2
Ac$_0$	Biomass	IXIM $_{\text{(P\&L – XNU)}}$	6	28051	29742	2332	0.75	0.831
		IXIM $_{\text{(P\&L – woXNU)}}$	6	28051	29447	1796	0.76	0.790
	Yield	IXIM $_{\text{(P\&L – XNU)}}$	6	13327	13305	751	0.89	0.806
		IXIM $_{\text{(P\&L – woXNU)}}$	6	13327	13730	607	0.93	0.926
	N uptake	IXIM $_{\text{(P\&L – XNU)}}$	6	330	316	25	0.88	0.711
		IXIM $_{\text{(P\&L – woXNU)}}$	6	330	337	23	0.90	0.875
Ac$_{300}$	Biomass	IXIM $_{\text{(P\&L – XNU)}}$	5	31891	33370	2632	0.79	0.838
		IXIM $_{\text{(P\&L – woXNU)}}$	5	31891	31378	758	0.96	0.986
	Yield	IXIM $_{\text{(P\&L – XNU)}}$	5	15176	14645	1023	0.84	0.788
		IXIM $_{\text{(P\&L – woXNU)}}$	5	15176	14558	674	0.94	0.997
	N uptake	IXIM $_{\text{(P\&L – XNU)}}$	5	397	407	34	0.54	0.614
		IXIM $_{\text{(P\&L – woXNU)}}$	5	397	410	24	0.51	0.608
Ap$_0$	Biomass	IXIM $_{\text{(P\&L – XNU)}}$	6	25655	25623	2272	0.87	0.880
		IXIM $_{\text{(P\&L – woXNU)}}$	6	25655	26121	1991	0.89	0.905
	Yield	IXIM $_{\text{(P\&L – XNU)}}$	6	12432	11982	1226	0.89	0.863
		IXIM $_{\text{(P\&L – woXNU)}}$	6	12432	12257	1040	0.90	0.827
	N uptake	IXIM $_{\text{(P\&L – XNU)}}$	6	282	274	30	0.88	0.823
		IXIM $_{\text{(P\&L – woXNU)}}$	6	282	292	33	0.85	0.757
Ap$_{300}$	Biomass	IXIM $_{\text{(P\&L – XNU)}}$	4	32555	31716	1108	0.98	0.999
		IXIM $_{\text{(P\&L – woXNU)}}$	4	32555	30223	3201	0.78	0.888
	Yield	IXIM $_{\text{(P\&L – XNU)}}$	4	14945	14673	637	0.93	0.893
		IXIM $_{\text{(P\&L – woXNU)}}$	4	14945	14226	941	0.86	0.933
	N uptake	IXIM $_{\text{(P\&L – XNU)}}$	4	415	394	28	0.57	0.497
		IXIM $_{\text{(P\&L – woXNU)}}$	4	415	400	18	0.74	0.931

N: number of observations; O_{avg}: average observed value; S_{avg}: average simulated value; RMSE: root mean square error; d: index of concordance (Willmott, 1982) and determination coefficient (R^2).

Where Ac$_0$, Ap$_0$ and Ac$_{300}$, Ap$_{300}$ referred to the fields Ac, Ap with 0, 300 kg N ha^{-1}, respectively.



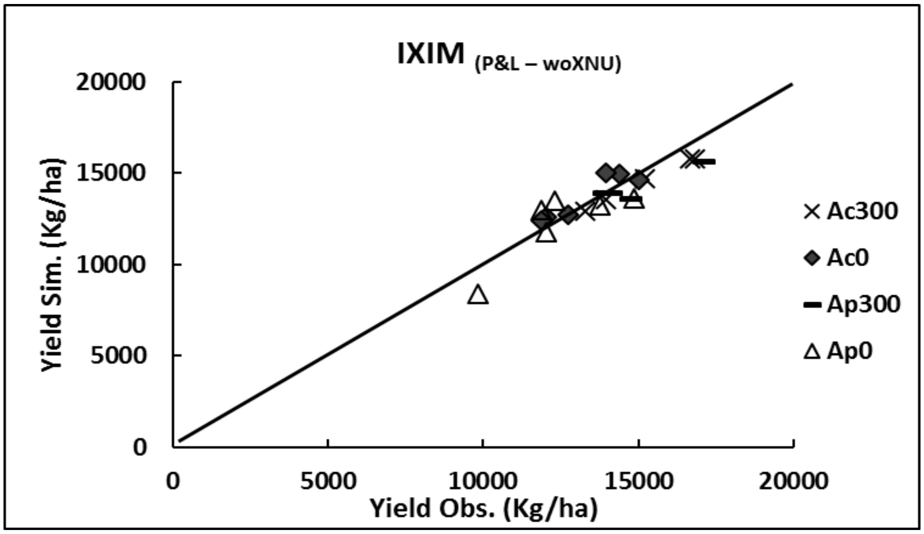


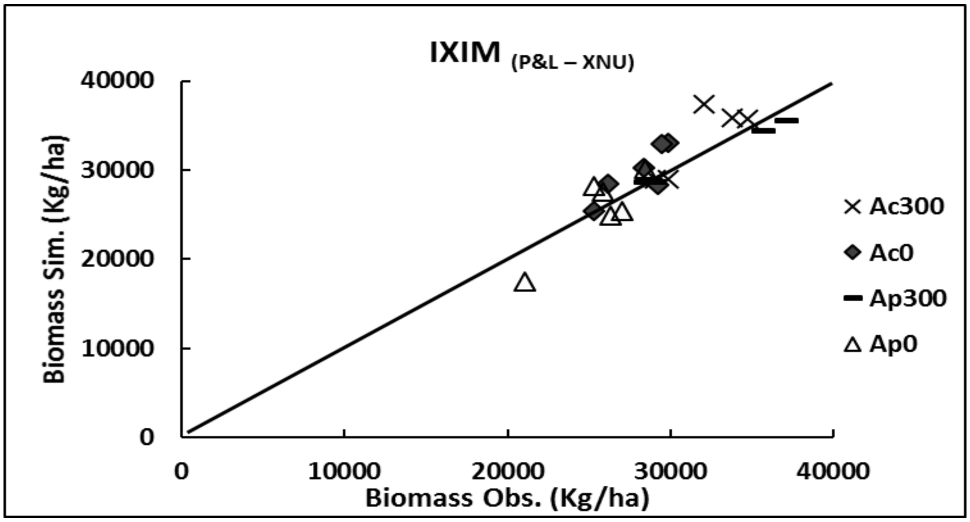
Figure 6.6. Simulated and observed values of grain yield expressed on a dry mass basis by IXIM $_{\text{(P\&L – XNU)}}$ and IXIM $_{\text{(P\&L – woXNU)}}$.

Where Ac_0, Ap_0 and Ac_{300}, Ap_{300} referred to the fields Ac, Ap with 0, 300 kg N ha^{-1}, respectively.

6.3.2.2 Total aboveground biomass evaluation

As given by several statistical indices (Table 6.6), IXIM $_{\text{(P\&L – XNU)}}$ and IXIM $_{\text{(P\&L – woXNU)}}$ correctly simulated aboveground biomass.

Values of RMSE were within the range of 794 to 1879 kg ha^{-1} for IXIM $_{\text{(Jones – XNU)}}$, 1886 to 3715 kg ha^{-1} for IXIM $_{\text{(Jones – woXNU)}}$, 1108 to 2632 kg ha^{-1} for IXIM $_{\text{(P\&L – XNU)}}$, and 758 to 3201 kg ha^{-1} for IXIM $_{\text{(P\&L – woXNU)}}$ (Table 6.5 and 6.6). These values and Figures 6.4 and 6.7 show that IXIM, when equipped with the maximum N uptake limitation (XNU, Eq. 10), simulated biomass at harvest better following the Jones (1983) approach. However, when deprived of XNU the Plénet and Lemaire (2000) approach produced better results.



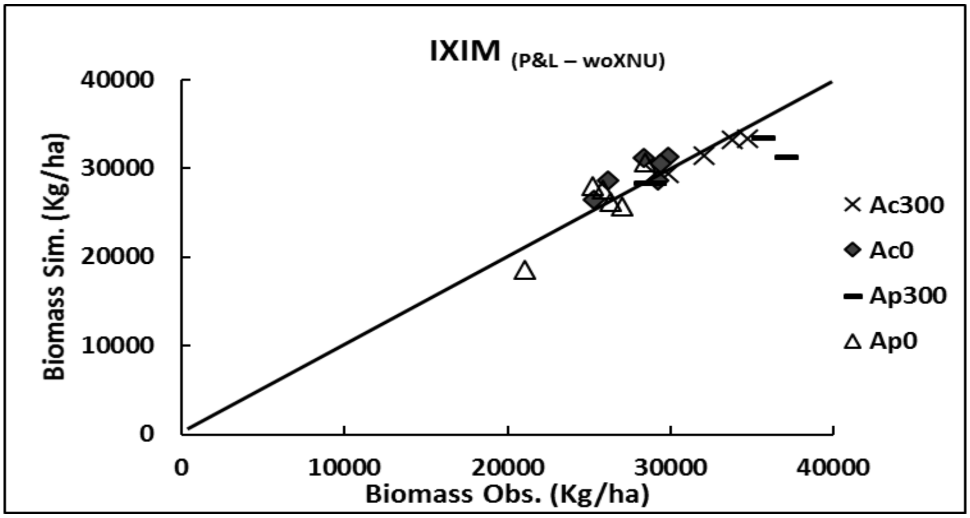


Figure 6.7. Simulated and observed values of Biomass by IXIM $_{(P\&L – XNU)}$ and IXIM $_{(P\&L – woXNU)}$.

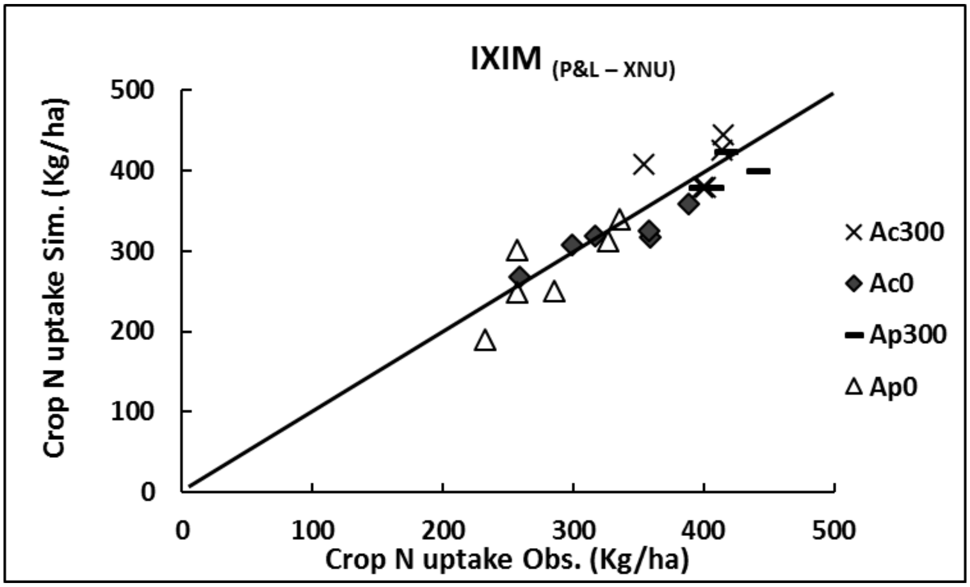
Where Ac_0, Ap_0 and Ac_{300}, Ap_{300} referred to the fields Ac, Ap with 0, 300 kg N ha^{-1}, respectively.

6.3.2.3 Crop N uptake evaluation

Crop N uptake was simulated correctly by IXIM with the approach based on Plénet and Lemaire (2000). When no N fertilization was applied *d* was 0.88 for IXIM $_{\text{(P\&L – XNU)}}$, and 0.85-0.90 for IXIM $_{\text{(P\&L – woXNU)}}$ (Table 6.6). When 300 kg N ha^{-1} were applied, the crop N uptake results were less accurate with *d* values (0.54 – 0.57) for IXIM $_{\text{(P\&L – XNU)}}$, and (0.51- 0.74) for IXIM $_{\text{(P\&L – woXNU)}}$ (Table 6.6).

As given by various statistical indices (Table 6.5 and 6.6) and figures 6.5 and 6.8, the IXIM with the approach to estimate crop N demand according to Plénet and Lemaire (2000) simulated the crop N uptake better than the IXIM based on Jones (1983).

Values of RMSE were within the range of 25 to 34 kg ha^{-1} for IXIM $_{\text{(P\&L – XNU)}}$, and 18 to 33 kg ha^{-1} for IXIM $_{\text{(P\&L – woXNU)}}$ (Table 6.6). These vales and Figure 6.8 show that IXIM $_{\text{(P\&L – woXNU)}}$ simulated crop N uptake better than IXIM $_{\text{(P\&L – XNU)}}$.



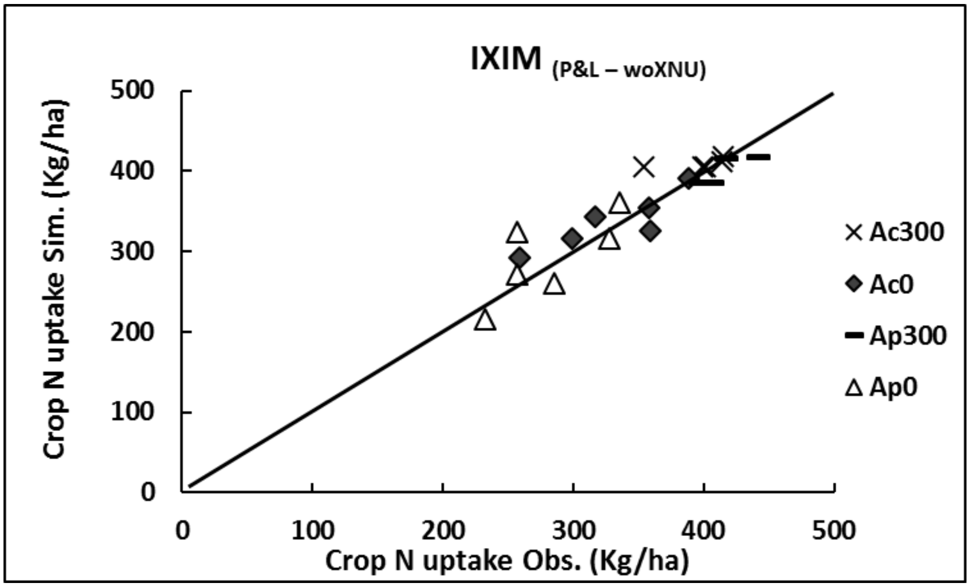


Figure 6.8. Simulated and observed values of crop N uptake by IXIM $_{(P\&L – XNU)}$ and IXIM $_{(P\&L – woXNU)}$.

Where Ac_0, Ap_0 and Ac_{300}, Ap_{300} referred to the fields Ac, Ap with 0, 300 kg N ha^{-1}, respectively.

6.4. Discussion

In this work we examined the ability of the DSSAT maize models to capture crop growth, grain yield, and N demand in highly productive environments. We were also interested in testing an alternative approach to estimate crop N demand, driven by crop growth, as opposed to the current approach driven by crop development.

Both maize models in DSSAT, CERES and IXIM, predicted crop phenology reasonably well. The difference between simulated and observed days to flowering and physiological maturity across the various hybrids over the 3 years were within 0 to 5 days. Roman-Paoli et al. (2000), Gungula et al. (2003) and Tojo-Soler et al. (2007) have also reported close prediction of days to flowering in maize by using CERES-Maize in different environments. These differences may also include some experimental error associated with observed field dates (Ferrer et al., 2000).

Both CERES and IXIM were able to capture growth, yield, and aboveground N uptake by maize crops. For grain yield, values of RMSE for CERES were within the range of 452 to 1692 kg ha^{-1}, 324 to 1528 kg ha^{-1} for IXIM $_{\text{(Jones – XNU)}}$. Mastrorilli et al. (2003) reported less than 13% variation in simulated and observed grain yield under Mediterranean conditions by using CERES-Maize model. Our results (within 1% to 10%) are in agreement with that finding. When Eq. 10 was used to limit maximum uptake calculated by IXIM (IXIM $_{\text{(Jones – XNU)}}$), yield simulation improved for treatments with N fertilization (300 kg N ha^{-1}) in the order of 27% up to 38% compared to IXIM $_{\text{(Jones – woXNU)}}$, according to Willmott's *d* (Table 5).

Aboveground biomass at harvest was simulated correctly by CERES and IXIM. There was however, some underestimation by the CERES model for the field Ac without fertilizer

(Ac0). Some disagreements between observed and simulated biomass by CERES have previously been reported by Ben Nouna et al. (2000). The *d* values for IXIM $_{\text{(Jones – XNU)}}$ were lower when no N was applied than when N was applied. This is in agreement with the findings of Lizaso et al. (2011).

The IXIM $_{\text{(Jones – XNU)}}$ model simulated crop N uptake better than CERES. This fact is consistent with the findings of Lizaso et al. (2011) who indicated that for IXIM $_{\text{(Jones – XNU)}}$ simulation improvements were in the order of 0.4% up to more than 15%. In our study, simulation improvements were in the order of 3% up to 127% compared to IXIM $_{\text{(Jones – woXNU)}}$, according to Willmott's *d* (Table 6.5). These substantial improvements under elevated N, resulted from the restriction of the excessive N uptake simulated by IXIM $_{\text{(Jones – woXNU)}}$ when soil N became highly available, especially following fertilization (Lizaso, et al., 2011).

We examined an alternative approach to estimate crop N demand. The new procedure is growth-based as opposed to the currently used development-based. Our evaluation found that in the case of IXIM the new procedure exhibited better results than the phenology-based procedure by Jones (1983). This will be in agreement with a number of reports showing a strong relationship between the crop carbon and nitrogen cycles in field growing crops (e.g. Greenwood et al., 1990).

The relationship between N and biomass accumulation in crops, relies on the interregulation of multiple crop physiological processes. Among these processes, N uptake, crop C assimilation and thus growth rate (Gastal and Lemaire, 2002).

Lemaire and Salette (1984) observed that the N concentration in plant shoots always decreased during growth cycles and they found allometric relationships between nitrogen uptake and dry matter accumulation in shoots.

Plénet and Lemaire (2000), evaluated a FAO 550 and two short season maize hybrids, and proposed a N uptake-Biomass relationship, differentiating critical and maximum levels (Fig. 6.9). They suggested these relationships could be incorporated into crop simulation models to estimate crop N demand. According to the authors, their relationships were valid for biomass values up to 24 Mg ha^{-1}.

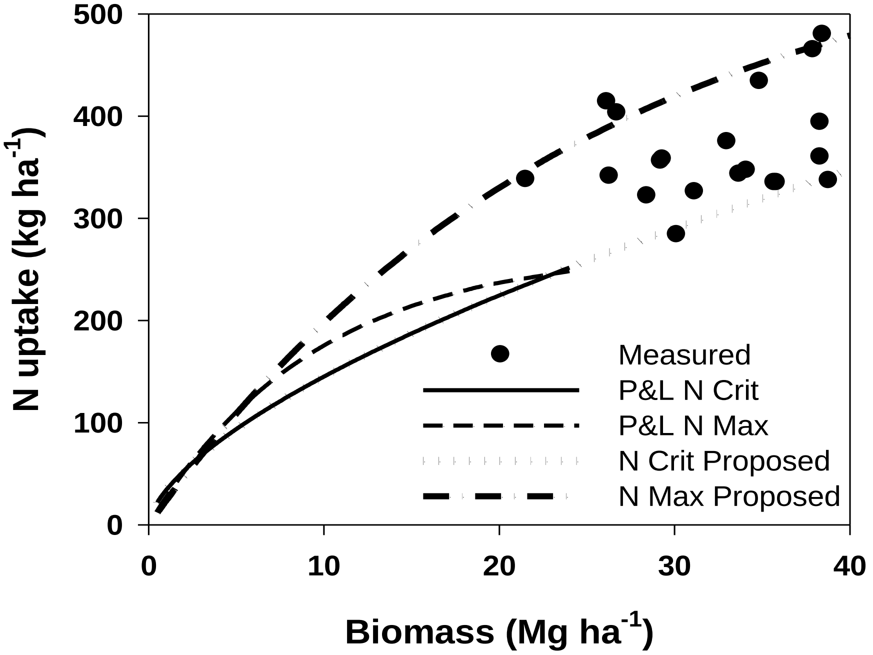


Figure 6.9. Relationship Biomass and Critical and Maximum N uptake (Plénet and Lemaire, 2000) and our field measurements.

Fig. 6.9 shows our field measurements compared to Plénet and Lemaire (2000) functions. Under our conditions, out of 23 data values, only one was under 24 Mg ha^{-1} and in this case, N uptake was well above the maximum indicated by Plénet and Lemaire (2000) relationship. Clearly, our long-season cultivars were outside range of cultivars explored by

Plénet and Lemaire work. So, the question arose whether Eq. 5 would be robust enough to represent the C-N relationship across maize cultivars of various growth cycles or should be modified. Our results indicated that the relationship to estimate crop N demand, described by Eq. 5, could be extended to incorporate full season, highly productive maize responses, in the top yielding irrigated environments (at least up to biomass values of 42 Mg ha^{-1}).

One issue that remains to be explored is the ability of Eq. 5 to represent the C-N relationship in old hybrids compared to modern hybrids. In this work, we have tested four modern commercial hybrids (Table 6.2). Since these new hybrids exhibit higher N use efficiency and stay-green traits (Duvick et al., 2004), it is possible that the relationship described by Eq. 5 may not be equally accurate when simulating older and newer hybrids.

6.5. Conclusions

In our study, the CERES and IXIM (IXIM $_{\text{(Jones – XNU)}}$, IXIM $_{\text{(Jones – woXNU)}}$) maize models in DSSAT version 4.5 were used to simulate the yield, total aboveground biomass and crop N uptake of irrigated maize in highly productive irrigated areas of the Ebro Valley (from 11 to 20 Mg ha^{-1}), depending on the N fertilization (N0 or N300), residue management (I or R), and the year.

The CERES and IXIM maize models predicted correctly the occurrence of developmental stages of maize. As given by several statistical indices, both models accurately simulated maize grain yield and aboveground biomass for a fairly wide range of treatments tested in this study; however, IXIM $_{\text{(Jones – XNU)}}$ model simulated aboveground biomass somewhat better than CERES.

The models simulated crop N uptake less accurately than yield and biomass. However the IXIM $_{\text{(Jones – XNU)}}$ model simulated crop N uptake better than CERES.

The IXIM model simulated crop N uptake better when Eq. 10 was used to limit maximum uptake calculated by IXIM (IXIM $_{\text{(Jones – XNU)}}$).

The IXIM model, supplied with the Plénet and Lemaire (2000) approach to estimate crop N demand, simulated grain yield and crop N uptake better than the IXIM with the current approach based on Jones (1983).

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7. GENERAL CONCLUSIONS

7. General conclusions

The main conclusions of this thesis are:

1. Under our high yielding irrigated maize conditions (up to 20 Mg ha^{-1}) grain yield, biomass, plant and grain N uptake, soil Nini and Nresi and SPAD-units all showed significant responses to N fertilisation rates.
2. In our soil conditions, maize responses to N fertilisation clearly depended on the initial soil NO_3^--N content.
3. In our study, high grain yields (19.93 and 19.20 Mg ha^{-1}) were achieved when N fertilization was applied at rates of 200 kg N ha^{-1} to soils with initially moderate NO_3^--N contents (average of 95 kg N ha^{-1} at a depth of 0 - 90 cm).
4. N lost was significantly affected by N rates and ranged from 44 Kg N ha^{-1} for the 100 kg N ha^{-1} rate to 138 kg N ha^{-1} for the 400 kg N ha^{-1} treatment.
5. Apparent N recovery and agronomic N efficiency were significantly affected by N rates and ranged from 0.40, 33.87 kg kg^{-1} for N400 to 0.57, 68.23 kg kg^{-1} for N100, respectively.
6. During the 5 years of continuous maize cultivation, the minimum N rates required to obtain the maximum SPAD readings varied from year to year, but never exceeded 190 kg N ha^{-1}.
7. Maize grain yield and biomass significantly correlated with plant height and chlorophyll (SPAD) content at the silking stage..
8. In the conditions of our high yielding experiment, farmers should be able to incorporate stover without any yield or biomass penalties and this should improve the SOC levels of their soils. There was no significant interaction between stover management and N fertilization rates.

9. Under our high yielding conditions, the DSSAT 4.5 versions of the CERES and IXIM (IXIM $_{\text{(Jones – XNU)}}$, IXIM $_{\text{(Jones – woXNU)}}$) maize models were able to correctly predict the timing of different stages of maize development, maize grain yields and aboveground biomass levels, whereas they were less efficient at estimating crop N uptake.
10. Under our high-yielding, irrigated maize conditions, the CSM-IXIM model was able to simulate the production of total aboveground biomass and crop N uptake better than the CSM–CERES model.
11. The IXIM model incorporating an alternative approach for estimating crop N demand based on Plénet and Lemaire (2000) (IXIM $_{\text{(P\&L – XNU)}}$, IXIM $_{\text{(P\&L – woXNU)}}$) was able to simulate grain yield and crop N uptake better than the IXIM model using the current approach based on Jones (1983) (IXIM $_{\text{(Jones – XNU)}}$, IXIM $_{\text{(Jones – woXNU)}}$).