ESTTA Tracking number: **ESTTA988205**
Filing date: **07/17/2019**

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
BEFORE THE TRADEMARK TRIAL AND APPEAL BOARD

Notice of Opposition

Notice is hereby given that the following party opposes registration of the indicated application.

Opposer Information

Name	Koch Agronomic Services, LLC
Granted to Date of previous extension	08/03/2019
Address	4111 EAST 37TH ST. N WICHITA, KS 67220 UNITED STATES

Attorney information	ALICIA GRAHN JONES KILPATRICK TOWNSEND & STOCKTON LLP 1100 PEACHTREE STREET, SUITE 2800 ATLANTA, GA 30309 UNITED STATES aljones@ktslaw.com, cgenteman@kilpatricktownsend.com, kteilhaber@kilpatricktownsend.com, tmadmin@ktslaw.com 4048156500

Applicant Information

Application No	88030304	Publication date	06/04/2019
Opposition Filing Date	07/17/2019	Opposition Period Ends	08/03/2019
Applicant	Verdesian Life Sciences U.S., LLC 1001 Winstead Drive, Suite 480 Cary, NC 27513 UNITED STATES		

Goods/Services Affected by Opposition

Class 001. First Use: 0 First Use In Commerce: 0
All goods and services in the class are opposed, namely: Fertilizers

Applicant Information

Application No	88057306	Publication date	06/04/2019
Opposition Filing Date	07/17/2019	Opposition Period Ends	
Applicant	Verdesian Life Sciences U.S., LLC 1001 Winstead Drive, Suite 480 Cary, NC 27513 UNITED STATES		

Goods/Services Affected by Opposition

Class 001. First Use: 0 First Use In Commerce: 0 All goods and services in the class are opposed, namely: Fertilizers; plant growth nutrients forcrops; chemicals for use in agriculturefor crop protection, except fungicides,herbicides, insecticides and parasiticides
Class 005. First Use: 0 First Use In Commerce: 0 All goods and services in the class are opposed, namely: Fungicides, herbicides, insecticides, and parasiticides

Grounds for Opposition

Other	The marks include a merely descriptive and generic term that must be disclaimed.

Attachments	2017.07.17 Opposition (NUE CHARGE and NUE UNIVERSITY).pdf(132958 bytes) Exhibit 1_Part1.pdf(4133222 bytes) Exhibit 1_Part2.pdf(4193438 bytes) Exhibit 1_Part3.pdf(4134323 bytes) Exhibit 1_Part4.pdf(3640923 bytes) Exhibit 2.pdf(120743 bytes) Exhibit 3.pdf(1623317 bytes) Exhibit 4.pdf(1162744 bytes) Exhibit 5.pdf(436601 bytes) Exhibit 6.pdf(11481 bytes)

Signature	/Alicia Grahn Jones/
Name	ALICIA GRAHN JONES
Date	07/17/2019

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
BEFORE THE TRADEMARK TRIAL AND APPEAL BOARD

KOCH AGRONOMIC SERVICES, LLC,	)	
Opposer,	)	Opposition No. _____________
v.	)	Application Nos. 88/030,304 & 88/057,306
VERDESIAN LIFE SCIENCES U.S., LLC	)	
Applicant.	)	

CONSOLIDATED NOTICE OF OPPOSITION

Koch Agronomic Services, LLC ("Koch Agronomic" or "Opposer"), a Delaware limited liability company with a principal place of business at 4111 East 37th Street North, Wichita, Kansas 67220, believes that it will be damaged by the issuance of trademark registrations for the phrases "NUE CHARGE" and "NUE UNIVERSITY" that are the subject of Application Ser. Nos. 88/030,304 and 88/057,306, respectively (the "Applications"), filed by Verdesian Life Sciences U.S., LLC ("Applicant"). Accordingly, pursuant to Section 13 of the Lanham Act, 15 U.S.C. § 1063, Koch Agronomic opposes the Applications.

As grounds for its opposition, Opposer alleges as follows, with knowledge concerning its own acts, and on information and belief as to all other matters:

1. Koch Agronomic is a global leader in plant nutrient solutions, using science and technology to provide growers with innovative solutions to boost yield potential, strengthen turf, reduce environmental impact, and optimize fertilizer investments.

2. Applicant is a Delaware limited liability company with an address of 1001 Winstead Drive, Suite 480, Cary, North Carolina 27513.

3. On July 9, 2018, Applicant filed an application to register the phrase "NUE CHARGE" for use in connection with "fertilizers," in Class 1.

4. On July 30, 2018, Applicant filed an application to register the phrase "NUE UNIVERSITY" for use in connection with "fertilizers; plant growth nutrients for crops; chemicals for use in agriculture for crop protection, except fungicides, herbicides, insecticides and parasiticides," in Class 1 and "fungicides, herbicides, insecticides, and parasiticides," in Class 5.

5. Neither of the Applications include a disclaimer of any term.

6. The Applications were published for opposition in the *Official Gazette* dated June 4, 2019. Koch Agronomic timely filed requests for extensions of time to oppose the Applications and thus is allowed until August 5, 2019 to file this Consolidated Notice of Opposition.

7. Koch Agronomic and third parties regularly use the generic or descriptive term "NUE" as an acronym for "nitrogen use efficiency" or "nutrient use efficiency," which is an indicator for the amount of applied nutrients (nitrogen) that are taken up by the crop. NUE is the measurement researchers, the academic community, and the agriculture industry use to compare the effectiveness of various fertilizer sources. Attached as **Exhibit 1** are printouts showing representative examples of such uses, including Opposer's use of NUE.

8. Applicant, in its counterclaim in a separate opposition proceeding, in fact admitted that "'NUE' is an acronym for the wording nutrient use efficiency" and argued that NUE is thus descriptive of fertilizer. Attached as **Exhibit 2** is a printout of Applicant's Answer and Counterclaim in Opposition No. 91246167.

9. In addition, Applicant's website repeatedly uses "NUE" an acronym for "nutrient use efficiency," explaining "Nutrient use efficiency (NUE) is simply a measure of how well

plants use the available mineral nutrients. It can also be defined as yield per unit input (e.g., fertilizer, nutrient content, etc.).” Attached as **Exhibit 3** are printouts of Applicant’s website showing examples of such use.

10. Applicant’s website also uses “NUE” to reference “nitrogen use efficiency.” Attached as **Exhibit 4** is a printout of Applicant’s website showing an example of such use.

11. Moreover, Applicant received an office action on December 28, 2018 to its application to register the phrase “A VERDESIAN NUE SOLUTION,” Application Ser. No. 88/123,749, for use in connection with “metabolic plant fertilizers and growth regulators for agricultural use,” in Class 1. The office action required a disclaimer of the term “NUE” on the basis that “‘NUE’ is an acronym for ‘Nitrogen Use Efficiency’ or ‘Nutrient Use Efficiency’” and “[t]hus, ‘NUE’ in the mark merely describes an ingredient, quality, characteristic, function, feature, purpose, or use of applicant’s goods because they are metabolic plant fertilizers and growth regulators for agricultural use that could be used to improve NUE.” Attached as **Exhibit 5** is a printout of the office action.

12. On June 18, 2019, Applicant filed a response to the office action adopting the following disclaimer and thus further admitting the descriptiveness of the term “NUE”: “No claim is made to the exclusive right to use NUE apart from the mark as shown.” Attached as **Exhibit 6** is a printout of Applicant’s June 18, 2019 office action response.

13. As evidenced by Applicant’s own admissions, the term “NUE” is generic, merely descriptive, and non-distinctive, when used in connection with Applicant’s goods covered by the Applications.

14. Based on Koch Agronomic’s offering of plant nutrient solutions related to increasing nitrogen use efficiency (NUE), Koch Agronomic has standing to oppose the

Applications and has a direct commercial interest in describing the products it sells using the generic or merely descriptive term "NUE."

15. Applicant should be required to adopt a disclaimer of the term "NUE" for both "NUE CHARGE" and "NUE UNIVERSITY" on the grounds that the term "NUE" is generic or merely descriptive and lacking acquired distinctiveness when used in connection with an indicator for the utilization of nitrogen and nutrients of the fertilizers, plant growth nutrients for crops, chemicals for use in agriculture for crop protection, fungicides, herbicides, insecticides, and parasiticides identified in Applicant's description of goods. Indeed, the term "NUE" is generic or does nothing more than describe a quality, characteristic, function, feature, purpose or use of Applicant's goods. As such, the term "NUE" must be disclaimed pursuant to Section 6(a) of the Lanham Act, 15 U.S.C. § 1056(a).

16. Koch Agronomic respectfully requests the Board to sustain this Notice of Opposition in Opposer's favor and require disclaimers of the term "NUE" in "NUE CHARGE" and "NUE UNIVERSITY" in Application Ser. Nos. 88/030,304 and 88/057,306. The required fee in the amount of $1,200.00 accompanies this notice. The Commissioner is authorized to debit the deposit account of Kilpatrick Townsend & Stockton LLP (Deposit Account No. 20-1430) for any deficiency in the required fee.

Dated: July 17, 2019

Respectfully submitted,

/Alicia Grahn Jones/
Alicia Grahn Jones
Crystal Genteman
KILPATRICK TOWNSEND & STOCKTON LLP
1100 Peachtree Street, Suite 2800
Atlanta, Georgia 30309
Phone: (404) 815-6500
Fax: 404-815-6555
aljones@kilpatricktownsend.com
cgenteman@kilpatricktownsend.com

CERTIFICATE OF TRANSMITTAL

I hereby certify that a true copy of the foregoing CONSOLIDATED NOTICE OF OPPOSITION is being filed electronically with the TTAB via ESTTA on this day, July 17, 2019.

/Alicia Grahn Jones/

Counsel for Opposer

EXHIBIT 1

Systems Approach to Nutrient Use Efficiency

By: Jim Krebsbach, Vice President of Sales · Nutrient Use Efficiency

Read any agricultural publication and you will see several articles or advertisements about "soil health" or "nutrient use efficiency" (NUE). Midwestern BioAg has been practicing soil health and nutrient use efficiency for over 30 years and is truly the leader within the Ag industry. So why are "soil health" or "NUE" just now becoming buzz words? Industry experts and growers are starting to understand that there is no silver bullet, no one product or practice to get to soil health or improved NUE. Only Midwestern BioAg can help you un-lock NUE in your fields.

Impacts of Nutrient Use Efficiency

Let's look at your crop and soil performance in a socioeconomic manner. As world population grows, 9 billion people projected by the year 2050, growers need to produce more food to keep up with demand. The US Corn Yield trend-line has been increasing for the last 20 years (figure 1):

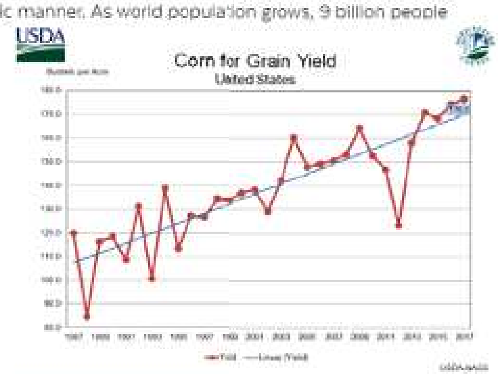

Figure 1 Source: Found at: https://www.nass.usda.gov/Charts_and_Maps/Field_Crops/cornyld.php

As yields increase, more nutrients are needed to be added to replace the nutrients removed in the grain/stover. Fertilizer prices have been up and down recently, and growers need to protect themselves from price volatility. Improving the return on fertilizer purchased is a must, it and starts with a healthy soil. Keeping fertilizer where it is applied is also critical. No one wants to see their nitrogen, let alone fertilizer dollars, flow down the Mississippi River or infiltrate Lake Erie or any other sensitive environmental watershed. Another aspect of NUE is social. Consumers are demanding healthier foods. Healthier food starts with healthier soils and protecting the environment in a sustainable way is essential to this process.

Soil health and NUE are all in the "Carbon" SYSTEM.

The system approach to farming, one that Midwestern BioAg has perfected, is the only way to optimize NUE and soil health. A simple start to building your farming system this spring is for you to take advantage of carbon delivery. Carbon is important as a food source for native soil biology. Carbon in the products in the subheadings below stimulates soil biology and improves NUE once they are applied.

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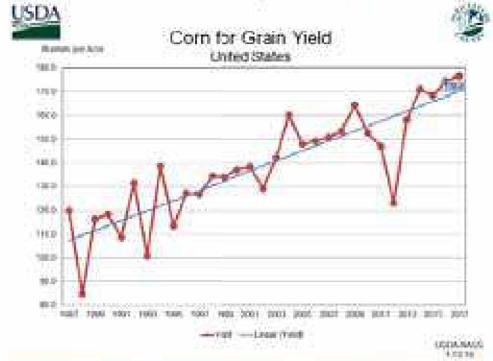

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Inclusion of TerraNu Nutrient Technology into your fertilizer blends.

TerraNu Nutrient Technology™ is an innovative technology that improves NUE by delivering quality, balanced nutrients in a carbon-delivery system. TerraNu Nutrient Technology is a granulated fertilizer that is homogenized with essential nutrients for plant growth. Midwestern BioAg can customize your fertilizer blend to optimize TerraNu inclusion for your field. Ask us today!

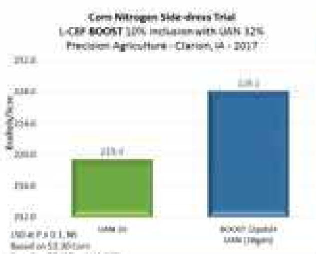

Figure 2: Shows the yield increase in a corn nitrogen side-dress trial in Clarion, IA. 219.4 bushels with 20 gallons of UAN. 228.1 bushels with 18 gallons of UAN and 2 gallons of L-CBF BOOST (10% inclusion rate).

Incorporate L-CBF products into your fertility system as a starter fertilizer or a blend companion.

L-CBF products are another great way to deliver essential nutrients to your crop in a carbon delivery system. Growers utilizing liquid starter fertilizer can take advantage of the benefits L-CBF 7-21-3 either in-furrow or in 2×2. Growers can also add L-CBF Boost into their side-dress or foliar applications. L-CBF Boost has shown consistently promising crop response (figure 2, left). Ask your Midwestern BioAg consultant for more information today!

‹ NUTRIENT USE EFFICIENCY ON ORGANIC FARMS

LIVING WITH LOWER PRICES AND INCREASED COSTS ›

Midwestern BIOAG
918 Deming Way, Suite 200
Madison, WI 53717
(800) 327-6012
Send Us a Message ›

Nutrient Use Efficiency

By: Edwin Suarez, MS, CCA, Technical Agronomist · Soil, Nutrient Use Efficiency

In the current agricultural climate of low commodity prices and increased fertilizer costs, we keep hearing about nutrient use efficiency (NUE) as a key component of farming success. NUE is commonly defined as the yield per unit of input. But why is it important? To illustrate this, let's use the analogy of two pick-up trucks. NUE is the difference between one truck getting 20 MPG compared to a different truck of the same make and model getting 35 MPG by using a higher-quality fuel source. Your crop acts in the exact same way as the truck: feed it a higher-quality input and it will utilize those nutrients more efficiently.

The Fuel: How Much of My Fertilizer Really Goes Into the Crop?

In keeping with the truck analogy, we can think about different grades of gasoline. Because of its quality, one is typically more expensive than the other. Fertilizer nutrients work the same way: plants perform better when a higher-quality, plant-preferred nutrient is provided.

For each macro and micro nutrient the plant needs, there are forms of those elements the plant prefers over others. For example, plants prefer the sulfate form of trace minerals over the oxide form. Taking into account the chemistry of ingredients in fertilizers is important because it directly impacts NUE and crop performance. A mistake growers often make during tough agricultural times, like the ones we face right now, is cutting back on fertilizer quality by buying "cheap" sources. This approach not only results in lower NUE (less BANG for every buck you spend) but it also affects your soil quality since cheap fertilizer sources can negatively impact your soil health. Tough agricultural markets should make us more efficient in our farming operations – and better selection of fertilizers is key.

The Engine: How is My Soil Health Influencing NUE?

The soil is the engine for your crop! Performance and NUE are directly related to your soil quality, just like the quality of your motor impacts your truck's performance. Soils with good structure, high organic matter and a lot of soil life directly improve crop NUE and performance. All nutrient cycles are biologically dependent. A healthy soil is a soil that can transform, transfer and transport nutrients to and from the soil to the plant.

Our slogan "Better Farming Through Better Soils" reflects the science and principles of NUE and optimum crop performance. We design fertilizers that are highly efficient that help you take advantage of the benefits of soil life. Our liquid and dry carbon based fertilizers that feed and enhance soil biology resulting in improved nutrient uptake and higher NUE. Good fertilizer sources in a healthy soil will result in better crops and higher yields and quality for your farm.

‹ NEW TOOLS FOR YOUR ANIMAL NUTRITION TOOLBOX

NUTRIENT USE EFFICIENCY ON ORGANIC FARMS ›

Nutrient Use Efficiency

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‹ NEW TOOLS FOR YOUR ANIMAL NUTRITION TOOLBOX

NUTRIENT USE EFFICIENCY ON ORGANIC FARMS ›

Plant Ecophysiology

© 2014

Nutrient Use Efficiency in Plants

Concepts and Approaches

Editors: **Hawkesford**, Malcolm J., **Kopriva**, Stanislav, **De Kok**, Luit J. (Eds.)

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- ISBN 978-3-319-10635-9

About this book

Nutrient Use Efficiency in Plants: Concepts and Approaches is the ninth volume in the Plant Ecophysiology series. It presents a broad overview of topics related to improvement of nutrient use efficiency of crops. Nutrient use efficiency (NUE) is a measure of how well plants use the available mineral nutrients. It can be defined as yield (biomass) per unit input (fertilizer, nutrient content). NUE is a complex trait: it depends on the ability to take up the nutrients from the soil, but also on

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Gruen, Astrid (et al.)
Pages 93-131

Micronutrient Use Efficiency – Cell Biology of Iron and Its Metabolic Interactions in Plants
Forieri, Ilaria (et al.)
Pages 133-152

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Rakshit, A. (et al.) (Eds.) (2015)

Recent Advances on Mycorrhizal Fungi
Pagano, M.C. (Ed.) (2016)

Crop Improvement
Hakeem, K.R. (et al.) (Eds.) (2013)

Regulation of Nutrient Uptake by Plants
Mitra, G.N. (2015)

DNA Methylation Protocols
Mills, K.I. (et al.) (Eds.) (2002)

Bibliographic Information

Book Title
Nutrient Use Efficiency in Plants

Book Subtitle
Concepts and Approaches

Editors
Malcolm J. Hawkesford
Stanislav Kopriva
Luit J. De Kok

Series Title
» Plant Ecophysiology

Series Volume
10

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2014

Publisher
Springer International Publishing

Copyright Holder
Springer International Publishing Switzerland

Distribution Rights
Distribution rights for India: Researchco Book Centre, New Delhi, India

eBook ISBN
978-3-319-10635-9

DOI
10.1007/978-3-319-10635-9

Hardcover ISBN
978-3-319-10634-2

Softcover ISBN
978-3-319-38217-3

Series ISSN
1572-5561

Edition Number
1

Number of Pages
X, 279

Number of Illustrations
14 b/w illustrations, 27 illustrations in colour

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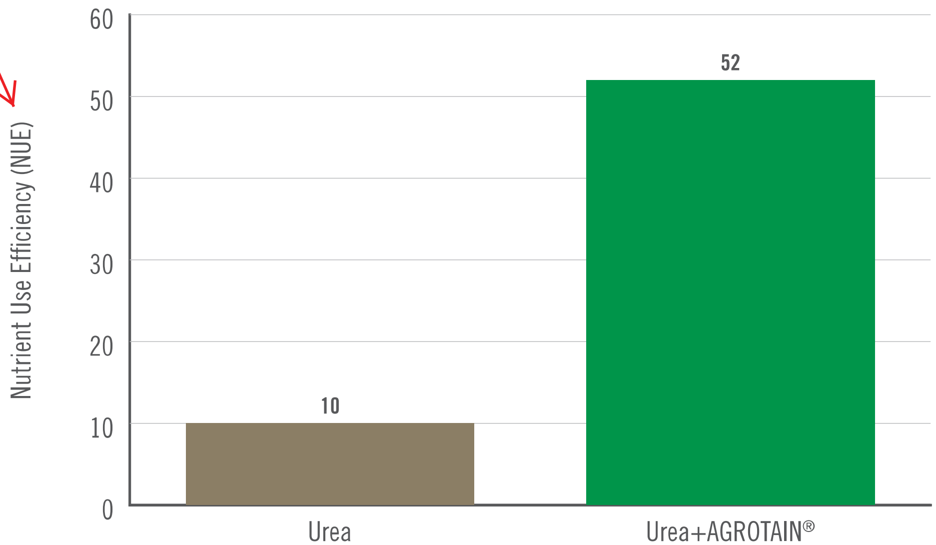

- Field study
- Crowley silt loam soil
- Nitrogen rate of 120 lbs. N/acre
- Source: Harrell, 2015. Louisiana State University.

AGROTAIN® treated urea increased nutrient use efficiency by 42% compared to untreated urea.

Nutrient Use Efficiency in Plants - Concepts and Approaches

Book · December 2014 *with* 3,463 Reads

DOI: 10.1007/978-3-319-10635-9
Publisher: 978-3-319-10634-2
Publisher: Springer

Malcolm Hawkesford
42.67 · Rothamsted Research

Stanislav Kopriva
42.32 · University of Cologne

Luit J. De Kok
40.13 · University of Groningen

Abstract

Nutrient Use Efficiency in Plants: Concepts and Approaches is the ninth volume in the Plant Ecophysiology series. It presents a broad overview of topics related to improvement of nutrient use efficiency of crops. Nutrient use efficiency (NUE) is a measure of how well plants use the available mineral nutrients. It can be defined as yield (biomass) per unit input (fertilizer, nutrient content). NUE is a complex trait: it depends on the ability to take up the nutrients from the soil, but also on transport, storage, mobilization, usage within the plant, and even on the environment. NUE is an important contributor to growth control and yield, the same levels of nutrients may cause growth and yield penalty in one species or variety but not in another one. NUE is of particular interest as a major target for crop improvement. Improvement of NUE is an essential pre-requisite for expansion of crop production into marginal lands with low nutrient availability but also a way to reduce use of inorganic fertilizer. Aspects of NUE have been covered in detail within the Plant Ecophysiology series, in the volumes on nitrogen, phosphorus, sulfur, or root physiology. In this volume the expanding field of nutrient use efficiency is comprehensively discussed, with the aim to present the current approaches, concepts, and ideas on how to better understand the genetic control of NUE and how to use this knowledge for its improvement. This volume, however, is special not only because of the new topic. It is also a presentation of a Marie Curie Initial Training Network BIONUT-ITN (BIOchemical and genetic dissection of control of plant NUTrition). BIONUT-ITN is a network of eight research institutions and one company who came together to provide state-of-the-art research training in different aspects of plant nutrient use efficiency. The individual student´s projects have been linked to ensure that a fully integrated approach is taken to get the whole picture of plant nutrition. This integration is a key feature of the network, as it advances the science beyond focusing on one mineral nutrient, such as nitrogen or sulfur, to look at the combined nutritional needs of the plant using models and crops, in the laboratory as well as in the field. BIONUT is also a hub for activities in plant nutrition field, organizing conferences and fostering new collaborations. This volume is evidence of such integration. The contributions of the eight students span a broad range of themes within NUE. There are detailed reviews focused on single nutrients - sulfur, phosphorus, iron, and boron. Thus, macronutrients are discussed alongside micronutrients needed in small quantities, but still essential. But these reviews stress also the importance of interaction between different nutrients and the need for integrative view on plant nutrition. Other chapters bring overviews of large and complex topics or approaches – natural variation, autophagy, or effects of elevated CO2. Included are contributions targeting nutrient deficiency on a molecular level as well as its monitoring in the field. Together with a thorough introduction into the NUE topic, the book presents ten chapters that wrap up the theme of NUE and the potential for crop improvement. We hope that this book will find broad audience. It is not only an overview of an interesting and important research area; it is also a snapshot of current activities in the field and introduction of new generation of scientists from the BIONUT-ITN. We believe that it will be of interest to graduate students and researchers in a wide range of disciplines including plant nutrition, plant physiology, plant biochemistry, and agriculture.

Chapters (10)

Physiological Basis of Plant Nutrient Use Efficiency – Concepts, Opportunities and Challenges for Its Improvement

Chapter

Dec 2014 · Nutrient Use Efficiency in Plants - Concepts and Approaches · pp.1-27

Martin Reich · Tahereh Aghajanzadeh · Luit J. De Kok

Knowledge on the underlying physiological processes and variables which bias their contribution to nutrient use efficiency (NUE) is crucial to develop strategies for improvement in agroecosystems. This chapter aims to contribute to the understanding of the physiological basis of NUE to develop strategies for improvement by modern breeding, but also conceive the challenges and current limits to do so. General concepts will be …

View

Natural Variation as a Tool to Investigate Nutrient Use Efficiency in Plants

Chapter

Sep 2014 · Nutrient Use Efficiency in Plants. Concepts and Approaches · pp.29-50

Giorgiana Chietera · Fabien Chardon

A huge natural variation exists between individuals within a given plant species. Most of the responses of growth-related traits to different environmental scenarios are genotype dependent. Hence, natural variation in plants provides an interesting and valuable source of genetic diversity to study plant responses to environmental factors. The identification of genes that underlie phenotypic variation has an enormous …

View

Macronutrient Use Efficiency – Sulfur in Arabidopsis thaliana

Chapter

Sep 2014 · Nutrient Use Efficiency in Plants · pp.51-91

Patrycja Baraniecka · Stanislav Kopriva

Sulfur is an essential macronutrient required for proper growth of not only plants but also fungi and prokaryotes. It is present in a wide variety of metabolites such as amino acids: cysteine and methionine, coenzymes, vitamins and many others having distinctive biological functions. Plants take up sulfur from the soil in the form of sulfate via sulfate transporters. It is then reduced and assimilated in bioorganic compounds where …

View

Efficient Mineral Nutrition: Genetic Improvement of Phosphate Uptake and Use Efficiency in Crops

Chapter

Sep 2014 · Nutrient Use Efficiency in Plants · pp.93-1

A. Grün · Martin R Broadley · Peter Buchner · kesford

Phosphorus (P) is an essential macronutrient for plan ich can be a major constraint for agricultural productivity. Economic, political and environmental factors have prioritized the need fo acquisition efficiency (PAE), P utilization efficiency (PUE) and P fertiliser uptake efficiency in crops. P has critical functions in plants and complex interactions in soils. Appropriate screening approaches and implications of…

View

Micronutrient Use Efficiency – Cell Biology of Iron and Its Metabolic Interactions in Plants

Chapter

Sep 2014 · Nutrient Use Efficiency in Plants · pp.133-152

Ilaria Forieri · Rüdiger Hell

Iron (Fe) is an intriguing nutrient due to its dual nature. Its redox properties make it essential for different vital processes in plant cells. But an excess of Fe can be toxic as it catalyses the formation of reactive oxygen species. Therefore Fe homeostasis must be tightly regulated. Different mechanisms contribute to the regulation, including the control of uptake, the intracellular chelation by different molecules and the partitioning into …

View

Boron: A Promising Nutrient for Increasing Growth and Yield of Plants

Chapter [Full-text available]

Sep 2014 · Nutrient Use Efficiency in Plants · pp.153-170

Himanshu Bariya · Snehal Bagtharia · Ashish Patel

Boron (B) is a vital nutrient for plant growth and metabolism. Lack of B in plant tissues causes reductions in crop yields, whilst an excess supply of B may also seriously damage plant tissues and sometimes leads to plant death. Appropriate amounts of B in plants are crucial for normal growth and it significantly increases seed germination and seedling growth. Moreover B has positive effects on the uptake and utilization of other nutrients…

View

Role of Autophagy in Plant Nutrient Deficiency

Chapter

Sep 2014 · Nutrient Use Efficiency in Plants · pp.171-203

Milagros Collados Rodríguez · Katarzyna Zientara-Rytter · Agnieszka Sirko

One of the environmental stresses frequently encountered by plants is nutrient deficiency. Therefore, reuse of valuable cellular nutrients is an important trait in nutrient use efficiency (NUE). High NUE is a desired trait in plants at all developmental steps to reach maximum potentials with minimum inputs. Two highly conserved evolutionary mechanisms are responsible for protein turnover at the cellular level, the ubiquitin-proteasome…

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Mineral Nutrient Depletion Affects Plant Development and Crop Yield

Chapter

Sep 2014 · Nutrient Use Efficiency in Plants · pp.205-228

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Optimal plant development depends on the availability of light, water, favourable temperatures and mineral nutrients. Insufficient availability of plant mineral nutrients leads to growth impairments and yield depressions. In natural environments as well as in agricultural systems, mineral nutrient availability is changing in space and time over the growth season of a plant. Therefore, plants have developed adaptation strategies to …

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Nutrient Use and Nutrient Use Efficiency of Crops in a High CO2 Atmosphere

Chapter

Sep 2014 · Nutrient Use Efficiency in Plants · pp.229-252

Sabine Tausz-Posch · Roger Armstrong · Michael Tausz

Atmospheric CO2 concentrations [CO2] are continually increasing and are predicted to reach ~550 μmol mol−1 by 2050, about a 40 % increase from 2013 levels. Such a large increase in one of the key resources for plant growth will have significant effects on all plants, as carbon assimilation and, consequently, growth and yield is stimulated by the so-called 'CO2 fertilisation effect'. The one sided increase in carbohydrate …

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Monitoring Plant Nutritional Status

Chapter

Sep 2014 · Nutrient Use Efficiency in Plants · pp.253-272

Moez Maghrebi · Fabio Francesco Nocito · GianAttilio Sacchi

Methods and techniques effective in achieving yield objectives, optimizing the use of resources and preventing environmental contamination are defined as agronomic Best Management Practices (BMPs). Considering fertilisations BMPs pursue the aims to match mineral nutrient supply with crop requirements, minimizing their losses from the field. If spatial and temporal information about crop needs were available, precision fertilisation…

View

Citations (8) References (842)

... In particular, plant capability to take up and accumulate Fe is strongly dependent on S availability in the growth medium (Astolfi et al., 2003;Bouranis et al., 2003;Astolfi et al., 2006a;Zuchi et al., 2012) and, on the other hand, Fe deficiency adaptation requires the adjustment of S uptake and assimilation rate (Astolfi et al., 2006b;Ciaffi et al., 2013). Recently, it has been demonstrated in wheat that providing S above adequate concentrations may result in the improvement of Fe use efficiency (Hawkesford et al., 2014) in wheat plants and this S nutritional effect seems to be especially advantageous for plants grown under severe Fe limitation (Zuchi et al., 2012). A possible explanation for this relationship could be that the higher S concentration might play a role in the PS biosynthetic pathway, being methionine the common precursor of both PS and nicotianamine (Mori and Nishizawa, 1987). ...

... Recently, it has been demonstrated in wheat that providing S above adequate concentrations may result in the improvement of Fe use efficiency (Hawkesford et al., 2014) in wheat plants and this S nutritional effect seems to be especially advantageous for plants grown under severe Fe limitation (Zuchi et al., 2012). ...

The effect of excess sulfate supply on iron accumulation in three graminaceous plants at the early vegetative phase

Article

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... As crop harvest removes a substantial amount of N resources from the agroecosystem, a better understanding of crop characteristics influencing N removal, i.e. crop NUE, has the potential to enhance the sustainability related to N depletion (Karp and Shield 2008, Brodt et al. 2011). Crops differing in life strategies, selection histories and photosynthetic pathways may have different characteristics in terms of N and biomass allocation and thus, NUE (Hawkesford et al. 2014). For example, the growth of many annual crops is strongly dependent on high N inputs, while some perennial crops can produce abundant dry matter yield with minimal N fertilization due to their efficient use of internal N (Karp and Shield 2008). ...

... According to the results of Paper IV, the N concentration in plants explained most of the variation in the element concentration pattern, indicating that N was the most limiting factor for wheat growth in this study. These results support the motivation for NUE assessments in crops; since assessment of the use efficiency of an element is reported to be meaningful when that element is the most growth-limiting factor (Hawkesford et al. 2014). ...

Nutrient Economy in Annual and Perennial Crops_ Comparisons Between and Within Crop Species in a Sustainability Context

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... High grain yields require high agronomic inputs, and among these, mineral fertilizers represent major investments, with approximately 13 and 24% of the total investment on sorghum (Sorghum bicolor (L.) Moench) crop production cycle (Wylie, 2008;USDA, 2016). However, despite the large costs, appropriate management of fertilizers and consequently of the soil fertility increases considerably the productivity of crops (Lopes and Guilherme, 2007; Hawkesford et al., 2014). ...

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... High grain yields require high agronomic inputs, and among these, mineral fertilizers represent major investments, with approximately 13 and 24% of the total investment on sorghum (Sorghum bicolor (L.) Moench) crop production cycle (Wylie, 2008;USDA, 2016). However, despite the large costs, appropriate management of fertilizers and consequently of the soil fertility increases considerably the productivity of crops (Lopes and Guilherme, 2007; Hawkesford et al., 2014). ...

Organic matter sources in the composition of pelletized organomineral fertilizers used in sorghum crops

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... For several reasons, researchers chose Se because of its application in ecological, ecotoxicological, and radio ecological sciences. Se may exert diverse beneficial effects at low concentrations including growth promoting activities of higher plants [58] [59][60][61], tolerance of plants by enhancing their antioxidative capacity [62][63][64]and increasing plant resistance against oxidative stress [65][66][67][68]. Different Se forms including organic and some salts have been used in studying its biological effects several years ago, whereas recently, nanoparticles of elemental selenium (SeO) have gained the attention as a possible source of this beneficial element [69]. ...

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December 2013 · Frontiers in Plant Science

Gianpiero Vigani · Graziano Zocchi · Khurram Bashir · [...] · Jean-Francois Briat

Iron (Fe) homeostasis represents an important topic in the plant mineral nutrition, since Fe is an essential cofactor for fundamental biochemical activities. Due to the low availability of Fe in most soils, plants are often limited in Fe content. As a consequence, plants must tightly regulate an effective Fe acquisition, distribution, and utilization in root and leaf cells in order to allow for ... [Show full abstract]

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Chapter

Role of Autophagy in Plant Nutrient Deficiency

September 2014

Milagros Collados Rodríguez · Katarzyna Zientara-Rytter · Agnieszka Sirko

One of the environmental stresses frequently encountered by plants is nutrient deficiency. Therefore, reuse of valuable cellular nutrients is an important trait in nutrient use efficiency (NUE). High NUE is a desired trait in plants at all developmental steps to reach maximum potentials with minimum inputs. Two highly conserved evolutionary mechanisms are responsible for protein turnover at the ... [Show full abstract]

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Nutrient Use and Nutrient Use Efficiency of Crops in a High CO2 Atmosphere

September 2014

Sabine Tausz-Posch · Roger Armstrong · Michael Tausz

Atmospheric CO2 concentrations [CO2] are continually increasing and are predicted to reach ~550 μmol mol−1 by 2050, about a 40 % increase from 2013 levels. Such a large increase in one of the key resources for plant growth will have significant effects on all plants, as carbon assimilation and, consequently, growth and yield is stimulated by the so-called ‘CO2 fertilisation effect’. The one sided ... [Show full abstract]

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Micronutrient Use Efficiency – Cell Biology of Iron and Its Metabolic Interactions in Plants

September 2014

Ilaria Forieri · Rüdiger Hell

Iron (Fe) is an intriguing nutrient due to its dual nature. Its redox properties make it essential for different vital processes in plant cells. But an excess of Fe can be toxic as it catalyses the formation of reactive oxygen species. Therefore Fe homeostasis must be tightly regulated. Different mechanisms contribute to the regulation, including the control of uptake, the intracellular chelation ... [Show full abstract]

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International Fertilizer Industry Association

IWMI International Water Management Institute

IPNI International Plant Nutrition Institute

International Potash Institute

Managing Water and Fertilizer for Sustainable Agricultural Intensification

Chapter 2

Nutrient/fertilizer use efficiency: Measurement, current situation and trends

Paul Fixen[1], Frank Brentrup[2], Tom W. Bruulsema[3], Fernando Garcia[4], Rob Norton[5] and Shamie Zingore[6]

Abstract

Nutrient use efficiency (NUE) is a critically important concept in the evaluation of crop production systems. It can be greatly impacted by fertilizer management as well as by soil- and plant-water management. The objective of nutrient use is to increase the overall performance of cropping systems by providing economically optimum nourishment to the crop while minimizing nutrient losses from the field. NUE addresses some, but not all, aspects of that performance. Therefore, system optimization goals necessarily include overall productivity as well as NUE. The most appropriate expression of NUE is determined by the question being asked and often by the spatial or temporal scale of interest for which reliable data are available. In this chapter, we suggest typical NUE levels for cereal crops when recommended practices are employed; however, such benchmarks are best set locally within the appropriate cropping system, soil, climate and management contexts. Global temporal trends in NUE vary by region. For N, P and K, partial nutrient balance (ratio of nutrients removed by crop harvest to fertilizer nutrients applied) and partial factor productivity (crop production per unit of nutrient applied) for Africa, North America, Europe, and the EU-15 are trending upwards, while in Latin America, India, and China they are trending downwards. Though these global regions can be divided into two groups based on temporal trends, great variability exists in factors behind the trends within each group. Numerous management and environmental factors, including plant water status, interact to influence NUE. Similarly, plant nutrient status can markedly influence water use efficiency. These relationships are covered in detail in other chapters of this book.

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used to estimate N recovery by five subsequent crops, reporting a range of 5.7 to 7.1%, excluding the first growing season. With the first growing season, total RE ranged from 35 to 60%.

Current status and trends in NUE for N

Current status of NUE for N

Ladha *et al*. (2005) conducted an extensive review of 93 published studies where NUE was measured in research plots (Table 6). This review provides estimates of the central tendency for NUE expressions for maize, wheat and rice. Values for PFP and AE were generally higher for maize and rice than for wheat, at least in part due to the higher N content of wheat grain. Values for RE varied widely across regions and crops with a 10th percentile value of 0.2 and a 90th percentile value of 0.9 (grain plus straw). Much of the range in values was attributed to variations among studies in soil, climate and management conditions. The overall average RE of 55% compares well with other published global estimates of 50% by Smil (1999) and 57% by Sheldrick *et al*. (2002) and with estimates for the US and Canada of 56% by Howarth *et al*. (2002) and 52% by Janzen *et al*. (2003) as summarized in Ladha *et al*. (2005).

Table 6. Common NUE values for N for maize, wheat, and rice and for various world regions in 93 published studies conducted in research plots compiled by Ladha *et al.* (2005).

Crop or region	Number of observa-tions*	Average rate of ferti-lizer use (kg ha^{-1})	PFP** (kg kg^{-1})	AE** (kg kg^{-1})	RE** (%)	PE** (kg kg^{-1})
Maize	35-62	123	72(6)	24(7)	65(5)	37(5)
Wheat	145-444	112	45(3)	18(4)	57(4)	29(4)
Rice	117-187	115	62(3)	22(3)	46(2)	53(3)
Africa	2-24	139	39(11)	14(6)	63(5)	23(6)
Europe	12-69	100	50(6)	21(9)	68(6)	28(6)
America	119-231	111	50(5)	20(7)	52(6)	28(8)
Asia	161-283	115	54(3)	22(2)	50(2)	47(3)
Average/ totals	**411**		**52(2)**	**20(2)**	**55(2)**	**41(3)**

*Range in number of observations across NUE indices.
**See Table 1 for definitions of each term; Value in parentheses is relative standard error of the mean (SEM/mean*100).

As mentioned earlier, measured NUE in production fields is often less than from research plots such as those summarized in Table 6. An example offered by Cassman *et al*. (2002) was that average RE for fertilizer N applied by rice farmers in the major rice producing regions of four Asian countries was 0.31 (179 farms) compared to 0.40 for field-specific management (112 farms) and 0.50-0.80 in well-managed field experiments. Balasubramanian *et al*. (2004) reported RE for N in cereals of 0.17-0.33 under current farming practices, 0.25-0.49 in research plots, and 0.55-0.96 as a maximum of research plots. In India, RE averaged 0.18 across 23 farms for wheat grown under poor weather conditions, but 0.49 across 21 farms when grown under good weather conditions (Cassman *et al*., 2002).

Whether trials are in farmer fields or on experiment stations, high-yield cereal systems tend to have higher AE than systems at lower yield levels. This should not be surprising since the higher nutrient requirements of crops at high yield levels are likely to exceed the nutrient supplying ability of soils without the application of fertilizers to a greater extent than at lower yield levels. This increases the difference between the yield of the crop with the application of fertilizers and the yield of the crop without the application of fertilizers. Additionally, a crop with a faster nutrient accumulation rate may reduce the potential for nutrient losses from the production field. In the dataset shown in Figure 3, which is composed of diverse summaries of cereal NUE from around the world, approximately one-third of the variability in AE for N could be explained

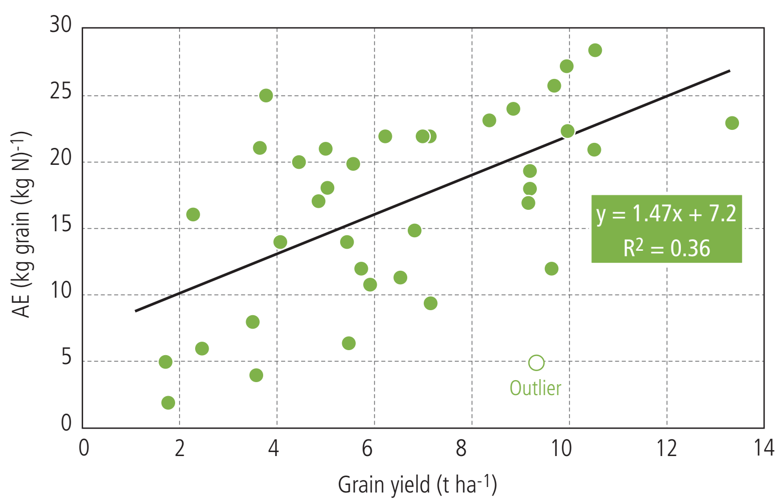

Figure 3. Influence of yield level of the fertilized treatment on typical AE for N reported in NUE summaries of farm and experiment station trials (n=37; data sources: Dobermann, 2007; Ladha *et al.*, 2005; Lester *et al.*, 2010; Liu *et al.*, 2011; Iowa State U. Agronomy Extension, 2011; Norton, R.M., Based on data from Long term NxP experiment in Australia – Dahlen, personal communication. 2011.; Singh *et al.*, 2007).

simply by average grain yield. Yield variation in the dataset was due to a multitude of factors including climate, cropping system, soil properties and system management.

Trends in NUE for N

The considerable variability existing in NUE across regions and cropping systems manifests itself in temporal trends as well. Countries with intensive agriculture—such as US, Germany, UK, and Japan—generally show increasing NUE as a result of stagnant or even decreasing N use and increasing crop yields (Dobermann and Cassman, 2005). However, cropping systems within these countries can vary greatly in temporal trends.

Understanding the whole-system context of NUE trends is critical to proper interpretation of these trends. Comparing PFP trends for N for maize and wheat in the US illustrates this point (Figure 4). Maize PFP increased approximately 50% from 1975 to 2005 while wheat PFP decreased 30% during this same time period, but then increased 30% from 2005 to 2010. The increase in maize PFP resulted mostly from

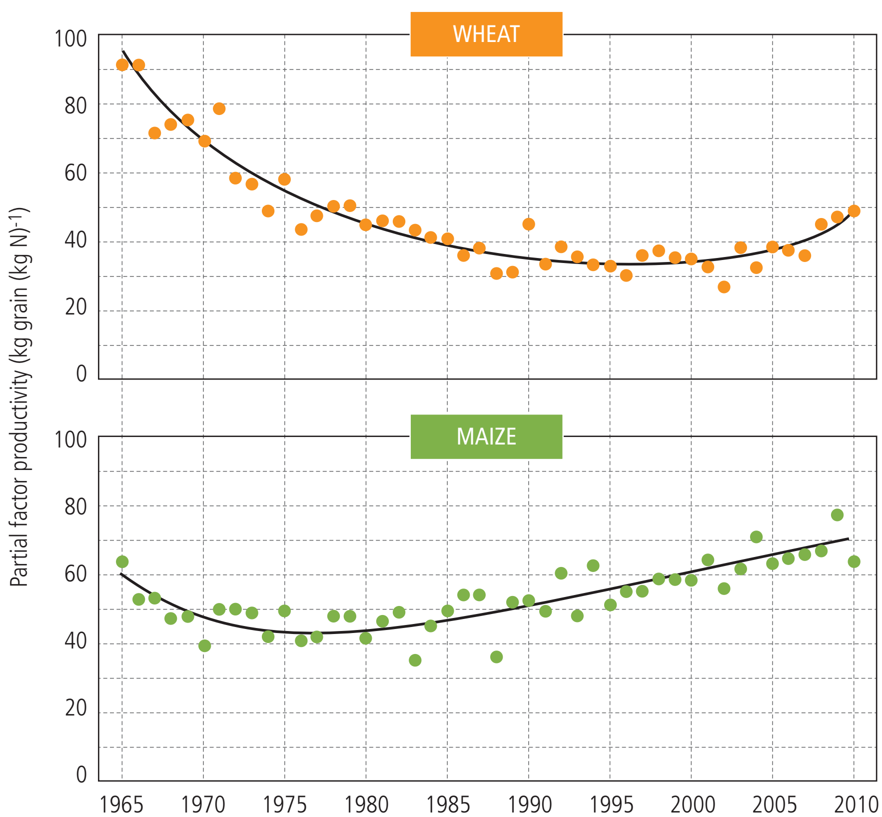

Figure 4. Partial factor productivity in the US for fertilizer N used on maize and wheat from 1965 to 2010 (adapted from USDA-ERS and USDA-NASS, 2011).

improved genetics and crop, soil and nutrient management, which boosted yields by over 80% during this 30-year period. The net effect has been a linear increase in PFP for the last 25 years at a rate of 0.9 kg grain (kg N)$^{-1}$.

So, in the same country where growers had the same access to technology and innovation, why did wheat production not show a similar trend? The answer likely lies in differences between the dominant maize and wheat regions in cropping, tillage and fertilizer application histories. The dominant wheat region has been undergoing a transition from management systems where the dominant N source was the tillage and fallow-induced mineralization of soil organic matter to a less tilled, more intensively cropped system that conserves or builds soil organic matter (Clay *et al*., 2012). During this transition, wheat production became more dependent on fertilizer as an N source because of the reduction in mining of soil organic N, reducing apparent PFP and PNB (closer to 1). Comparison of PNB between Illinois (a maize-dominant state) and Montana (a wheat dominant state) shows unsustainably high N balances in the past for Montana which have been declining for the past 20 years, while Illinois had potential for closing the gap in the N balance (Table 7). More recently, the PFP trend for wheat has reversed due likely to the same factors that have been increasing PFP for maize systems (Figure 4).

Table 7. Partial nutrient balance for N in Illinois and Montana from 1987 to 2007 (IPNI, 2012a).

State	Dominant cropping system	Partial nutrient balance by year*				
		1987	1992	1997	2002	2007
Illinois	Maize-soybean	0.71	0.76	0.76	0.86	0.87
Montana	Wheat	1.35	1.33	1.00	1.04	1.01

*(Removal by harvest) (Fertilizer N + Recovered manure N + biological N fixation)$^{-1}$

In countries where agriculture is in general undergoing intensification, PFP often shows decreasing trends because fertilizer N use increases at a faster rate than crop yields, though yields are also increasing (diminishing returns). Such is the case for wheat and maize in Argentina (Figure 5). As in the above case for wheat in the US, such declines in PFP are often accompanied with more sustainable PNB relationships where less mining of soil nutrients is occurring. If biological N fixation is not included in the N balances, such shifts can be misleading if the frequency of legumes in the rotation changes over time.

Developing a picture of regional trends in NUE around the world requires a systematic approach where all regions are estimated using a consistent protocol over time. We used that approach in developing Figures 6 and 7 for N and Figures 11 to 14 for P and K. The figures show NUE trends from 1983 to 2007 with each point representing the average of a 5-year period. Data availability (FAO, 2012; IFA, 2012) limited the indicators estimated to PFP and PNB. For nutrient inputs, only mineral fertilizer consumption was considered, excluding nutrients in livestock manure, atmospheric deposition,

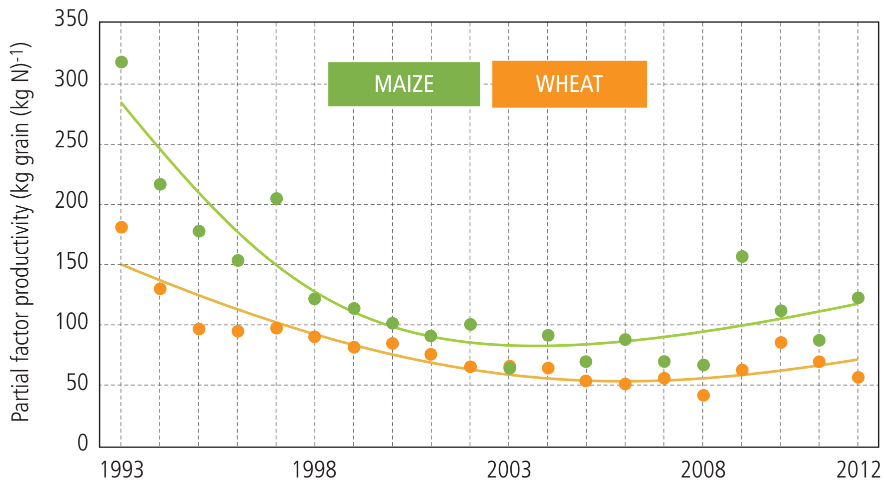

Figure 5. Partial factor productivity in Argentina for fertilizer N used on maize and wheat from 1993 to 2011 (adapted from Garcia and Salvagiotti, 2009).

biological N fixation, and municipal wastes. The crops included from the FAO database were 38 fruits and vegetables, 9 cereals, 9 oil crops, 6 pulse crops, 5 root or tuber crops, and 5 other crops. The major category not included was forage crops that included crops such as silage maize, alfalfa and other hay. This category can be a large source of productivity and nutrient removal in regions where significant confinement livestock operations exist. For example, in the US alfalfa and "other hay" account for over 15% of the total national P removal and over 40% of the K removal (PPI/PPIC/FAR, 2002). However, a proportion of the nutrients contained in forage crops will be returned to the fields as animal manure, but since both forage crops as output and manure as input are excluded from these NUE estimates, the error introduced should in most cases not be large at this broad regional scale. Since biological N fixation was not included for the input estimate, N removal by legumes was also not included for calculating PNB. This may skew regions with more legumes in the rotation towards higher PNB estimates. The nutrient concentration of harvested crops was based on literature values or research trial data (J. Kuesters (Yara), personal communication, 2012).

World PFP and PNB levels have shown a very slight increase over this 25-year period. Regional temporal trends in PFP for N are, in most cases, similar to PNB but trends among global regions clearly differ (Figures 6 and 7). Africa and Latin America in 1985 had by far the highest PFP and PNB values but with trends in opposite directions. The PFP data show that both these regions have extremely high productivity per unit of fertilizer N applied. However, the excessive PNB values for Africa show that it is becoming more dependent on non-fertilizer sources to balance crop removal of N, a precarious and unsustainable situation. In contrast, Latin America has maintained very

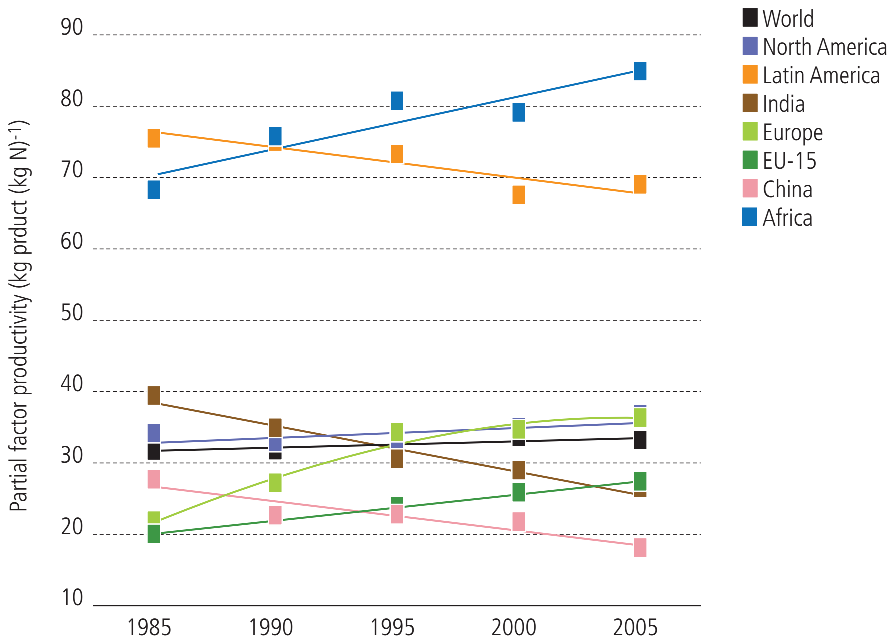

Figure 6. Partial factor productivity for N in global regions, 1983-2007.

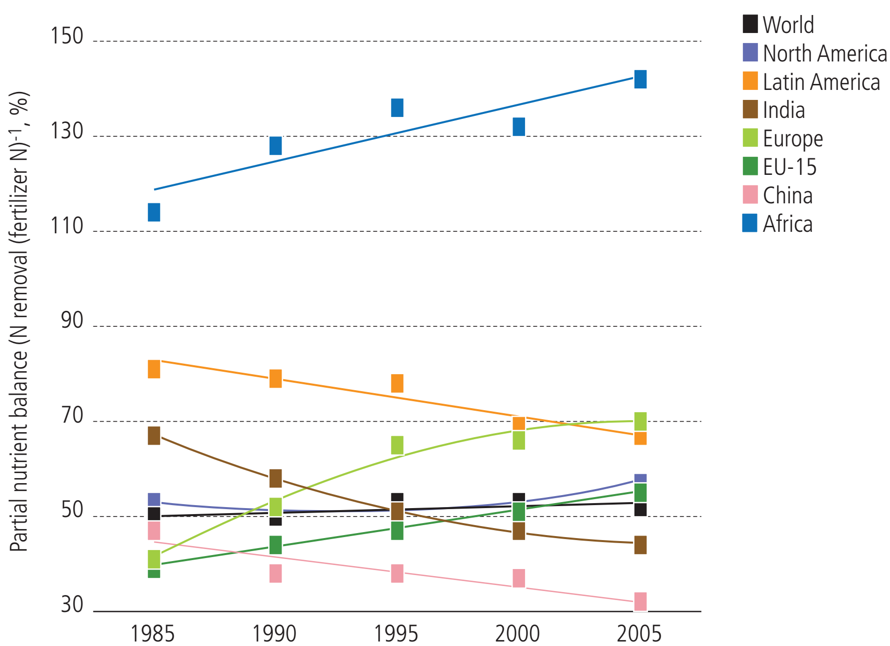

Figure 7. Partial nutrient balance for N in global regions, 1983-2007.

high productivity per unit of N but has also moved towards a more sustainable nutrient balance.

In general, PNB and PFP for Africa, North America, Europe, and the EU-15 are trending upwards, while Latin America, India, and China are trending downwards. It is interesting to note that PNB for Europe during the last decade appears to have leveled off at around 70%, and that PNB for Latin America, India, and China has been declining at about the same rate for the 25-year period.

Trends in NUE for P and K

The major effects of soil properties and typically large legacy effects of previous management dominate NUE relationships for P and K. While most of the benefit and recovery of N addition occur during the year of application, much of the benefit of P and K application on many soils occurs in subsequent years due to effects on soil fertility (Syers *et al*., 2008). Appropriate evaluation of the current status and long-term trends of NUE for P and K needs to consider these residual effects. Short-term AE, RE and PFP for P and K are usually best interpreted within the context of current soil fertility status and associated PNB which indicates future soil fertility status if the current PNB remains unchanged.

Efficiency measures are greatly influenced by nutrient rate applied and by soil fertility. The P data summarized in Figure 8 are from research conducted in farmer fields in the Southern Cone of South America. Available P in all fields tested was lower than critical values so that a profitable response to P was expected. Agronomic efficiency was highest

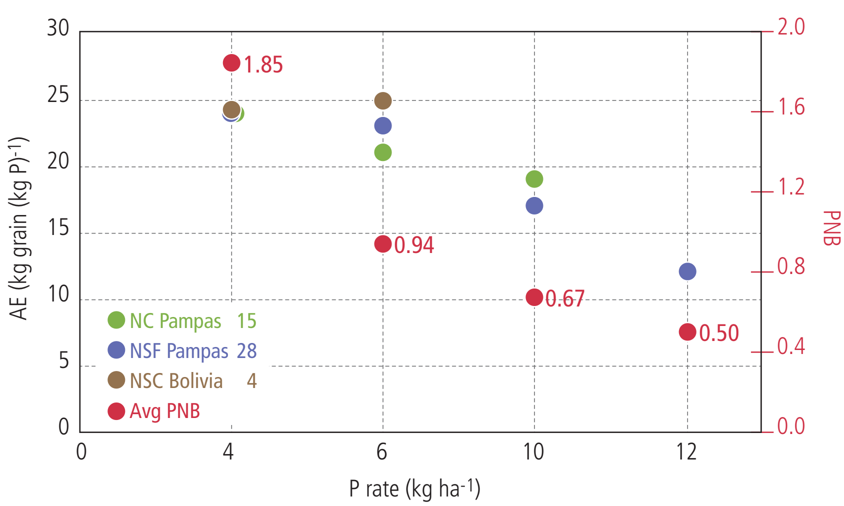

Figure 8. Influence of P rate on agronomic efficiency and partial nutrient balance of soybean in the Southern Cone of South America (adapted from Ferrari *et al.*, 2005; H. Fontanetto, pers. comm.; and Terrazas *et al.*, 2011). Numbers for each group in the legend indicate the number of field trials (n)

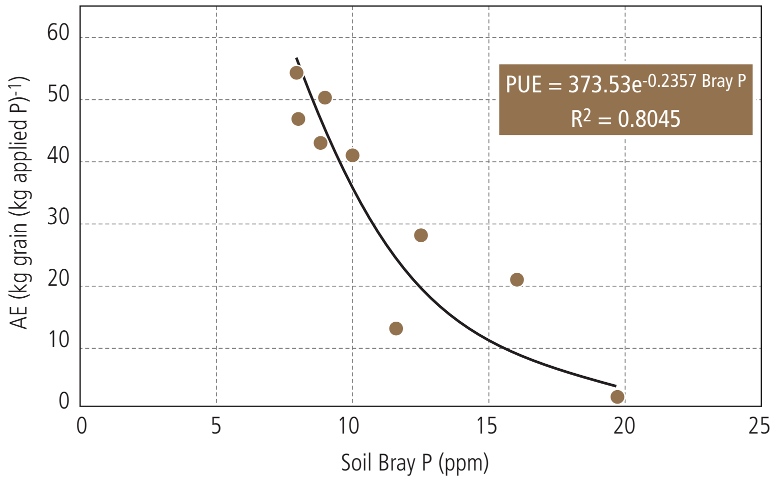

Figure 9. Influence of soil fertility on agronomic efficiency of P fertilizer in wheat experiments in Argentina (Garcia, 2004).

at low rates of P with the lowest rate (10 kg ha^{-1}) being common for soybean-based cropping systems of the region. This rate resulted in an average PNB of 1.85 where soil P levels would be depleted over time – a non-sustainable situation, but better than no fertilizer P at all. The higher rates generated somewhat lower AE values but had PNB values less than one where soil P would be maintained or increased with time. These data illustrate the value in considering multiple NUE indicators when assessing P management.

The effect of soil P fertility on AE and RE is illustrated by wheat experiments from Argentina (Figure 9). Very high AE and RE are measured when soil fertility is well below critical levels and rapidly decline as soil fertility increases. Sustainability is associated with the intermediate AE and RE values observed when rates applied are close to removal, and soil fertility levels are maintained near the critical level.

First year RE in field trials across Asia indicates P recoveries near 25% are typical in that region when fertilizer P is applied at recommended rates (Table 8). These studies were mostly on soils with low P fixation potential and were under favorable climate and management conditions. Dobermann (2007) pointed out that though the average RE values were similar across studies, within-studies RE varied widely from zero to nearly 100%, but that 50% of all data fell in the 10 to 35% RE range. Such variability is to be expected due to the soil fertility and the effects of application rate of fertilizers discussed above.

Regional aggregate data can be used to evaluate the current status of P use and its impact on temporal trends of soil fertility and to test the assumption that P balance impacts soil fertility. Soil tests conducted for the 2005 and 2010 crops in North America by private and public soil-testing laboratories were summarized by IPNI. In Figure 10, the change in median soil P levels for the 12 Corn Belt states over this 5-year period is plotted against the PNB for this same time period. Values of PNB above 0.94 resulted

Table 8. Average RE of P and K from mineral fertilizers in field trials with rice, wheat and maize in Asia. Values shown refer to recommended fertilizer rates or in the case of rice, those that were currently being applied by farmers (Dobermann, 2007; Liu *et al.*, 2006).

Crop, region or management	Number of field trials	Time period	P RE (%)	K RE (%)
*Rice in Asia; farmer's practice	179	1997-1998	24	38
*Rice in Asia; site-specific management	179	1997-1998	25	44
Wheat in India	22	1970-1998	27	51
Wheat in China	744	1985-1995	22	47
Maize in China	592	1985-1995	24	44

*China, India, Indonesia, Philippines, Thailand, and Vietnam.

in declining soil P levels with substantial declines measured for the states with the most negative P balance. These data suggest that long-term PNB is a reasonably good indicator of the future direction of soil P fertility on non-P fixing soils. These relationships would likely differ for low P Oxisols and Andisols that typically have a high capacity to sorb or "fix" applied P; in these soils, a considerably lower PNB would be needed initially to

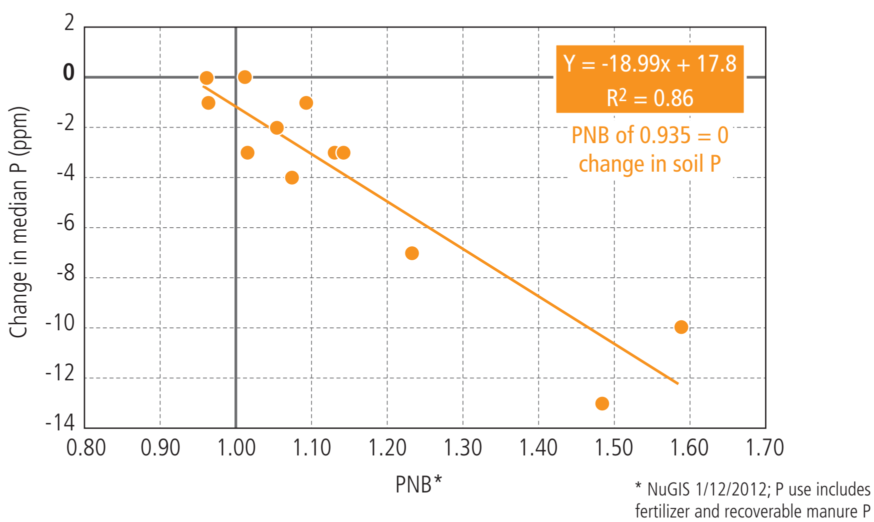

Figure 10. Change in median soil P level for 12 US Corn Belt states as related to state PNB, 2005-2009 (updated from Fixen *et al.*, 2010).

build soil P fertility until high affinity sorption sites are satisfied. Soils with large amounts of free calcium carbonate where precipitation reactions control P in solution, such as those in southern Australia, would also be exceptions where fertilizer P effectiveness in building soil fertility would remain low (McLaughlin, 2012).

The same approach used for N in developing a picture of regional trends in NUE around the world was used for P (Figures 11 and 12). As with N, world PFP and PNB for P have increased over this 25-year period with PFP in the last 5-year period (2003-2007) approaching 195 kg production per kg P and PNB approaching 70%. Regionally, Africa has markedly separated itself from all other regions in terms of both PFP and PNB. In the 1983-1987 period, Africa, India and China had nearly identical PNB levels for P of around 90%, but moved in opposite directions over the 25-year period with PNB in Africa doubling to over 180% while in China and India it dropped to approximately 50%. The PNB value for Africa indicates extreme mining of soil P while the values in China and India indicate that soil P levels should be increasing. These values do not take into account changes in the use of local rock phosphate but there is no evidence that this was significant. There is a paucity of reliable information on the use of rock phosphate as a direct application fertilizer in Africa, but various sources indicate that amounts used have remained very low. Average application rates at the country level are less than 0.5 kg ha^{-1}, even for countries with the highest application rates, indicating insignificant P contribution from rock phosphate sources.

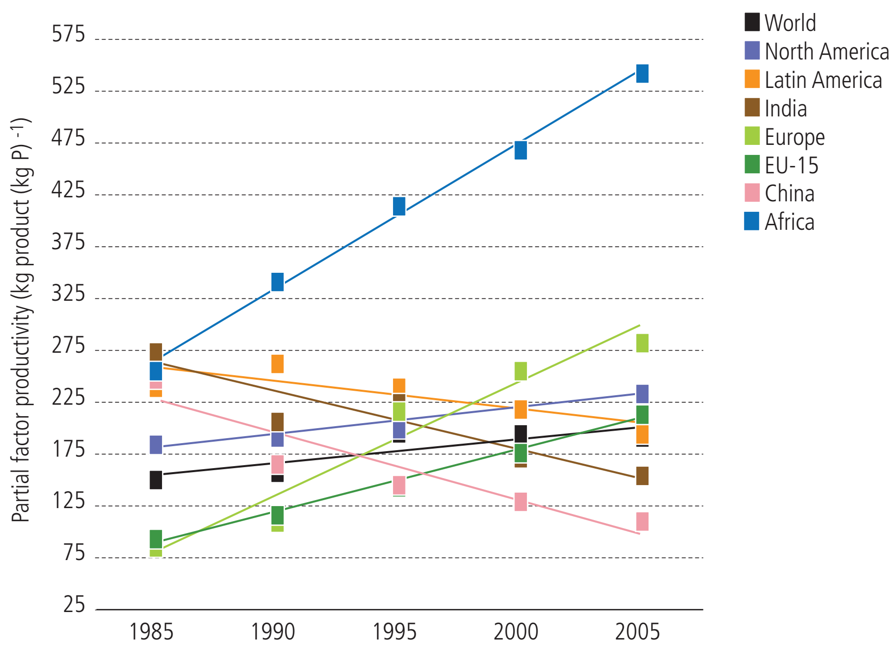

Figure 11. Partial factor productivity for P in global regions, 1983-2007.

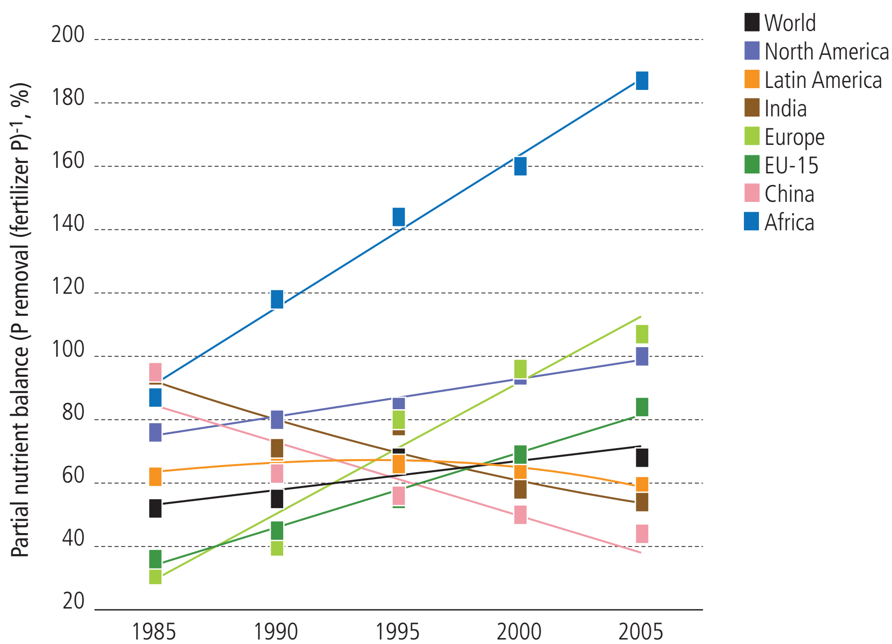

Figure 12. Partial nutrient balance for P in global regions, 1983-2007.

In general, PNB and PFP for Africa, North America, Europe, and EU15 are trending upwards in P, while Latin America, India, and China are trending downwards, just as was the case for N. The absence of manure inputs in these NUE estimates impacts some regions much more than others and should be kept in mind in comparing the absolute values of the expressions. Differences in temporal trends (slopes of the lines) are likely to be more reliable.

Information on K use efficiency is more limited than either N or P. This is partly due to the environmentally benign nature of K where interest in efficiency is driven primarily by agronomic or economic factors. The result is less support for research and education on efficient use. The first year recovery efficiency for K is generally believed to be higher than for P with the exception of some strongly fixing clay soils. The first year recovery of applied K has been reported in the range of 20 to 60% (Baligar and Bennet, 1986). Dobermann (2007) summarized average recovery efficiencies in field trials in Asia conducted prior to 1998 showing a range of 38 to 51% (Table 8). Jin (2012) summarized field trials on cereal crops in China, conducted from 2002 to 2006 using an omission plot design, and showed RE for K in the 25 to 32% range and average AE values of 8 to 12 (Table 4). In a more recent set of field trials on winter wheat in North-Central China, RE values for K were somewhat higher in the 34 to 44% range but AE values were again in the 8 to 10 range (Table 9; He *et al.*, 2012). The researchers indicated that

Table 9. NUE of K from mineral fertilizers in three field trials with winter wheat in North-Central China. Average of 2007-2009 (He *et al.*, 2012).

Province	Average rate (kg K ha^{-1})	RE (%)	AE (kg kg K^{-1})
Hebei	81	43	10.2
Shandong	75	44	9.9
Shanxi	100	34	8.1

the lower AE was likely due to K application rates exceeding the optimum for the soil K supply of individual site-years. Dobermann (2007) suggested that AE levels for K of 10-20 were realistic targets for cereals on soils that do not have high available K reserves.

The same approach used for N and P in developing a picture of regional trends in NUE around the world was used for K (Figures 13 and 14). As with N and P, world PFP and PNB for K have increased over this 25-year period, with PFP in the last 5-year period (2003-2007) approaching 145 kg of production kg^{-1} K and PNB approaching 140%. Globally, non-forage crops were removing 40% more K than was being applied as commercial fertilizer during this 5-year period. Regionally, across the 25-year period China underwent the greatest change in PNB, from removing more than 5 times as much K as was being applied to a PNB approaching 100% where K removal and fertilizer

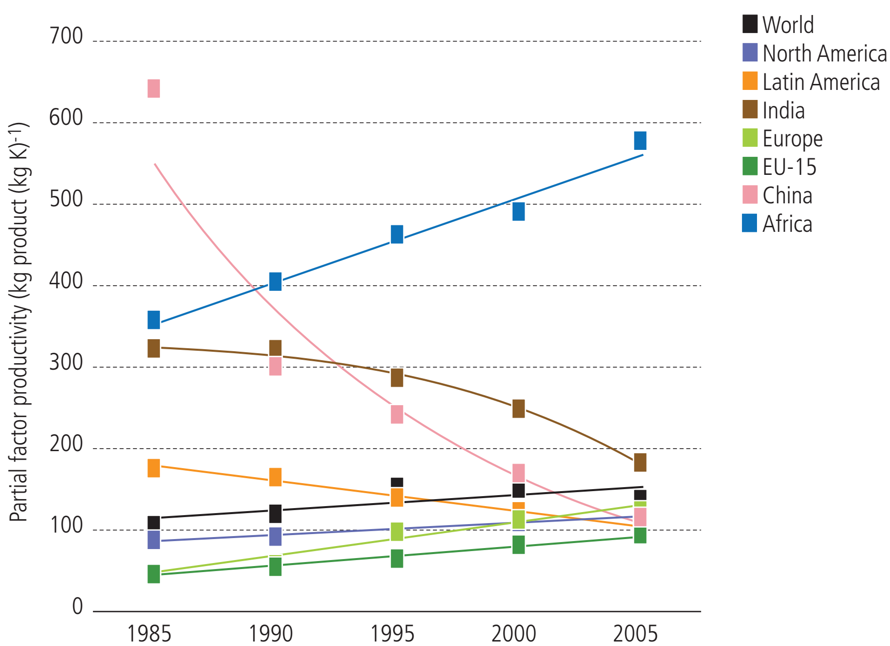

Figure 13. Partial factor productivity for K in global regions, 1983-2007.

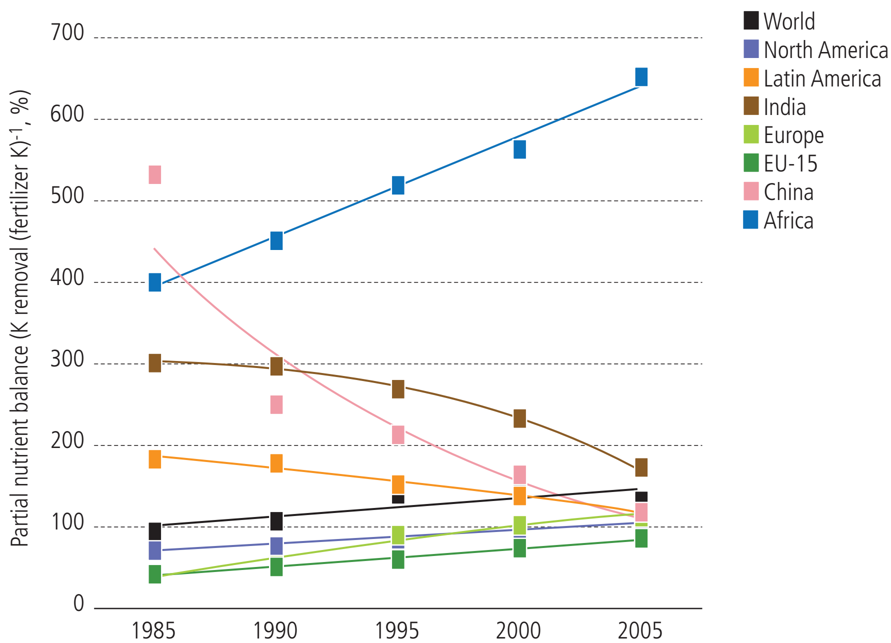

Figure 14. Partial nutrient balance for K in global regions, 1983-2007.

K application are equal. For Africa, both PFP and PNB increased markedly across the 25 years with a PNB in 2003-2007 indicating that crops removed more than six times the amount of K that was applied as fertilizer.

In general, PNB and PFP for Africa, North America, Europe, and EU-15 are trending upwards in K, while Latin America, India, and China are trending downwards, just as was the case for N and P. The absence of forage crop production and K removal in these NUE estimates impacts some regions much more than others and should be kept in mind in comparing the absolute values of the expressions. Differences in temporal trends (slopes of the lines) are likely to be more reliable.

NUE, water and a look forward

Numerous management and environmental factors interact to influence NUE including plant water status. Similarly, plant nutrient status can markedly influence water use efficiency (WUE). The rest of this book will explore the interaction between these two critical crop growth factors. WUE can be improved through nutrient management (Hatfield *et al.*, 2001) although in arid environments it can be important to balance preanthesis and postanthesis growth to ensure adequate water remains to fill grain (van Herwaarden *et al.*, 1998). Nutrient availability affects aboveground biomass, canopy cover to reduce soil evaporation, plant residue production, nutrient dynamics in soil, and thereby improves crop growth and WUE (Maskina *et al.*, 1993; Halvorson *et al.*, 1999; Norton and Wachsmann, 2006). Adequate nutrient supply has shown to improve WUE in several crops (Smika *et al.*, 1965; Corak *et al.*, 1991; Campbell *et al.*, 1992; Varvel, 1994; Payne *et al.*, 1995; Davis and Quick, 1998; Correndo *et al.*, 2012).

Data from a lysimeter experiment conducted in Canada on spring wheat offers an excellent example of the relationship between NUE measures and WUE across a range of N levels (Figure 15). The study included both rainfed (dry) and irrigated (irr) treatments and shows the tremendous impact water status can have on yield response to N and the resulting AE and PNB. The lower graph in the figure shows that a water deficit markedly reduced both AE and PNB at all N levels, but that the efficiency reduction was considerably greater at the lower N levels. The upper graph in Figure 15 shows

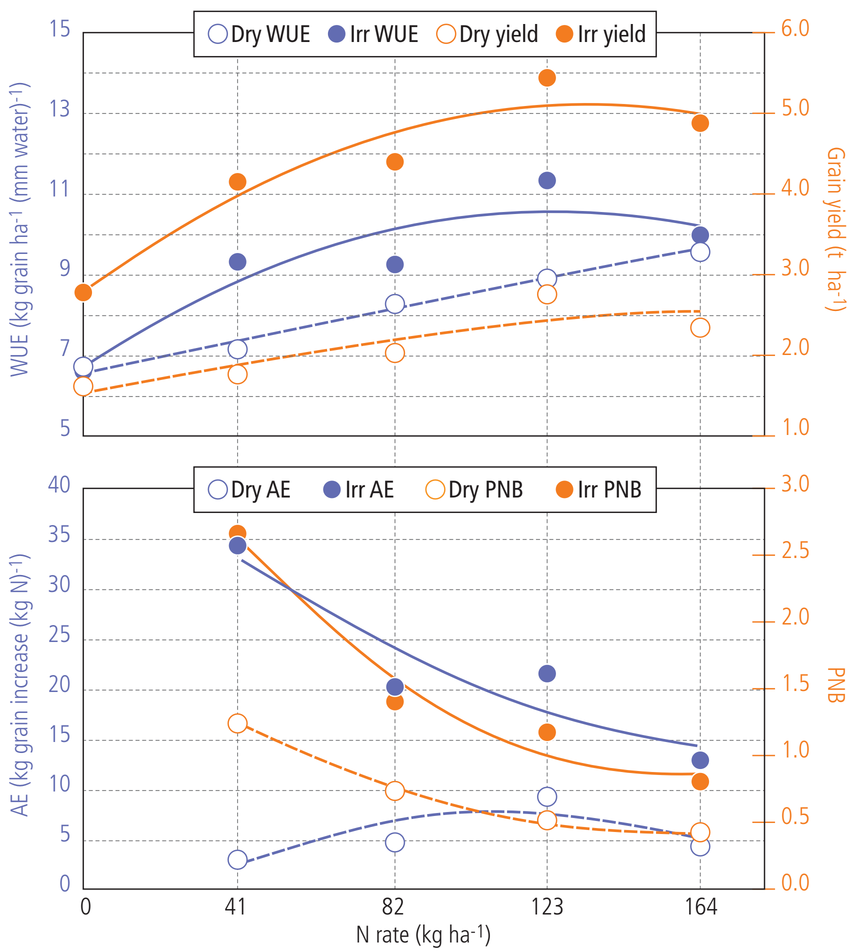

Figure 15. Influence of water status and N application on spring wheat yield and water and N use efficiency in a lysimeter experiment in Saskatchewan, Canada (adapted from Kröbel *et al.*, 2011 and Kröbel *et al.*, 2012, based on original data from Campbell *et al.*, 1977a,b).

improvement in WUE as N levels increase for both the dryland and irrigated treatments. The lower apparent optimum N level for both yield and WUE for the irrigated treatment reflects higher NUE under irrigation shown in the bottom graph.

We draw this chapter to a close reinforcing a point made earlier – that the objective of nutrient use is to increase the overall performance of cropping systems. The data in Figure 15 illustrate that even though NUE generally decreased as N rates increased, the simultaneous increase in WUE and yield until an optimum N rate was attained improved overall system performance. Efficient and effective use of either water or crop nutrients requires that both be managed at optimum levels for the specific system.

Continuous improvement in system performance is a fundamental objective in sustainable intensification. Such improvement is the product of management changes made by individual farmers for individual fields. Numerous efficiency and productivity enhancing nutrient management technologies and practices exist today and are described elsewhere in this book, but many are underutilized. Looking forward, locally defined guidelines for NUE indices that are specific for nutrients, soils, and cropping systems and that can be readily determined by farmers are needed. Such guidelines would help farmers identify what to measure and where improvement is most needed and may be easiest to advance. Guidelines would help define the need for and impact of changes in management on system performance.

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20 Jul 2001

Nutrient Use Efficiency Articles

Latin American Nutrient Use Efficiency Symposium Proceedings Translated to English

Whether in the large-scale production regions of the Cerrado of Brazil or the Pampas of Argentina or in the small-holder fields of Central American mountain villages, nutrient use efficiency (NUE) will be of growing importance in the future. In November 2009, the International Plant Nutrition Institute (IPNI) presented a Symposium called "Nutrient Use Efficiency" at the XVIII Latin American Congress of Soil Science in San José, Costa Rica. The original proceedings of this Symposium were published in Spanish. The six presentations in the proceedings have been translated to English and are available here as a PDF file, containing 50+ pages. Since the principles of appropriate nutrient management are universal, the first three papers from the symposium focus on general principles. However, because best management practices — which are the in-field manifestation of appropriate nutrient stewardship — are site-specific, the second part of the Symposium proceedings focuses on specific regions of Latin America.

The PDF file posted here is available free for download. It is also available on CD. To obtain the Symposium Proceedings publication in Spanish, contact Dr. José Espinosa at >jespinosa@ipni.net< or Dr. Fernando García at >fgarcia@ipni.net<.

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Nutrient Use Efficiency and Effectiveness in North America: Indices of Agronomic and Environmental Benefit

MINERAL FERTILIZERS have made it possible to sustain the world's growing population, sparing millions of acres of natural and ecologically-sensitive systems that otherwise would have been converted to agriculture. Today, economic and environmental challenges are driving increased interest in nutrient use efficiency. Higher prices for both crops and fertilizers have heightened interest in efficiency-improving technologies and practices that also improve productivity. In addition, nutrient losses that harm air and water quality can be reduced by improving use efficiencies of nutrients, particularly for nitrogen (N) and phosphorus (P).

The world's population, growing in both numbers and purchasing power, is projected to consume more food, feed, fiber, and fuel—increasing global demand for fertilizer nutrients. Since fertilizers are made from non-renewable resources, pressure to increase their use efficiencies will continue. At the same time, efforts should increase to enhance fertilizer use effectiveness for improved productivity and profitability of cropping systems.

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Recent Developments of Fertilizer Production and Use to Improve Nutrient Efficiency and Minimize Environmental Impacts

This chapter was written by S. H. Chien, L. I. Prochnow, and H. Cantarella, and published in 2009 in *Advances in Agronomy*, volume 102. We thank Elsevier Inc. for authorizing its public distribution.

Information is provided on some recent developments of fertilizer production and use that improve nutrient efficiency and minimize environmental impact. The nutrients discussed are mainly N, P, and S.

Improving N nutrient efficiency includes use of (1) controlled-release coated urea products, (2) slow release urea–aldehyde polymer products, (3) urea supergranules for deep placement, (4) nitrification inhibitors to reduce nitrate leaching and denitrification, (5) urease inhibitors to reduce ammonia volatilization from urea, and (6) ammonium sulfate to enhance N efficiency of urea.

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Improving efficiency of conventional P fertilizers includes use of (1) coated water-soluble P fertilizers, (2) urea supergranules containing P and K nutrients, and (3) fluid P fertilizers. Use of nonconventional P fertilizers includes (1) phosphate rock (PR) for direct application with a newly developed computer-based phosphate rock decision support system (PRDSS), (2) a mixture of PR and water-soluble P sources, (3) calcined nonapatite PR for direct application, and (4) nonconventional acidulated P fertilizers containingwater-insoluble but citrate-soluble P compounds.

The agronomic effectiveness of newly developed granular NP fertilizers containing elemental S to provide S nutrient is discussed.

Two processes of producing (1) partially acidulated P fertilizers and (2) compound fertilizers of NP and K by bulk blending are recommended for reducing Cd uptake from P fertilizers by crops. The use of these nonconventional fertilizers may result in an increased relative economic benefit with respect to the use of conventional fertilizers in terms of saving fertilizer cost, enhancing nutrient efficiency, or increasing crop yield.

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Original Articles

NUTRIENT USE EFFICIENCY IN PLANTS

V. C. Baligar, N. K. Fageria & Z. L. He

Pages 921-950 | Published online: 05 Feb 2007
Download citation https://doi.org/10.1081/CSS-100104098

Abstract

Invariably, many agricultural soils of the world are deficient in one or more of the essential nutrients needed to support healthy plants. Acidity, alkalinity, salinity, anthropogenic processes, nature of farming, and erosion can lead to soil degradation. Additions of fertilizers and/or amendments are essential for a proper nutrient supply and maximum yields. Estimates of overall efficiency of applied fertilizer have been reported to be about or lower than 50% for N, less than 10% for P, and about 40% for K. Plants that are efficient in absorption and utilization of nutrients greatly enhance the efficiency of applied fertilizers, reducing cost of inputs, and preventing losses of nutrients to ecosystems. Inter- and intra-specific variation for plant growth and mineral nutrient use efficiency(NUE) are known to be under genetic and physiological control and are modified by plant interactions with environmental variables. There is need for breeding programs to focus on developing cultivars with high NUE. Identification of traits such as nutrient absorption, transport, utilization, and mobilization in plant cultivars should greatly enhance fertilizer use efficiency. The development of new cultivars with higher NUE, coupled with best management practices (BMPs) will contribute to sustainable agricultural systems that protect and promote soil, water and air quality.

Article

Fertilizer use efficiency: Maximising fertilizer efficiency by overcoming constraints to crop growth

George W. Cooke

Journal of Plant Nutrition
Volume 10, 1987 - Issue 9-16

Published online: 21 Nov 2008

Article

The Role of Nutrient Efficient Plants in Improving Crop Yields in the Twenty First Century

N. K. Fageria et al.

Journal of Plant Nutrition
Volume 31, 2008 - Issue 6

Published online: 4 Jun 2008

Article

Nitrogen Use Efficiency of Crop Plants: Physiological Constraints upon Nitrogen Absorption

Anthony D. M. Glass

Critical Reviews in Plant Sciences
Volume 22, 2003 - Issue 5

Published online: 24 Jun 2010

Article

Effects of Nutrient Antagonism and Synergism on Yield and Fertilizer Use Efficiency

René P. J. J. Rietra et al.

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Agronomy Journal - Biofuels

Switchgrass Cultivar, Yield, and Nutrient Removal Responses to Harvest Timing

A. J. Ashworth *[a], F. L. Allen[b], J. L. Bacon[b], C. E. Sams[b], W. E. Hart[c], J. F. Grant[d], P. A. Moore Jr.[a] and D. H. Pote[a]

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doi:10.2134/agronj2017.01.0018

Core Ideas:

- Phosphorus and K are assumedly remobilized in switchgrass post-senescence.
- Yields peaked early November, but P and K removal did not vary across harvests.
- Nutrient removal was lesser for upland compared to lowland cultivars.
- Switchgrass can be harvested as early as mid-September without removing greater amounts of P and K.

Abstract

Finite nutrients, such as P and K are assumedly remobilized post-senescence in herbaceous feedstocks like switchgrass (*Panicum virgatum* L.) as a function of environmental signaling and genotype. Harvesting early during the maturation phase may result in yield reductions and higher nutrient removal in biomass depending on ecotype. Therefore, it is necessary to target harvest dates that optimize yield while minimizing nutrient removal per cultivar. Consequently, objectives were to compare yields from 2010–2011 on eight widely used and experimental upland and lowland genotype (whole plot) at two locations in Tennessee, to determine: (i) which harvest timing (split-plot) provides maximum yield; (ii) effects of harvest timing (mid-September, October, November, and late October) on overall total P and K removal, and, (iii) how results are affected by cultivar. Among all post-senescence harvests, yields peaked early November (13.2 Mg ha^{-1}), which was greater than all other harvests ($P < 0.05$), with mid-October and late October not differing from one another. Because yields peaked in early November, P and K removal did not vary across harvest dates (despite both P and K concentrations declining mid-October). Lowland cultivars yielded 3.9 Mg ha^{-1} more biomass annually than upland entries, suggesting lowland cultivars are better suited to environments in the Southeast. Due to lower yields, P and K removals were lower for upland (Blackwell and C62), compared with lowland cultivars. Consequently, switchgrass can be harvested as early as mid-September without removing greater amounts of P and K, although variations within upland and lowland cultivars will likely occur.

Abbreviations

DNS, data not shown; ETREC, East Tennessee Research and Education Center; HRREC, Highland Rim Research and Education Center; ICP, inductively coupled plasma; LRR, Land Resource Region; MLRA, Major Land Resource Area; NUE, nutrient-use efficiency

Switchgrass yields and mineral nutrition can be affected by harvest timing and latitude, which in turn affect desired feedstock traits and producer profitability (Adler et al., 2006; Madakadze et al., 1999; Vogel et al., 2002; Casler and Boe, 2003). Current recommendations for a one-cut switchgrass biomass harvest in the southeastern United States is following the first killing frost or 1 November, whichever occurs first (Garland, 2008). This recommendation is based on maximizing biomass yield and minimizing removal of essential nutrients such as P and K. However, curing conditions are often challenging during this time period due to weather.

Various studies in the United States have found maximum yield varies according to geographic location and cultivar due to genotype × environment interactions. In a 3-yr study on cultivar Alamo, Sanderson et al. (1999) found that highest biomass yields in a one-cut system occurred in mid-September. Parrish et al. (2003) also observed greater yields during September, but reported that implementing a one-cut harvest in September rather than November decreased yields the following year. Therefore intra-seasonal gains may offset long-term yield benefits (Parrish et al., 2003). The observation that early (September) harvesting leads to decreased switchgrass yields the following season has been attributed to removal of higher P and K and depleting carbohydrate reserves that could ordinarily be translocated during the fall from aboveground biomass (leaves and stems) to roots. Nutrient remobilization is believed to occur in response to environmental signaling, and allows plants to store greater quantities of essential nutrients belowground for plant growth and development the following season. However, data reported by Bacon et al. (2016) showed that significant translocation of P and K did not occur from September to October in eight switchgrass cultivars grown in Tennessee. As a result, authors concluded that earlier harvesting (mid-September) may not affect nutrient removal in climatic conditions of the southeastern United States.

Switchgrass is classified by ecotype and as either an upland or lowland cultivar. With few exceptions, most upland types are octoploids (i.e., $2n = 8x = 72$), whereas lowland types are tetraploids (i.e., $2n = 4x = 36$; Parrish and Fike, 2005). Lowland types are generally taller and more robust than upland ecotypes, with larger panicles (Parrish and Fike, 2005; Casler, 2010; Porter, 1966). Although, latitude-of-origin largely drives productivity and survival, particularly

This article in AJ

Vol. 109 No. 6, p. 2598-2605

OPEN ACCESS

Received: Jan 12, 2017
Accepted: Aug 24, 2017
Published: October 5, 2017

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If large volumes of mineral P and K are removed from soils via harvested plant tissue without replacement, soils can become deficient and require fertilizer additions. Furthermore, fertilizer sources of P (i.e., phosphate rock) are finite, making conservative use of this element important (Cordell et al., 2009). Lemus et al. (2009) determined biomass nutrient concentrations are affected by location, management, and harvest date, while location and management affected total nutrient removal. In addition, elevated inorganic minerals (e.g., P and K) in switchgrass tissue can cause slagging in combustion chambers when thermochemically converted, making high concentrations of these nutrients adverse to feedstock quality (Boateng et al., 2007). According to Ashworth et al. (2016) P and K remobilization, ethanol yield, fermentable sugars, and in-field dry-down are greater for overwintering harvests, although 22% yield losses occurred. Therefore, nutrient removal tends to be higher earlier in the season, and yield may also suffer if harvest is executed too early (Heaton et al., 2009). Maximizing yield is a priori for producers; but, management strategies that support high yields with low inputs are most desirable (Parrish and Fike, 2005).

Yang et al. (2009) suggested genotype, in addition to harvest timing, can dictate nutrient losses, meaning cultivars with higher nutrient-use efficiencies (NUE) may be important for long-term biomass sustainability. Also, NUE has shown to increase over time with harvesting after killing frosts, which suggests improved nutrient cycling with delayed harvests. Alamo and Kanlow are benchmark lowland cultivars; however, recently released cultivars may have greater NUE and be higher yielding at certain harvest dates due to genotype ' environment responses, although this has not been confirmed. In addition, no data are available on how P and K removal varies spatially for upland and lowland cultivars, post growing-season. Therefore, data are needed to determine removal timing impacts throughout the harvest window across diverse cultivars and plant ecotypes. Consequently, the purpose of this study was to compare multi-year yield data from eight widely used and experimental upland and lowland switchgrass cultivars in Tennessee to determine for the southeastern region: (i) which harvest timing provides maximum yield, (ii) effects of harvest timing on overall P and K removal (in leaves and stems); and, (iii) how results are affected by switchgrass cultivar.

MATERIALS AND METHODS

Site Description and Characterization

This study was conducted at two physiographic areas in Tennessee. The first location was at the East Tennessee Research and Education Center in Knoxville [ETREC (35°8' N, 83°9' W)] on a Sequatchie loam (fine-loamy, siliceous, semiactive, thermic Humic Hapludult). This site had a mean annual temperature of 14°C from 2010–2011 and received 1235 mm of rainfall in 2010, and 1505 mm in 2011 (Fig. 1). The first fall killing frost (≤0°C) occurred on 19 Oct. 2010, and 7 Nov. 2011 (Fig. 1). Prior to experimentation, this site was under tall fescue [*Lolium arundinaceum* (Schreb.)] hay production. This location is situated in the East and Central Farming and Forest Region (Natural Resources Conservation Service [NRCS], Major Land Resource Area [MLRA] 128 classified as the southern Appalachian Ridges and Valleys in the Land Resource Region [LRR]) "N"). This LRR is typical of southwestern Virginia, north-central Alabama, and northwestern Georgia. Maximum precipitation occurs in midwinter and midsummer, with the minimum occurring in autumn (NRCS-MLRA, 2006).

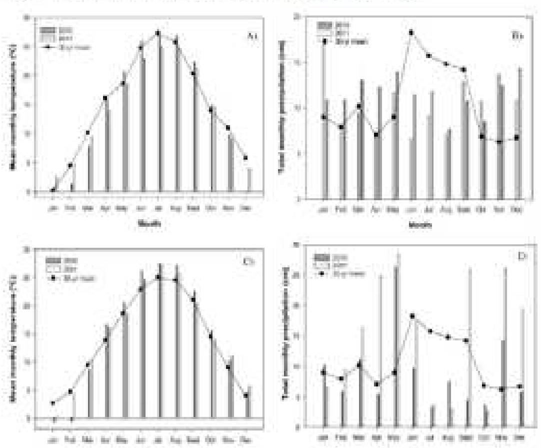

Fig. 1.

Mean monthly temperature at (a) the East Tennessee Research and Education Center, Knoxville and (b) the Highland Rim Research and Education Center, Springhill, TN, from 2010 to 2011. Total monthly precipitation (c) the East Tennessee Research and Education Center, Knoxville, TN, and (d) the Highland Rim Research and Education

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Mean monthly temperature at (a) the East Tennessee Research and Education Center, Knoxville and (b) the Highland Rim Research and Education Center, Springhill, TN, from 2010 to 2011. Total monthly precipitation (c) the East Tennessee Research and Education Center, Knoxville, TN, and (d) the Highland Rim Research and Education Center, Springhill, TN from 2010 to 2011. Thirty-year mean temperature and precipitation data (1981–2010) were taken at the research centers and obtained from NOAA (2013).

The second site was at the Highland Rim Research and Education Center (HRREC) in Springfield, TN (36°3′ N, 86°5′ W). This site had a mean annual temperature of 14°C in 2010–2011 and received slightly lower precipitation in 2010 (1078 mm) than the Knoxville site, with 1484 mm of precipitation in 2011 (Fig. 1). The first fall freeze occurred on 29 October in both 2010 and 2011. Soils at the HRREC site are classified as Dickson silt loam (fine-silty, siliceous, semiactive, thermic Glossic Fragiudult). Prior to experimentation, the site was under winter wheat (*Triticum aestivum* L.) production. This location is situated in the East and central Farming and Forest Region (NRCS, MLRA) 123 classified as the Nashville Basin (LRR) 'N'. Most of this area is characterized by having low interior plateaus, with narrow rolling ridgetops.

Soil samples were taken at a depth of 15 cm to determine initial Mehlich-1 (Mehlich, 1984) extractable nutrients by inductively coupled plasma (ICP) using a 7300 ICP–optical emission spectroscopy (OES) DV (PerkinElmer, Waltham, MA). The pH was determined on a 1:1 soil/water ratio using an AS3010D Dual pH Analyzer (Labfit, Burswood, Australia). Soil P levels tested medium or high at ETREC and HRREC (23–37 and 49–83 kg P ha^{-1}, respectively; Table 1); as such, no P or K was applied during the experimental period (Garland, 2008). For both locations, an annual rate of 67 kg N ha^{-1} was applied in the form of ammonium nitrate (NH_4NO_3) when switchgrass was approximately 30 cm tall (approximately mid-April).

Table 1. View Full Table | Close Full View

Baseline soil test (Mehlich-1 extractable nutrients by inductively coupled plasma [ICP]) results to a 0- to 15-cm depth and ratings per harvest date at East Tennessee Research and Education Center (ETREC) and Highland Rim Research and Education Center (HRREC) in 2010 (adopted from Bacon et al., 2016).

Location†	Harvest date	P	K	pH
		kg ha^{-1}		
ETREC	Mid-Sept.	35 (M)†	161 (M)	6.8
	Mid-Oct.	34 (M)	149 (M)	6.8
	Late Oct.	23 (M)	206 (M)	6.7
	Early Nov.	29 (M)	166 (M)	6.7
HRREC	Mid-Sept.	56 (H)	62 (L)	7.4
	Mid-Oct.	58 (H)	75 (L)	7.1
	Late Oct.	83 (H)	123 (L)	7.5
	Early Nov.	49 (H)	49 (L)	7.8

†M = medium; H = high for switchgrass production, per designation by Utah Soil, Plant, and Pest Center (Nashville, TN [Garland, 2008]).

Plant Material Descriptions and Tissue Sampling

To determine differences in late growing-season P and K accumulation, eight lowland and upland switchgrass cultivars or experimental lines (hereafter referred to as cultivars) were established in a randomized complete block design with three blocks each at ETREC and HRREC in May and June 2007, respectively. Treatments were assigned in a split-plot design (cultivars being the whole plot and harvest date being the split-plot). The eight cultivars included Alamo and Kanlow (Bamert Seed Co., Muleshoe, TX), Cimarron and Oklahoma NSL-2001-1 (hereafter, OK NSL; Oklahoma Agricultural Experiment Station, Stillwater), C62, C77, and C75 (experimental lines; Noble Foundation, Ardmore, OK), and Blackwell (USDA Plant Materials Center and Kansas Agricultural Experiment Station [Sharp Bros. Seed Co., 2011]). Alamo and Kanlow are two standard lowland cultivars that serve as benchmarks for new and forthcoming cultivars. All of the aforementioned cultivars are lowland accessions, except C62 and Blackwell, which are upland cultivars (Ceres, Inc., 2008). Alamo is the standard lowland cultivar grown in the southeastern United States; therefore, Alamo is of particular interest on a commercial scale. Kanlow is a lowland cultivar that is comparable to Alamo and is also of interest in commercial switchgrass production. A more recent commercial cultivar is Cimarron, which was released as a commercial lowland cultivar in 2008 by the Oklahoma Agricultural Experiment Station (Oklahoma State University, 2011). Seeds were no-till drilled at a rate of 9 kg pure live seed ha^{-1} using a five-row Hege 1000 plot drill (Colwich, KS) at both locations.

Phosphorus and K levels in leaves and stems were determined for each cultivar during mid-September, mid-October, late October, and early November at both ETREC and HRREC from 2010 to 2011. Ten random plant tillers from each plot were clipped 3 to 5 cm aboveground during each harvest date for subsequent tissue analysis. Stems and leaves were separated for each tiller sample and analyzed separately. Yields were determined following tiller sampling (20.3-cm stubble height) with a Carter plot harvester (Brookston, IN). Whole plots were 1.5 by 7.7 and 1.5 by 9.1 m, with harvested subplot size being 0.9 by 1.5 and 1.5 by 1.8 m at ETREC and HRREC, respectively. Harvest dates were 17 Sept. 2010, 15 Oct. 2010, 29 Oct. 2010, and 11 Nov. 2010 at ETREC; and 17 Sept. 2010, 15 Oct. 2010, 1 Nov. 2010, and 22 November at HRREC. In 2011, harvest dates were 17 September, 15 October, 29 October, and 11 November at ETREC; and, 17 September, 15 October, 1 November, and 22 November at HRREC. Grab samples (1–2 kg) from plot harvests were collected to determine moisture content. Fresh weight of each sample was measured and then dried in a batch oven (Wisconsin Oven Corporation, East Troy, WI) for a minimum of 48 h at 55°C, and dry weight was measured. Samples were ground to pass through a 2-mm screen using a Wiley Mill (Thomas Scientific, Swedesboro, NJ). Predicted removals of P and K in harvested biomass on a unit land area basis were calculated (biomass yield × nutrient concentration [weight averaged for stems and leaves based on mass and adjusted accordingly]).

22 November at HRREC. In 2011, harvest dates were 17 September, 15 October, 29 October, and 11 November at ETREC; and, 17 September, 15 October, 1 November, and 22 November at HRREC. Grab samples (1–2 kg) from plot harvests were collected to determine moisture content. Fresh weight of each sample was measured and then dried in a batch oven (Wisconsin Oven Corporation, East Troy, WI) for a minimum of 48 h at 55°C, and dry weight was measured. Samples were ground to pass through a 2-mm screen using a Wiley Mill (Thomas Scientific, Swedesboro, NJ). Predicted removals of P and K in harvested biomass on a unit land area basis were calculated (biomass yield × nutrient concentration [weight averaged for stems and leaves based on mass and adjusted accordingly]).

Phosphorus and Potassium Analysis

Tillers were analyzed for P and K (stems and leaves separately) by placing 0.5 g of dried ground tissue in a 16 by 100 mm glass tube and ashed at 450°C for 4 to 6 h. Ten milliliters HNO_3 (70%) was used to dissolve ash (Huang and Schulte, 1985). Samples were analyzed using an inductively coupled plasma mass spectrometer (ICP–MS, Model 7500ce, Agilent Technologies) at the University of Tennessee, Knoxville (Banckman et al., 2013). Digestions were diluted with 2% HNO3/0.5% HCl, and elemental measurements were made using an Agilent 7500ce ICP–MS system (Agilent Technologies). The ICP–MS system was equipped with an octapole collision/reaction cell, Agilent 7500 ICP–MS ChemStation software, a micromist nebulizer, a water-cooled quartz spray chamber, and a CETAC (ASX-510; CETAC, Omaha, NE) auto-sampler. The instrument was optimized daily in terms of sensitivity (Li, Y, Tl), level of oxide (Ce), and doubly charged ion (Ce) using a tuning solution containing 10 μg L^{-1} of Li, Y, Tl, Ce, and Co in a 2% HNO_3/0.5% HCl matrix. Mineral elements were expressed on a dry matter basis.

Statistical Analysis

Switchgrass yield and tissue nutrient concentration (dependent, explanatory variables) by cultivar and harvest date (fixed effects) were analyzed under analysis of variance tests using the Proc Mixed procedure (SAS V9.3; SAS Institute, 2016), wherein, cultivar (whole plot); harvest date (split-plot), and year were considered fixed effects. Block and location were entered as random effects. A global model was initially analyzed (in which data were combined across years, harvest dates, cultivars, locations, etc.) to assess individual main effects. Thereafter, based on interaction probability levels, models analyzed yield and P and K removal (by harvest date and cultivar) to assess interactions. Mean separations were performed by the SAS macro "pdmix800" (Saxton, 1998) and, when main effects or interaction differences were found, means were separated with Fisher's LSD at a Type I error rate of 5% (SAS Institute, 2016).

RESULTS AND DISCUSSION

Yield Variance by Cultivar and Harvest Date

Study results revealed yield differences among cultivars ($P = 0.03$) and harvest dates ($P < 0.001$), although not for cultivar × harvest date interactions ($P = 0.23$, Table 2). When averaged across locations, years, and cultivars ($P = 0.05$) yields were greatest during early November (13.2 Mg ha^{-1}), ($P < 0.05$, data not shown [DNS]). Harvests during mid-October and late October did not differ (10.4 and 10.2 Mg ha^{-1}, respectively); however, both were greater than the earliest harvest date (mid-September, 8.9 Mg ha^{-1}; DNS). These results were contrary to those from Parrish and Wolf (1993), who reported 10% dry matter reductions from early September to late October throughout the upper Southeast, with Sanderson et al. (1999) reporting 12% losses in central Texas. However, all years and locations of the aforementioned studies had excessive (>50% higher) precipitation, which causes leaf loss and can promote lodging. Conversely, yields in this study increased 32% between mid-September and early November, and 22% between mid-to late October and early November. This atypical switchgrass growth pattern is likely due to greater-than-average temperatures (17°C departure from 30-yr average) occurring September to October, as well as a killing frost not occurring until late October to early November in 2011 (Fig. 1). Similarly, in a time-course biomass yield and composition study in Arkansas, Ashworth et al. (2017) observed peak yield later in the season (27 September). This indicates precipitation and killing frost frequency may be a main driver for biomass losses post-growing-season. First killing frosts in warm-temperate Tennessee did not occur until 19 October to 7 November; therefore, green tissue was likely still photosynthesizing and accumulating carbohydrates. Based on these results, under similar environmental conditions, switchgrass harvests can be initiated in September and October to take advantage of better curing conditions; however, harvesting after the first killing frost allows for further moisture loss in the standing crop.

Table 2. View Full Table | Close Full View

Analysis of variance for fixed effects for switchgrass yield, P removal, and K removal at two Research and Education Centers in Tennessee (ETREC, Knoxville, and HRREC, Spring Field) across fall harvest periods (mid-September, October, November, and late October) from 2010–2011.

Fixed effect	Numerator df	Denominator df	*F* value	*P*>
Switchgrass yield				
Cultivar	7	21	2.70	0.036
Harvest date	3	350	23.63	<0.00
Year	1	322	150.87	<0.00
Cultivar × Harvest date	21	350	1.22	0.233
Cultivar × Year	7	322	1.75	0.096
Year × Harvest date	3	322	7.71	<0.00
Cultivar × Year × Harvest date	21	322	0.44	0.986
Phosphorus removal				
Cultivar	7	84	4.08	0.000
Harvest date	3	9	0.72	0.560
Year	1	322	122.21	<0.00
Cultivar × Harvest date	21	84	0.57	0.926
Cultivar × Year	7	322	1.69	0.110
Year × Harvest date	3	322	5.95	0.000
Cultivar × Year × Harvest date	21	322	0.79	0.733
Potassium removal				
Cultivar	7	84	4.44	0.000

Year	1	322	122.21	<0.00
Cultivar × Harvest date	21	84	0.57	0.926
Cultivar × Year	7	322	1.69	0.110
Year × Harvest date	3	322	5.95	0.000
Cultivar × Year × Harvest date	21	322	0.79	0.733
Potassium removal				
Cultivar	7	84	4.44	0.000
Harvest date	3	9	0.51	0.684
Year	1	322	111.04	<0.00
Cultivar × Harvest date	21	85	0.87	0.628
Cultivar × Year	7	322	0.91	0.496
Year × Harvest date	3	322	5.86	<0.00
Cultivar × Year × Harvest date	21	322	1.09	0.362

When compared by year, differences did occur among harvest dates, given that Year-1 cumulative yield was substantially ($P < 0.05$) lower compared with 2011 (8.0 vs. 13.5 Mg ha^{-1}, respectively; DNS). Furthermore, differences occurred within harvest timing × year ($P < 0.05$). No yield differences occurred among harvest dates for 2010, and earlier harvests in 2010 did not result in lower yields in 2011 (Fig. 2). Yields differed among harvest dates in 2011, but primarily due to the higher yield in November (Fig. 2). Specifically, between both years and among harvest dates, greatest yields occurred early November during the second experimental year (2011), followed by mid-October, with mid-September and late October not differing (Fig. 2). These data suggests that in some years, detrimental yield impacts may occur from earlier post-senescence harvests removing carbohydrate reserves. These results support those reported by Parrish et al. (2003), de Koff and Allison (2015), and Gorlitsky et al. (2015).

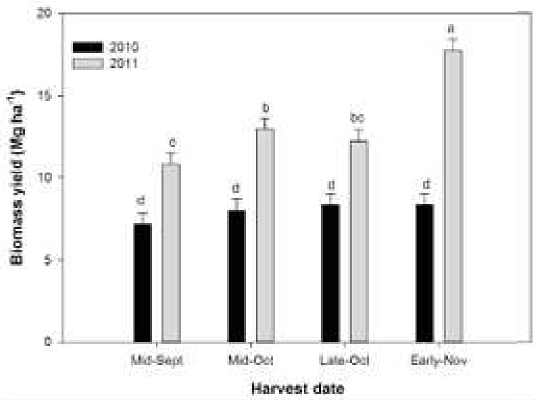

Fig. 2.

Switchgrass biomass yield for upland and lowland cultivars per fall harvest dates (mid-September, October, November, and late October) averaged across locations (East Tennessee and Highland Rim Research and Education Centers) from 2010–2011. Different letters indicate significant differences across harvest dates.

Yield varied among upland and lowland cultivars, with lowland entries exceeding that of upland species. Specifically, Blackwell and C62 were lowest (6.6 and 8.8 Mg ha^{-1}, respectively), with Cimarron being the greatest (12.5 Mg ha^{-1}; Table 3). Cimarron also did not differ from benchmark cultivars (Alamo and Kanlow), or C75 and C77, with Oklahoma NSL not differing from any cultivar (10.1 Mg ha^{-1}; Table 3). These results suggest that lowland cultivars are better suited to environments similar to those tested in the Southeast; however, cultivars reportedly better suited to mid-latitudes, such as Kanlow, can provide comparable yields to benchmark cultivars in the humid mid-South. This result was consistent with Lemus et al. (2002), who reported Alamo and Kanlow were among the most prolific producers of dry matter among switchgrass cultivars. Furthermore, Wullschleger et al. (2010) reported that Alamo and Kanlow, produced on average 4.6 Mg ha^{-1} more dry matter annually than upland cultivars; however, our results indicates a difference of 3.9 is more reasonable for the climates and soils of humid Tennessee.

Table 3. View Full Table | Close Full View

Switchgrass P and K tissue (weight averaged across leaves and stems) concentrations and removal averaged across fall harvest periods (mid-September, October, November, and late October) at East Tennessee and Highland Rim Research and Education Centers from 2010–2011.

Cultivar	Yield	Measured concentration		Estimated removal	
		P	K	P	K
	Mg ha^{-1}	kg Mg DM^{-1}		kg ha^{-1}	
Upland					
C62	8.8bc	1.5abc	8.0a	13.2bc	68.2bc
Blackwell	6.9c	1.6a	8.2a	10.2c	52.4c
Lowland					
Alamo	12.0ab	1.4bc	7.6a	17.2ab	89.7a
C75	11.8ab	1.4c	7.9a	15.7b	89.8a
C77	11.7ab	1.5bc	7.6a	17.1ab	86.8ab
Kanlow	11.8ab	1.3c	7.7a	16.6ab	90.1a
Cimarron	12.5a	1.6ab	7.7a	19.9a	93.5a

Blackwell	6.9c	1.6a	8.2a	10.2c	52.4c
Lowland					
Alamo	12.0ab	1.4bc	7.6a	17.2ab	89.7a
C75	11.8ab	1.4c	7.9a	15.7b	89.8a
C77	11.7ab	1.5bc	7.6a	17.1ab	86.8ab
Kanlow	11.8ab	1.3c	7.7a	16.6ab	90.1a
Cimarron	12.5a	1.6ab	7.7a	19.9a	93.5a
Oklahoma NSL	10.1abc	1.6ab	7.5a	16.5ab	77.2ab

*Different letters indicate a significant difference based on Least Significant Difference Test, averaged across harvest dates, $P = 0.007$ (harvest date × cultivar $P = 0.50$)

Phosphorus and Potassium Concentrations and Estimated Removal in Harvested Biomass

Cultivar × year × harvest date did not impact P and K removal ($P > 0.05$), although year × harvest timing interacted to affect mineral P and K tissue removal (Table 2). Phosphorus and K mineral plant nutrition did not vary by location, which was contrary to expectations, considering differences in soil P and K concentrations per location (Table 1). Cultivars and years resulted in variations ($P < 0.05$) in aboveground (leaf and stem) P and K removal, whereas harvest date, harvest date × cultivar, and cultivar × year interactions did not (Table 2). Specifically, P and K removal was lowest for the upland cultivars, Blackwell and C52. Conversely, P and K removal was highest for lowland cultivars, Kanlow, Cimarron, and Alamo (Table 3). This result suggests that these lowland cultivars may not be ideal feedstocks in thermo-chemical conversion systems, considering P and K are major constituents of ash, which causes slagging in combustion systems (Boateng et al., 2007; Bacon et al., 2016). Therefore, breeding programs could select cultivars with high NUE and improved switchgrass mineral dynamics and crop productivity.

Both P and K concentrations declined late October and early November compared with earlier harvest dates (Fig. 3). However, because of the inverse relationship with yield, there were no detectable increases in removal rates ($P > 0.05$). Measured P concentrations (post-senescence) were similar (1.1 kg Mg^{-1} dry matter) to those reported by Kering et al. (2012); however, K concentrations were greater than those reported by others (2.7 kg Mg^{-1} dry matter). These results suggest that while P or K concentrations declined post-senescence, removal rates do not differ due to slightly lower biomass yields from earlier harvests. Therefore, neither plant tissue (Fig. 2) nor soil mineral (Table 1) concentrations decreased from mid-September to mid-November in 2010 and are therefore negligible. However, there was a trade-off with lower biomass yield mid-September compared to later harvest dates. Given that P and K levels may continually decline throughout the winter due to nutrient translocation and leaching from plant tissue, further research is needed to determine P and K levels in plant parts over-winter. The amount of P and K sequestered post-growing season and potentially leached in senesced material has implications for feedstock usage in thermal conversions, soil fertility, and nutrient cycling, as well as sustainable nutrient input requirements long term in biomass systems.

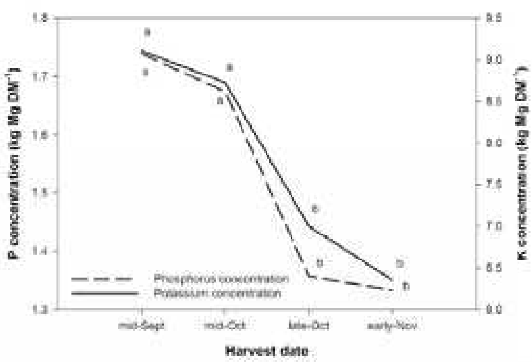

Fig. 3.

Switchgrass P and K tissue (leaf and stem) concentrations across fall harvest dates averaged across upland and lowland cultivars at East Tennessee and Highland Rim Research and Education Centers from 2010–2011. Different letters indicate significant differences across harvest dates.

We hypothesized that P and K removal rates would be reduced into the fall due to increased nutrient translocation and minimal yield declines post-senescence; however, this was repudiated in that neither P nor K mineral removal varied during fall harvest periods (mid-September, October, November, and late October). Potassium removal was more than four times greater than P removal, which has been observed by others (Woodson et al., 2013; Ashworth et al., 2017). Switchgrass P and K removal (via biomass harvests) was estimated at 10.2 to 19.9 and 52.4 to 93.5 kg ha^{-1} yr^{-1}, respectively, across harvest dates (Table 3). Based on associated removal rates, annual fertilization would have to add back approximately 11 to 20 and 53 to 94 kg ha^{-1} yr^{-1} of P and K, respectively, to maintain soil test levels.

CONCLUSION

Among all post-senescence harvest dates tested in this study, (mid-September, mid-October, late October, and early November), yield peaked in early November (13.2 Mg ha^{-1}). Because yields peaked in early November, P and K removal did not vary across harvest dates despite both P and K declining in late October and early November compared with earlier harvest dates. This was due to the inverse relationship observed with yield and P and K concentrations. Therefore, from a nutrient removal standpoint, upland and lowland switchgrass can be harvested as early as mid-September in Tennessee without removing greater amounts of P and K in harvested biomass. However, there could be a trade-off in some years of obtaining 20 to 30% lower biomass yields from earlier harvests and potential yield detriments over time, albeit more temporally and spatially diverse data are needed.

Yield varied among upland and lowland cultivars, with lowland entries producing greater levels of harvestable biomass. Specifically, Blackwell and C52 were lowest, with Cimarron being the greatest (when averaged across locations and years). These results bolster previous work dates. This was due to the inverse relationship observed with yield and P and K concentrations. Therefore, from a nutrient removal standpoint, upland and lowland switchgrass can be harvested as early as mid-September in Tennessee without removing greater amounts of P and K in harvested biomass. However, there could be a trade-of in some years of obtaining 20 to 30% lower biomass yields from earlier harvests and potential yield detriments over time, albeit more temporally and spatially diverse data are needed.

Yield varied among upland and lowland cultivars, with lowland entries producing greater levels of harvestable biomass. Specifically, Blackwell and C62 were lowest, with Cimarron being the greatest (when averaged across locations and years). These results bolster previous work that suggests lowland cultivars are better suited to environments in the Southeast; however, cultivars reportedly better suited to mid-latitudes, such as Kanlow, can provide comparable yields to benchmark cultivars in the humid mid-South. Furthermore, P and K removal was lowest for upland cultivars, Blackwell and C62, and highest for lowland cultivars, Kanlow, Cimarron, and Alamo. This is indicative of the genetic diversity across switchgrass cultivars, as well as the potential for developing cultivars with improved NUE.

Acknowledgments

Authors extend gratitude to the directors at the East Tennessee (Lee Ellis) and Highland Rim (Dr. Barry Sims) Research and Education Centers for making this research possible.

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Agronomy Journal - Review & Interpretation

Understanding Global and Historical Nutrient Use Efficiencies for Closing Maize Yield Gaps

This article in AJ

Vol. 106 No. 6, p. 2107-2117

OPEN ACCESS

Received: Jan 13, 2014
Published: September 15, 2014

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doi:10.2134/agronj14.0025

Abstract

Global food security must address the dual challenges of closing yield gaps (i.e., actual vs. potential yield) while improving environmental sustainability. Nutrient balance is essential for achieving global food security. Historical (in distinct "Eras" from late 1800s to 2012) and geographical (in United States vs. remainder of World) changes in maize (*Zea mays* L.) grain yields and plant nutrient content (N, P, and K) were characterized from studies (>150) with known plant densities. At the community scale, greater yield to nutrient content ratios (physiological efficiency, PE) were documented for United States vs. World. The U.S. historical trend displayed increasing gains for community-scale yield and nutrient uptake, except for a recent decline attributed to weather. At the individual-plant scale, geographic PE differences over time were primarily explained by changes in yield, and secondarily by nutrient content changes. Despite wide variation, high-yield maize in both geographies was associated with balanced N/P (5:1) and N/K (1:1) ratios. More scope exists for maize nutrient PE gains in developing regions. Achieving balanced nutrition in optimally integrated soil-crop management cropping systems will facilitate simultaneous realization of high-yield and bio-fortification goals in maize improvement efforts.

Abbreviations

NA, nitrogen accumulation; ND, nitrogen dilution; NRE, nitrogen recovery efficiency; NUE, nitrogen use efficiency; OPV, open pollinated varieties; PE, physiological efficiency; PEN, physiological efficiency for nitrogen; PRE, phosphorus recovery efficiency; PUE, phosphorus use efficiency

The term "food security" has been recently defined in a myriad of ways (Pinstrup-Andersen, 2009; Barrett, 2010).[1] Food security goals vary among nations and their economic development status. In developing countries, the challenge is not only to improve crop yields but also to ensure adequate food accessibility. For developed countries, however, the main goal is to sustainably maximize productivity per unit of arable land. In Sub-Saharan Africa and South America, crop yields and land area depicted parallel positive changes from 1990 to 2005, but in North America superior yields were achieved with minor changes in land area (Rudel et al., 2009). Projected growing imbalances between land demand and cropland supply (Lambin and Meyfroidt, 2011) emphasizes the importance of intensifying productivity for a burgeoning population from existing lands.

Reducing yield gaps (potential biological-genetic yield vs. actual farm yield) is one of the main goals of food security research. Scientists have devoted large resources to characterizing yield gap issues for multiple crops around the globe (Foley et al., 2011; van Ittersum et al., 2013). Recent studies have revealed slowing or stagnating yield trends associated, in part, to implementation of agricultural policies (e.g., European "environmental-friendly" production systems with reduced fertilizer; Peltonen-Sainio et al., 2009; Finger, 2010; Cassman, 2012). Leveling-off of cereal crop yields from 1990 to 2010 in many countries with high production levels (Grassini et al., 2013), whether due to changing regulations, resources, or climate, constrains progress in shrinking yield gaps.

From a nutritional viewpoint, grain nutrient composition is also vital to food security. For cereal crops, modern genotypes exhibited declining protein (N) trends as an outcome of continuous yield improvement over time (Calderini et al., 1995; Ciampitti and Vyn, 2012, 2013). Crop yield-gain efforts should not overlook the macro- and micronutrient nutritional quality of its products. Biofortification has been investigated in different crops using diverse approaches (e.g., vitamin biofortification of maize endosperm; Naqvi et al., 2009). However, the nutrient question of primary importance to all societies is that of the overall efficiency with which plant nutrients can help achieve future incremental gains in crop yields. This review study was performed with the primary objective of collecting, summarizing, interpreting, and advancing the understanding of maize yield and nutrient uptake associations from both historical and geographical perspectives. An equally important question for food security involves the prospects for increasing nutrient use efficiency in maize without jeopardizing nutritional quality. For this investigation, we understood nutrient use efficiency from a physiological viewpoint as the coefficient of the association between grain yield and plant nutrient uptake (nutrient PE).

Maize (alternately a food, feed, fiber, and/or biofuel crop) has become an ever more vital component of global food security due to genetic and management practice changes that have driven yield gains over the last century. Productivity gains (from the 1800s to present) can be characterized in four periods denoting core changes in maize yield at the farmer-scale and also in the final maize yield potential: ([1] 1850–1930) dominated by open-pollinated varieties (OPVs); ([2] 1931–1960) yield improvement enabled by double cross-hybrids; ([3]

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Maize (alternately a food, feed, fiber, and/or biofuel crop) has become an ever more vital component of global food security due to genetic and management practice changes that have driven yield gains over the last century. Productivity gains (from the 1800s to present) can be characterized in four periods denoting core changes in maize yield at the farmer-scale and also in the final maize yield potential: ([1] 1850–1930) dominated by open-pollinated varieties (OPVs); ([2] 1931–1960) yield improvement enabled by double cross-hybrids; ([3] 1961–1990) further yield gains facilitated by single-cross hybrids; and ([4] 1991–2012) single-cross hybrids with transgenic tolerance to insect pests, herbicides, and drought tolerance (Crow, 2009; Edmeades, 2013; Cooper et al., 2014).

During the last 60 yr, world maize production in the United States and China increased 4 to 6 Mg ha^{-1} with similar improvements for France, Argentina, and Canada (FAO, 2012). In 2012, overall national maize yield for the United States was 9 Mg ha^{-1} while in China and Argentina it was 6 Mg ha^{-1} (FAO, 2012). Current yields (<5 Mg ha^{-1}) deviate most from potential yields in developing regions (FAO, 2012). Nutrient and water management are considered as main driving factors for closing yield gaps for maize, rice (*Oryza sativa* L.), and wheat (*Triticum aestivum* L.) crops around the globe (Mueller et al., 2012). Maize yield gaps in nutrient-limited regions of Central America, east-central South America, eastern Europe, Sub-Saharan Africa, and southern and eastern Asia were predicted to decline by increasing nutrient applications by 18, 7, and 29% for N, P, and K, respectively (Mueller et al., 2012). However, excess nutrient applications promote nutrient imbalances that exacerbate inefficiencies in nutrient use, expressed as the ratio of yield to nutrient applied (Vitousek et al., 2009; Liu et al., 2013) and jeopardize future productivity. Fertilizer N use for 2050 is projected to exceed grain N removal in several regions (e.g., projected doubling of fertilizer N use for southern Asia and Latin America, Sutton and Bleeker, 2013). Nutrient use efficiency improvements are essential to mitigate potential environmental contamination, improve farmer income, and accelerate crop yield progress for food security goals (Cassman, 1999).

One potential avenue for increasing nutrient use efficiency is to increase plant nutrient uptake and partitioning to grain. Prior reviews have examined associations between maize yield and plant N dynamics (Ciampitti and Vyn, 2012, 2013), but a complete summary is needed for essential macronutrients beyond N alone. A novel analysis of available literature (>100 yr) on associations between maize yield and plant nutrient uptake was performed with the research goal of better understanding PE changes (N, P, and K) over time between the United States vs. the World. All accessible research data (161 sources from the earliest available records, 1888, until 2012) were grouped by era and geographical clusters. Identification of maize changes over time in macronutrient uptake, PE, and nutrient ratios should be considered by researchers for providing information on concurrent gains in yield plus nutrient use efficiencies.

MATERIALS AND METHODS

Data Inclusion Criteria

The data inclusion criteria followed a similar procedure as previously presented by Ciampitti and Vyn (2012). Refereed journal papers and relevant unpublished information (13 MS and Ph.D. theses as well as ongoing public-sector research) were included to increase the database size. Public-sector data sources needed to meet several criteria (minimum reporting of yield, plant N, P, and K uptake, and plant density) to be included in the global database. When plant density was not explicitly recorded, authors were contacted. Multi-year and multi-site data was included for capturing environmental variation. Lastly, investigations were excluded if selective results were presented (e.g., reporting only significant effects). One important distinction to be made is that the synthesis-analysis provides a unique opportunity in aggregating the information and summarizing research trends, with the limitation that the information does not provide a quantitative measurement of the effect sizes (standard measure for comparing outcomes). A meta-analysis provides the unique opportunity to calculate effect sizes, but a measurement of the variation (individual replications, standard deviation/error, or even *p* values) is needed. The trade-off between the synthesis- and meta-analyses is clear, the former allows collecting historical and geographical information (more studies), while the latter has as its main restriction the need for complete datasets (and therefore far fewer studies can be considered). Unfortunately, most of the scientific papers published in our discipline did not present individual variation per treatment. For this review synthesis study, experimental designs varied across studies (Supplemental Table S1)–some designs were not specified in the paper-, some observations were unbalanced (dissimilar number of points per study), and most variances were unknown. We therefore selected a synthesis-analysis because insufficient information was available for estimating the study effect, and performing a meta-analysis ignoring this effect can result in highly biased estimators (St-Pierre, 2001).

Data Transformation

All data categories were transformed to the same scale (kg ha^{-1}, g $plant^{-1}$, or Mg ha^{-1}). Maize grain yield was adjusted to 155 g kg^{-1} moisture content and plant nutrient uptake was adjusted to a dry basis level. Maize genotypes were predominantly hybrids with a single-ear trait, but OPVs, semi-prolific or prolific hybrids were included. Plant-scale analyses were performed following adjustment of each parameter by the specific-research treatment plant density. Both terms "plant biomass" and "plant nutrient uptake" refer to the aboveground mass and nutrient content without accounting for the root system (due to infrequent reporting of root data).

Data Description

Nearly 2500 treatment means for maize grain yield and plant nutrient uptake were gathered. We recorded specific research factors including: (i) country and year(s) of original research, (ii) plant density and fertilizer nutrient applications (when available), (iii) genotype employed, (iv) experimental layout, and (v) research features (Supplemental Table S1) such as management practices implemented. The origins of our database were 48% from the United States, 6% from South America (Argentina, Brazil, Chile, Colombia, Ecuador, and Venezuela), 4% from North America excluding United States (Canada and Mexico), <1% from Central America (Belize and Trinidad), 2% from Europe (Bulgaria, France, Poland, Hungary, Russia, and Spain), 8% from Africa (Benin, Ethiopia, Kenya, Egypt, Tanzania, and Nigeria), 30% from Asia (China–which also includes summer maize–, Bangladesh, Thailand, Philippines, Indonesia, Israel, India, and Palestine), and <1% from Oceania (New Zealand). The global database was arbitrarily divided into six Eras (1880–1960, 1961–1975, 1976–1985, 1986–1995, 1996–2005, 2006–2012) for United States and five Eras for the World (due to the small number of observations between 1880 and 1960), and into two geographic origins. The geographical division between United States and World (excluding the United States) was arbitrarily decided due to the similar data-size pools and normality of the distribution for both

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Descriptive and Statistical Analysis

Frequency distributions and their descriptive parameters (mean, median, 25%, and 75% quartiles) were determined using the R function "hist" (R Development Core Team 2009). The histograms were modeled for plant density, N/P and N/K ratios, and per-plant scale-analysis of grain yield, plant nutrient (N, P, and K) uptake and fertilizer application rates. Furthermore, the R package "psych" and its R function "describe" were used to obtain skewness and kurtosis values for each frequency distribution evaluated. For the plant-scale analysis, envelopes portraying the maximum and minimum boundaries (0.99 and 0.01 quartiles) were calculated using the R program. Bubble graphs were employed to describe yield effects (larger bubble sizes refer to high-yielding points) in figures displaying N/P and N/K ratios.

Relationships between grain yield and nutrient uptake (for N, P, and K) were implemented with GraphPad Prism 6 software (Motulsky and Christopoulos, 2003) using the power function, GraphPad equation: $Y_1 = \beta_2 X^{\wedge}\beta_1$ (Fig. 1A–1C), forcing intercepts to zero. Relationships between yield and nutrient uptake were also performed with GraphPad Prism 6 software (Fig. 2). A similar procedure was followed for fitting the association at the plant level (Fig. 3A–3C). Final functions were selected by comparing independent fits with a global fit that shared selected parameters. In addition, both parameters, β_1 and β_2, were selected to test whether one curve adequately fit the entire data set after testing with the extra sum-of-squares F test ($P \leq 0.05$).

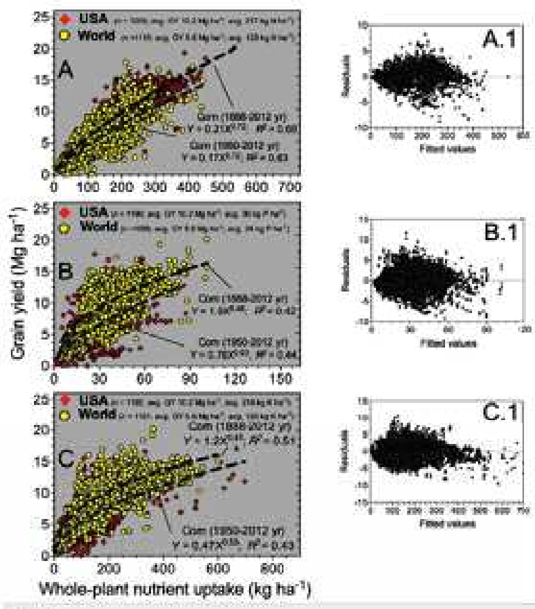

Fig. 1.

Research data summary for the association at community-scale (per-unit-area) between maize grain yield and nutrient ([A] N, [B] P, and [C] K) content at maturity for both geographical clusters (United States vs. World). Maize grain yield expressed at 155 g kg^{-1} moisture content, Mg ha^{-1}, and plant nutrient uptake at maturity expressed on a dry basis. Residual distributions for each association evaluated (residuals vs. fitted values) are also shown (A.1, B.1, C.1).

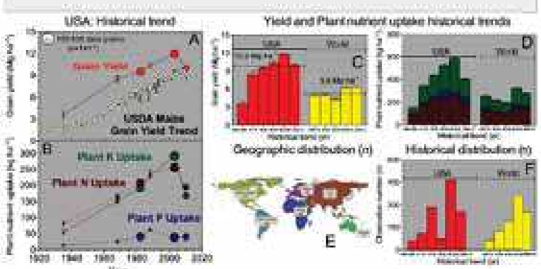

Fig. 2.

Historical U.S. research database and USDA-NASS trend for (A) yield and (B) plant nutrient uptake (for N, P, and K). (C) Maize crop yield (C) and (D) nutrient uptake histograms for the historical trend evaluated and for the geographical division (United States vs. the World). Research locations ([E] continents) and (F) historical data distribution (both for grain yield and nutrient uptake) for the entire dataset (n = 2500 means). Bubble sizes represent number of observations gathered for each Era evaluated, overall mean value per Era. Error bars represent the standard error.

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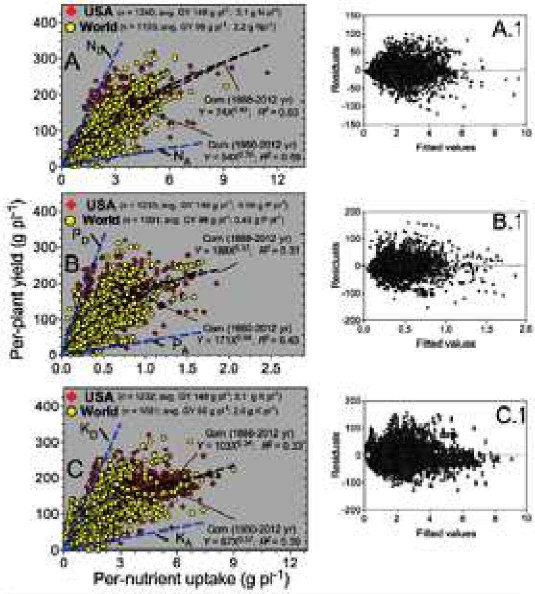
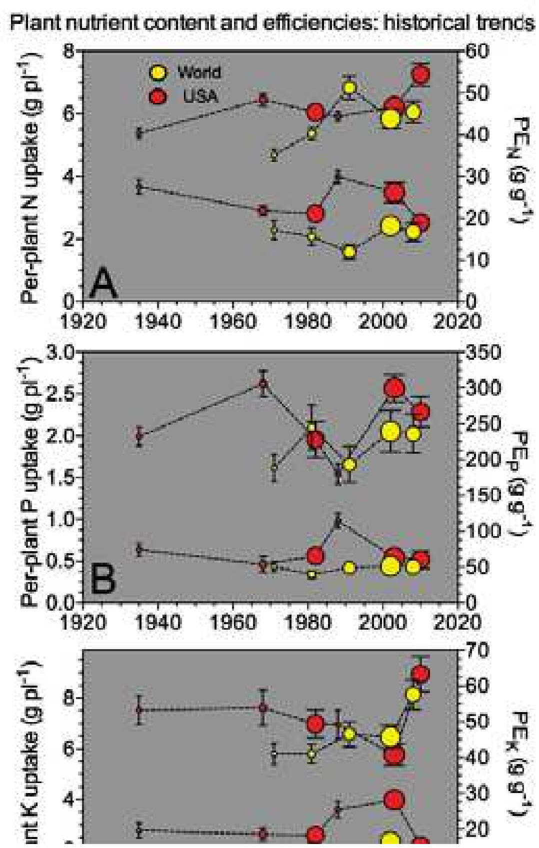


Fig. 3.

Plant-scale analysis for the summary of the association between maize yield and nutrient uptake at maturity for (A) N, (B) P, and (C) K. Per-plant maize grain yield at 155 g kg^{-1} moisture content and plant nutrient uptake at maturity expressed on a dry basis. Blue dash lines represent the maximum nutrient dilution (N_D, P_D, K_D) and maximum nutrient accumulation (N_A, P_A, K_A), range of nutrient variation expected. Residual distributions for each association evaluated (residuals vs. fitted values) are also shown (A.1, B.1, C.1).

Historical plant-scale relationships for nutrient uptake and grain yield (Fig. 4A–4C) were also performed with the GraphPad Prism 6 software. Bar figures were used for graphing the grain yield (Fig. 2C), plant nutrient uptake (Fig. 2E), and number of observations as related to their historical trends for both geographical clusters (United States vs. World). Histograms with relevant frequencies were developed for the N/P (Fig. 5B, 5C) and N/K (Fig. 5E, 5F) ratios (GraphPad Prism 6 software).



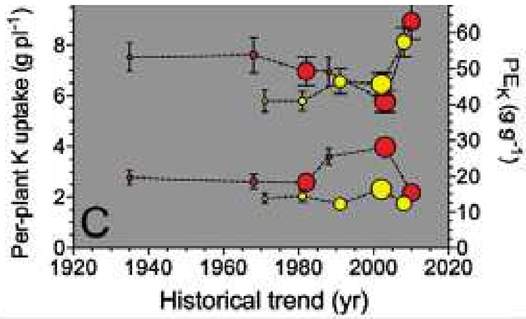


Fig. 4.

Historical (>100 yr) and geographical (United States vs. World) trends for the per-plant nutrient uptake and physiological efficiency (PE, grain yield to nutrient content ratio at maturity) for (A) N, (B) P, and (C) K. Bubble sizes represent number of observations gathered for each Era evaluated, overall mean value per Era. Error bars represent the standard error.

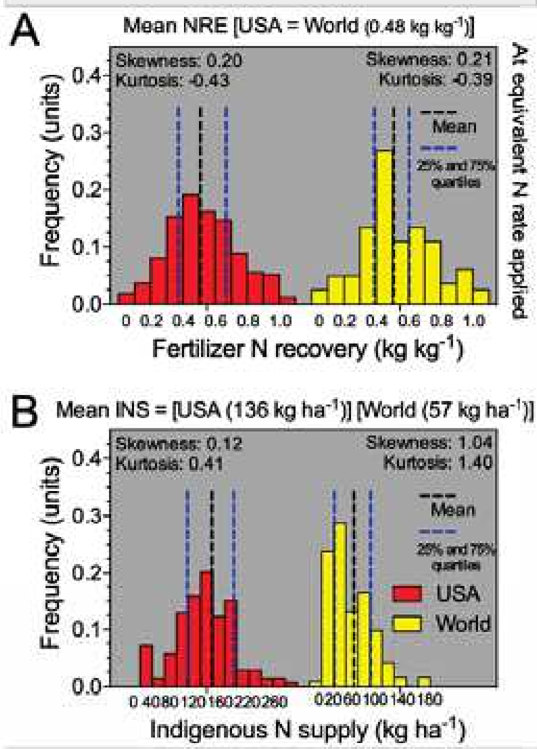


Fig. 5.

Frequency distribution (mean, median, and 25 and 75% quartiles, skewness and kurtosis coefficients) of the estimated fertilizer N recovery from the differential plant N uptake levels when N was applied as compared to the (A) nonfertilized control plot, and (B) the estimated indigenous N supply from the omission plots (plant N uptake values when no N was applied), from the information gathered for the United States (red bars) and the World (yellow bars) geographical clusters. For panel A, the total number of observations analyzed was 139 for the United States and 122 for the World datasets. For panel B, the total number of observations analyzed was 424 for the United States and 82 for the World datasets.

RESULTS AND DISCUSSION

Maize Grain Yield and Plant Nutrient Uptake

The compiled information was divided into two geographic locations characterized as either United States or World (i.e., not United States) and five (World) to six (U.S.) historical periods (1880–2012; Table 1). At the community scale, yield and plant nutrient (N, P, and K) uptake was greater for the United States than the World across historical periods (Table 1, Fig. 1A–1C). Historically, the relationship of maize grain yield to plant N content increased proportionally more for the United States than the World (Fig. 1A). Geographical clusters were tested for model fitting, although the degree of curvilinearity (β1) did not differ between regions, the initial slope (maximum N internal efficiency) was significantly greater for United States as compared with the World group. Historical mean yields (across all periods) were 4.6 Mg ha^{-1} greater for the United States than the World (Fig. 2C). Mean plant N uptake was 217 kg ha^{-1} in the United States vs. 129 kg ha^{-1} in the World (Fig. 1A). Cassman et al. (2002) documented a similar association for maize yield and N content from a U.S. dataset based on modern maize genotypes. In the current research, the yield–nutrient relationship slopes increased linearly at low to moderate nutrient uptake ranges; however, yield response increments declined as plant nutrient uptake climbed further (Fig. 1A–1C). Mean plant P and K contents were almost twofold greater for the United States vs. the World (39 vs. 24 kg P ha^{-1}, and 218 vs. 120 kg K ha^{-1}). The yield–nutrient relationship was more robust for N, followed by P and K with less intensity (lower R^2 values) in both geographical clusters across years, genotypes, and management systems. However, the U.S. data displayed consistently more efficient nutrient yield conversion (at similar nutrient contents) for N, P, and K.

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Table 1. View Full Table | Close Full View

Dataset summary (~160 research papers; n = 2306 treatment means) for grain yield (155 g kg^{-1}, moisture content) and plant nutrient uptake (dry basis) evaluated at crop maturity and mean plant density for each historical period (and corresponding mean year and observation number) in the United States and the World. For grain yield and plant nutrient (N, P, and K) uptake, values within parenthesis refer to the standard error calculated for each historical period and for both geographical clusters.

Geographical cluster	United States				
Parameters	Year and no. means	Grain yield	Plant nutrient upt		
			N	P	
	n		kg ha^{-1}		
Historical periods					
1880–1960	1935 n = 59	3591 (468)	81 (10.5)	13 (1.7)	5
1961–1975	1968 n = 110	8471 (437)	166 (6.7)	26 (1.0)	1
1976–1985	1982 n = 284	9486 (186)	209 (4.4)	41 (1.0)	1
1986–1995	1988 n = 69	10,357 (364)	234 (10.6)	62 (2.7)	2
1996–2005	2003 n = 455	11,947 (96)	255 (2.9)	39 (0.7)	2
2006–2012	2010 n = 253	10,028 (175)	194 (3.2)	40 (0.7)	1

For the United States, both grain yield and nutrient uptake climbed from the early 1900s to 1996 to 2005, and declined thereafter (Table 1, Fig. 2A, 2B). Grain yields in the first interval (1880–1960) increased at a rate of 149 kg ha^{-1} yr^{-1}, and a fairly constant yield gain of 100 kg ha^{-1} yr^{-1} occurred in research investigations from 1961 to 2005. For the entire historical U.S. period (1880–2012), annual maize grain yield increased at a rate of 123 kg ha^{-1} yr^{-1}; comparable to the corresponding USDA-NASS national yield gain of 113 kg ha^{-1} yr^{-1}. The U.S. yield reduction documented in the last historical period (2006–2012; Table 1) was similar to that reported nationally by the USDA for the same period (−274 vs. −230 kg ha^{-1} yr^{-1}, respectively). This decline pattern was influenced by the 2012 drought (national yield 7.7 Mg ha^{-1}) and yield declines in 2010 and 2011 following record national yields in 2009 (10.3 Mg ha^{-1}). Yields from research trials consistently exceeded the national average by 2 Mg ha^{-1} (Fig. 2A). Average plant nutrient contents at maturity mimicked the yield trend (Fig. 2B). Both N and K contents were relatively parallel for the entire period, but a greater K reduction was apparent during the final period (2006–2012; Table 1). Plant K content fell more than N and P from 2006 to 2012, presumably due to differential impacts of climate stress timing during the critical pre-flowering K accumulation period (Ciampitti et al., 2013a; Fig. 1B).

The World dataset reflects a lower yield level, relatively stable yields for the first half of the 20th century, and a substantial increase during the last 30 yr (Fig. 2C, Table 1). A partial explanation may be slow replacement of OPVs for single- and double-cross hybrids (e.g., in China OPVs were widely planted until the 1950s; while in the United States the change occurred 20 yr earlier; Duvick et al., 2004; Wang et al., 2011). Cumulative plant nutrient uptake followed yield trends (Fig. 2D), and the World database also demonstrated a smaller reduction in plant K uptake (relative to N and P) than the United States in the latest period. The geographical dataset distribution (Fig. 2E) demonstrates a critical need for more maize nutrient efficiency investigations in developing regions, but recent research data gains are encouraging (Fig. 2F). Recently, for the United States, a critical update for corn nutrient uptake (N, P, and K) evolution and partitioning was delivered by Abendroth et al. (2011), which was included in the "Corn growth and development" book. For the United States, maize yield plus nutrient uptake evaluations were prolific from the mid-1970s to the mid-1990s, but a similar peak was delayed 20 yr in developing countries. This delay in research progress parallels the lag phase documented in the national fertilizer consumption that flourished much later in the World (except for Europe) than in the United States (FAO, 2012). We can hypothesize that similar nutrient use efficiencies and yield improvement will be expected in productive agricultural regions around the globe if best production and nutrient management practices are employed together with adapted and best performance maize hybrids for each specific environment. Still, as modeled by Mueller et al. (2012), we can speculate that achieving a substantial reduction in the maize yield gap in developing countries and/or low yield regions will only come about by changing the farming culture related to nutrient and water management in appropriate ways for specific environments and genotype capabilities. Accordingly, 11 technologies were recently identified by Rosegrant et al. (2014) for shrinking yield gaps: among them no-till, integrated nutrient management, precision and organic agriculture, N use efficiency, water harvesting, drip and sprinkle irrigation, improved genotypes for heat and drought, and crop protection. In this research study, yield improvement for both geographies cannot be solely attributed to changes in nutrient application, but also reflects the combined effects of other production practices affecting the entire cropping systems such as timeliness of field operations, water management, and pests. In Canada, one study identifying major yield limiting factors in maize highlighted 27 to 38% yield reductions due to lack of weed control; while both low plant density and low nutrient application (omission of N and K) reduced yields about 9 to 18% (Subedi and Ma, 2009). In China, Chen et al. (2011) found that yields at the farm-scale nearly doubled when integrated crop production and nutrient practices were adopted, even when N rates did not increase as compared with the farmer's practice (the latter involved overuse of N). The latter studies clearly reflect the concept that implementation of a balanced nutrient approach in isolation (without proper integration and multi-factor optimization of maize production practices) will be an obstacle for capturing the environment-specific exploitable yield gap.

Plant-Scale Analyses for Grain Yield, Plant Nutrient Uptake, and Nutrient Use Efficiencies

Yield–nutrient relationships (Fig. 1A–1C) for the contrasting geographic regions became negligible following adjustments for plant density (Fig. 3A–3C). Nonetheless, for all nutrients, were adopted, even when N rates did not increase as compared with the farmer's practice (the latter involved overuse of N). The latter studies clearly reflect the concept that implementation of a balanced nutrient approach in isolation (without proper integration and multi-factor optimization of maize production practices) will be an obstacle for capturing the environment-specific exploitable yield gap.

Plant-Scale Analyses for Grain Yield, Plant Nutrient Uptake, and Nutrient Use Efficiencies

Yield–nutrient relationships (Fig. 1A–1C) for the contrasting geographic regions became negligible following adjustments for plant density (Fig. 3A–3C). Nonetheless, for all nutrients, model functions fitted presented statistical differences in their components (β_1 and β_2) when both geographical clusters were analyzed (Fig. 3A–3C). Overall, yield–N relationships at the individual-plant scale (Fig. 3A) portray common variation related to the PE for nitrogen (PE_N, change in yield per unit of change in N content). For the entire dataset, the maximum nitrogen dilution (N_D) occurred when N was a major yield-limiting factor ("severe nutrient deficiency"). In contrast, maximum nitrogen accumulation (N_A) resulted when non-N factors such as less-than-optimum cultural practices and biotic or abiotic stress (e.g., drought, heat, and pests) limited maize yield. Maximum nutrient accumulation occurs when nutrient uptake is beyond crop nutrient requirement ("luxury nutrient uptake") for that specific grain yield level. Luxury nutrient consumption also occurs if soil levels of a particular macronutrient are high and final nutrient requirement and crop removal tends to be greater than normal, promoting imbalances in nutrient ratios in the plant.

For P and K, PE was superior in the United States vs. the World at mid-to-low individual-plant nutrient uptakes (for $P < 1$ g plant^{-1} and for K < 5 g plant^{-1}; Fig. 3B, 3C). The PE advantage for the United States disappeared when yields were high (>14 Mg ha^{-1} or 200 g plant^{-1}). Data envelopes for yield P (P_A to P_D) and yield K (K_A to K_D) were broader than for yield N (N_A to N_D; Fig. 3A–3C). The 82% mean U.S. relative yield advantage per-unit-area (averaging 10.2 for United States vs. 5.6 Mg ha^{-1} for the World; Fig. 1) was reduced when expressed on a per-plant scale (averaging 148 for the United States vs. 96 g plant^{-1} for the World; Supplemental Fig. S1). Yield gaps between geographical groups widened progressively with time (Table 1). Although overall plant N, P, and K uptake per-unit area was nearly double in the United States, per-plant nutrient accumulation gains were less dramatic (Fig. 4A–4C).

For the last historical Era, PE_N was 54 g g^{-1} for the United States vs. 45 g g^{-1} for World (Fig. 4A). The narrower PE_N gap observed between the United States and the World for the modern Era was distorted by the 2012 U.S. drought because of its low yields. The PE_P for the United States exceeded the World by 20% (300 vs. 240 g g^{-1}) during 1996 to 2005 and by 11% (266 vs. 238 g g^{-1}) from 2006 to 2012 (Fig. 4B). The PE_K improved by 9% for the last period (Fig. 4C). Across all periods and geographies, PE changes were more a consequence of yield changes rather than plant nutrient content. The main factors contributing to continued maize yield gain in the United States were related to: (i) genetic and crop physiology components such as resistance to barrenness, leaf angle, greater anthesis-silking synchrony, improvement of leaf stay green, transgenic tolerance to pests and drought, and greater tolerance to crowding; and (ii) management practice components such as application of commercial fertilizers, pest control, earlier planting dates, tillage systems, and water management (Cassman et al., 2002). A recent research paper (Grassini et al., 2013) studied the yield advances for maize using historical crop production trends (since the start of the Green Revolution in the 1960s). The latter study clearly emphasized the yield gap between the United States vs. Brazil, China, India, and Central Africa. High yield improvement potential was particularly evident for Brazil, India, and Central Africa, where maize yields remained static from 1960s until 1990s. In our analysis at the community scale, higher PE improvement in the United States vs. the World was the outcome of an overall superior maize cropping system with substantially more inputs for producing an overall yield at the country scale above 9 Mg ha^{-1} (FAO, 2012).

From the nutrient use efficiency perspective, per-plant nutrient content in the United States (1880–1960 vs. 2006–2012) was 31, 22, and 19% less for N, P, and K, respectively (Fig. 4A-4C), while mean per-plant grain yield was only 7% less. Therefore, superior nutrient use efficiency was primarily achieved with lower nutrient content at the plant level (implying a nutrient dilution process) at crop maturity. The historical trend of lower maize grain and plant N concentrations over time has been previously documented (Ciampitti and Vyn, 2012, 2013) for a shorter historical time interval (70 yr) after utilizing a different summary of research studies, but this is the first report on historical P and K status changes over time. Appropriate "crop metrics" in future maize improvement should target yield gains together with superior nutritional quality (Morris and Sands, 2006) as well as nutrient use efficiency for a range of essential nutrients.

Apparent Nutrient Budgets

Consideration of apparent nutrient budgets, modestly defined as the nutrient quantity harvested per unit of nutrient added, are integral to this analysis. All calculations for fertilizer nutrient application and recovery, and plant nutrient uptake were performed employing the same sub-database. Average fertilizer N added was 178 kg ha^{-1} for the United States and 138 kg ha^{-1} for the World (Supplemental Fig. S2). At a global scale, maize nitrogen recovery efficiency (NRE, defined as the ratio of plant N uptake to the total N inputs) has been estimated at almost 60% (Liu et al., 2010). At equivalent fertilizer N rates applied (200 kg N ha^{-1}), fertilizer NRE was similar (0.48 kg N uptake kg^{-1} fertilizer N) for the United States and World databases (Fig. 5A). The overall NRE data responses reflected comparable skewedness (asymmetry) and kurtosis (peakedness), but the World's observations were more concentrated within the 25 to 75% quartiles than those of the United States. Thus, if a similar NRE can be assumed, the other source of variation for crop N supply is the indigenous N pool. This latter N source can be estimated using N omission plots (i.e., no fertilizer N added). Mean indigenous nitrogen supply (INS) was 136 kg N ha^{-1} (50% quartile, 107–170 kg N ha^{-1}; $n = 139$ points) for the United States vs. only 57 kg N ha^{-1} (50% quartile, 30–80 kg N ha^{-1}; $n = 122$) for the World dataset (Fig. 5B). Distribution for the INS term was more peaked, less asymmetric, and more concentrated (narrower range between 25 and 75% quartiles) for the World as compared with the United States. Similar differences in INS in the United States vs. Asia were observed in rice (Cassman et al., 2002).

Across all time intervals, plant N uptake averaged 218 kg ha^{-1} for the United States and 121 kg ha^{-1} for the World (Fig. 1A). Fertilizer N accounted for 40 and 55% of the total N supply needed by maize for the United States and World databases, respectively. Mean NUE in the United States averaged 57 kg grain kg^{-1} N applied, while NUE averaged 41 kg grain kg^{-1} N applied in the World database. The previous NUE differential is partially related to the U.S. yield advantage (Fig. 1F), but may also be explained by lower indigenous N and N fertility rate adjustments in the World (e.g., excess fertilizer N commonly applied in China [Chen et al., 2011]). For short-term goals, improving N fertilizer synchronization could further increase yields without increasing N applications [e.g., in China on-farm research yields were doubled without increasing N rates (Chen et al., 2011)]. Biotechnology is currently exploring the development of transgenic N-efficient crops (McAllister et al., 2012), but these efforts are long-kg ha^{-1} for the World (Fig. 1A). Fertilizer N accounted for 40 and 55% of the total N supply needed by maize for the United States and World databases, respectively. Mean NUE in the United States averaged 57 kg grain kg^{-1} N applied, while NUE averaged 41 kg grain kg^{-1} N applied in the World database. The previous NUE differential is partially related to the U.S. yield advantage (Fig. 1F), but may also be explained by lower indigenous N and N fertility rate adjustments in the World (e.g., excess fertilizer N commonly applied in China [Chen et al., 2011]). For short-term goals, improving N fertilizer synchronization could further increase yields without increasing N applications [e.g., in China on-farm research yields were doubled without increasing N rates (Chen et al., 2011)]. Biotechnology is currently exploring the development of transgenic N-efficient crops (McAllister et al., 2012), but these efforts are long-term, complex, and uncertain to make substantive gains.

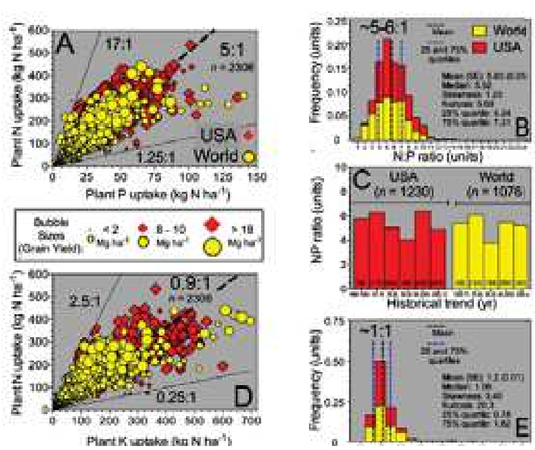
For P, the mean fertilizer rate (across all historical data) was 43 and 53 kg ha^{-1} for the United States and the World, respectively (Supplemental Fig. S2); while plant P uptake was 39 and 25 kg ha^{-1}, respectively. A neutral budget can be attained when grain P removal equals P applied. Thus, assuming a grain P removal of 80% (Ciampitti et al., 2013a), the United States resulted in an apparent P budget with lower P surplus (+8 kg P ha^{-1}) as compared with the World (+31 kg P ha^{-1}). One important aspect that should also be considered in this simplistic analysis is the fertilizer phosphorus recovery efficiency (PRE). At the global-scale, PRE for maize was reported to be 45% (Tilman et al., 2002). Thus, approximately less than half of the P applied was potentially harvested or recovered (Sattari et al., 2012). Low PRE is predictable on many soils due to the strong interaction of this nutrient with the soil matrix. For example, strong soil-retention of P occurs under low pH (below 6) when P is fixed by Fe and Al and under high pH (above 7) when P is fixed by Ca (Sample et al., 1980). Thus more plant-available P would be expected for a given P fertilization rate when soil pH ranges between 6 and 7 units.

For K, mean fertilizer K rate applied was 96 kg ha^{-1} for the United States and 128 kg ha^{-1} for the World (Supplemental Fig. S2); while plant K uptake was 217 and 121 kg K ha^{-1}, respectively. The negative K budget for the United States may be an artifact due to insufficient publication records concerning fertilizer and manure K applications when maize was rotated with other crops. Another recent K budget analysis based on soil-test lab results in the United States depicted higher K application than crop K removal from 1960 to 1990, but a negative K budget for the United States from 2005 to 2012 (Fixen and Murrell 2002). For North America, K fertilizer consumption remained stagnant since 1980s (IFA, 2014), which might be related to land tenure and price fluctuations in both grain and potash fertilizer commodities. For the World dataset, K application and uptake patterns reflected a near-neutral K budget (+7 kg K ha^{-1}).

For both nutrients, two points are noteworthy: (i) soil test levels and (ii) potential soil nutrient supply. A negative budget does not necessarily mean a lack of nutrient balance if the soil test level for that nutrient is above the sufficiency range or if the soil possesses a high potential supply. Thus, our emphasis on a balanced approach to fertilization does not properly account for these two main factors that can highly influence the response of the crop to the applications of nutrients and the final calculation of the nutrient budgets. Any comprehensive fertilization strategy requires that nutrient applications should be based on soil test, potential soil nutrient supply (e.g., indigenous nutrient supply from organic sources), and expected yield and crop nutrient removal. Under high or sufficiency nutrient status, net return to the investment decreases as soil nutrient supply increases. Therefore, a comprehensive nutrient fertilization strategy should consider both soil and crop factors when balancing nutrient supply (soil-based process) with demand (plant-based process). Following this rationale, a successful approach implemented at a large scale in China (Chen et al., 2011) nearly doubled maize farmer's yield with the use of an integrated soil–crop system management–ISSM (13 vs. 6.8 Mg ha^{-1}). The ISSM strategy was not only based on increasing the synchrony between nutrient demand and supply (via split N applications), but also on capturing and shrinking yield gaps via optimization of the crop production practices such as planting date (later planting), plant density (higher densities), and maize genotypes (modern materials).

Nutrient Stoichiometry (N/P and N/K ratios) and Crop Productivity

Plant nutrient ratios can be employed as a valuable tool for determining nutrient imbalances. Nutrient balances were calculated as the N/P and N/K ratios at maturity (Fig. 6A–6F). Mean N/P association was five units of N per unit of P (5:1 ratio) but with a variation from 17:1 (maximum N accumulation) to 1.25:1 (maximum N dilution; Fig. 6A). Yield level was not strictly related to N/P balance, but in potential yield maize systems (>18 Mg ha^{-1}) the N/P ratio ranged narrowly from five to six units. In general terms, in-season N/P ratios decline as plant mass increases (Kerkhoff et al., 2006; Greenwood et al., 2008). Thus, N/P ratio is sensitive to changes in biomass, decreasing as the proportion of the storage/structure/growth tissues increases. From a physiological standpoint, improvements in grain nutrient quality governed by changes in P concentration (e.g., phytate content) might have a potential effect in reducing the final plant N/P ratio. The frequency distribution for the N/P ratio was positively skewed (>50% of entire dataset was concentrated between 4:1 to 7:1; Fig. 6B) but with equal geographical scattering (Fig. 6C). Notwithstanding the similar scattering and overall values between geographies, maize results from the World dataset achieved this N/P ratio with greater imbalances in fertilizer application rates as compared to the United States. Similar N/P ratios (averaging 5.6 units) were previously summarized for cereals (Sadras 2006). In addition, Sadras (2006) also documented narrow N/P variation range from four to six units for maximizing yields in oilseeds and cereals (including maize).



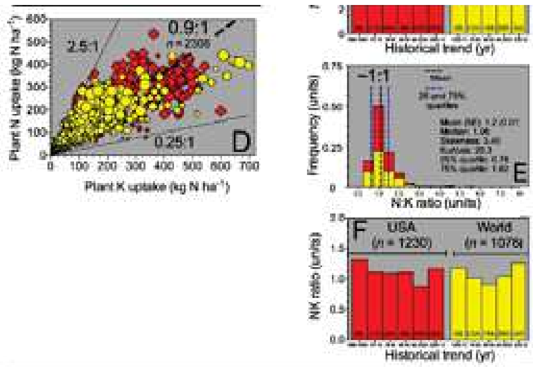


Fig. 6.

Plant nutrient balance at maturity for the entire dataset (involving historical trend 1880–2012 yr) and for the geographical division of United States and World (all but the U.S.) groups. (A, B, C) Plant N/P ratio, frequency and historical distribution. (D, E, F) Plant N/K ratio, frequency and historical distribution. For panels A and D, black dash lines represent the maximum and minimum nutrient ratio, range of nutrient variation expected. For panels C and F, error bars refer to the standard error measurement calculated for each geographical cluster and historical period.

From this review paper, changes in the N/P ratio were more related to plant P changes (excess or deficiency) rather than to plant N. Prior research observed that largest P surpluses were spatially clustered in the United States and South Asia (India, Pakistan, and Thailand), while largest P deficits were concentrated in South America and eastern Europe (MacDonald et al., 2011). Furthermore, phosphorus use efficiency (PUE) followed a general rule relative to P budgets (P surplus coincided with low PUE, while P deficits coincided with high PUE). Neither scenario is desirable as both compromise sustainable food production systems: the former contributes to eutrophication of surface waters, while the latter mines soil P (jeopardizing inherent soil fertility).

The overall N/K ratio value across temporal and geographical groups was close to 1:1 (Fig. 6D). The maximum to minimum K dilution varied 10-fold (N/K ratio from 2.5 to 0.25:1 ratio). High-yielding data points (>18 Mg ha^{-1}) portrayed a narrow N/K variation (0.6 to 1.3 units). The frequency distribution revealed similar geographical scattering (Fig. 6E), with more than 50% of the entire dataset around a 1:1 N/K ratio. Only a relatively narrow N/K variation was evident over time (ranging from 0.8–1.2:1 N/K units; Fig. 6F). In-season plant N/K ratios increased as N uptake progressed during the reproductive period (Ciampitti et al., 2013a). In addition, K storage in vegetative structures (stover fraction) is hypothesized to govern the changes in the N/K ratio as crop matures. High-yielding maize demonstrated a N/K ratio close to 1:1 that was related to improvement in stover K concentration, but was also associated with grain N dilution (i.e., N protein declined as yields improved; previously reviewed by Ciampitti and Vyn, 2012, 2013).

A recent global-scale analysis for multiple field crops documented N budgets that were near-neutral for North America, positive for Oceania, and generally negative for Africa and South America (Liu et al., 2010). The amount of K in maize residues at maturity represents around 70 to 80% of the plant K uptake (Ciampitti et al., 2013a). Although most K taken up by maize is recycled back to soil when only grain is harvested, optimum plant growth relies on sufficient exchangeable K. Potassium budgets (actual K applied vs. grain K removal per unit land area) are frequently negative in South America (e.g., Argentina, Uruguay, and Paraguay), Africa, and Central-South China regions, due to low or no fertilizer K application. Occasionally K additions may not be required due to high indigenous K reservoirs (e.g., Argentina). However, the hidden cost for this management approach is that soil K is progressively mined as crop intensification increases.

Changes in N/P and N/K ratios between the United States and the World were primarily dominated by yield range variations, and secondarily governed by changes in nutrient contents. The overall superior yield levels explored for the U.S. cluster were at least partially associated with greater fertilizer N applications (Supplemental Fig. 2A), even though N fertilizer efficiency was similar between geographies (Fig. 5A), and indigenous N supply levels (Fig. 5B). In addition, the World depicted higher applications of P and K (Supplemental Fig. 2B) producing overall lower yields as compared to the United States, reflecting either excessive nutrient use relative to crop requirements or intentional buildup of soil-test levels.

In summary, even when nutrient ratio values for the United States and the World were similar (Fig. 6C, 6F), distribution of these ratios was less balanced for the World and more uniform (concentrated) for the U.S. geographical cluster (Fig. 6B, 6E). A much greater nutrient ratio disparity was documented for the World database, which reflects that there is realistic potential for simultaneous achieving balanced nutrient ratios and higher yields. Thus, a focus on large-scale and easy-to-implement yield improvement practices using integrated approaches, such as increasing soil-crop N synchrony via split N applications (Chen et al., 2011), would allow developing and/or low-yield regions to sustainably produce high yields with balanced nutrient ratios.

Major-Limiting Factors for Closing Maize Yield Gaps: A Need for Future Research

Prospects for concurrent improvement in yields and nutrient use efficiency is a critical issue. Within the database employed in this paper, some of the critical factors to consider for narrowing yield gaps in developing countries or low yielding regions are improvements in nutrient management with particular emphasis on more optimum N fertilizer rates and better synchrony of N fertilizer application to maize plant uptake in both vegetative and reproductive growth stages. Yield limitations were also observed under moderate to severe P and K limitations in soils with low soil test values and potential nutrient supply. From the production management side, improving plant density in medium to high-yielding environments can be one of the key factors for capturing a superior yield and closing gaps. Inadequate understanding of yield limiting factors in already high-yielding cropping systems (>14 Mg ha^{-1}) will further impair maize yield improvement progress.

In this review, we highlighted several studies that identified maize yield-limiting factors (Cassman et al., 2002; Subedi and Ma, 2009; Chen et al., 2011; Mueller et al., 2012). These synchrony of N fertilizer application to maize plant uptake in both vegetative and reproductive growth stages. Yield limitations were also observed under moderate to severe P and K limitations in soils with low soil test values and potential nutrient supply. From the production management side, improving plant density in medium to high-yielding environments can be one of the key factors for capturing a superior yield and closing gaps. Inadequate understanding of yield limiting factors in already high-yielding cropping systems (>14 Mg ha^{-1}) will further impair maize yield improvement progress.

In this review, we highlighted several studies that identified maize yield-limiting factors (Cassman et al., 2002; Subedi and Ma, 2009; Chen et al., 2011; Mueller et al., 2012). These factors can be divided into three categories: (i) genotypic-related, closely associated with breeding improvement, (ii) management practices, involving all production and nutrient practices, and (iii) environment and weather-related factors. Except under water irrigation scenarios, producers have a strong influence on the first two components. Hybrid selection, planting date, plant density, nutrient (quantity and timing), crop protection practices (e.g., whether genetic or chemical applications) are among major yield-limiting factors identified in this and other research studies. There are still many more facets to explore to achieve superior understanding of critical factors for shrinking current yield gaps.

More integrated-approaches (at plant- and community-scales) based on physiological-driven changes beyond plant density stress tolerance alone (e.g., modifications in plant processes such as nutrient partitioning, kernel establishment, ear size, number of ears per plant, among others) should be pursued. Formation of kernels row per ear starts early during the vegetative period (V5 stage) with final ear size and potential kernel number defined around mid-to-late vegetative (V12 stage); unbalanced nutrient uptake early during maize growing season can affect plant nutrient concentration, biomass, and produce early abortion of the potential number of kernels (Ciampitti et al., 2013b). Nitrogen can affect ear size and the final number of kernels. Although potential kernel number (before flowering) was slightly reduced by N stress, post-flowering abortion with low N reduced the final kernel number much more (Ciampitti et al., 2013b). The effects of N, P, and K nutrients on biomass, yield, and final nutrient partitioning was also recently investigated by Ciampitti et al. (2013a, 2013b); these studies documented a proportionality for P and K responses to biomass and N partitioning (vegetative to reproductive organs) patterns from early flowering stage until maturity. Yield improvement based on optimizing plant nutrient balance ratios should be focused on understanding complex and physiological plant growth and nutrient uptake pathways. In summary, maize genotype (G) evaluations under varying management practices (M) and environments (E) are essential for characterizing the potential for simultaneously improving yield and nutrient use efficiency in developed and developing regions around the globe.

CONCLUSIONS

Five points are noteworthy from this review: (i) at a community scale, the United States reflected greater PE (grain yield to plant nutrient content) for N, P, and K than the database gathered from the World; the latter was associated with improvements at the cropping-system scale, such as the utilization of combinations of crop management practices interacting to achieve positive gains (i.e., not in isolation); (ii) at a plant-scale (adjusted by plant density), differences in PE were negligible for both the historical and geographical analyses; (iii) historical PEs improvements were primarily achieved by reductions in per-plant nutrient contents; (iv) apparent nutrient budgets were close to neutral for N and P for the United States, but greater nutrient asynchrony was apparent for the rest of the World; and (v) overall nutrient ratios for N/P (5–6:1) and N/K (1:1) were comparable across Eras and geographies, with high-yielding maize systems requiring better balance and more nutrients. There is still considerable scope, particularly in developing regions, for better nutrient management practices (improving utilization by increasing or reducing rates, depending on the region) to help close maize yield gaps and improve overall nutrient PE. Future demands from maize production (including biofuels) will only accelerate utilization of non-grain plant fractions and therefore intensify nutrient use considerations for the whole production system. Multiple nutrient efficiency foundations should be given greater prominence in maize improvement research endeavors addressing the food security challenge.

Acknowledgments

We express our thanks to Alicia West, Dario Romagnoli, Ana Julia Carvalho Basilio de Azevedo, (time input); and Peter Kovács, Juan Pablo Burzaco, Jason Roth, and Keru Chen for sharing data from their Purdue University thesis research projects for our review paper. The authors wish to thank the following scientists and their institutions: F.O. Garcia, S.T. Murrell, P. Fixen, S. Kartaatmadja, J.M. Pasuquin, C. Witt (all IPNI), C.L. Mann, D. Binder, G. Teichman, C. Wortmann, R. Ferguson, C. Shapiro, D. Tarkalson, G. Hergert, K. Cassman, D. Walters (deceased), T. Setiyono (all University of Nebraska), A. Dobermann (IRRI); S.S. Girsang (AIAT North Sumatera), A.M. Murni (AIAT Lampung), S. Hadisiswoyo (AIAT Central Java), Supadmo (AIAT Central Java), Suwono (AIAT East Java), P. Tandisau (AIAT South Sulawesi), Sania Saenong and Subandi (ICRI), T.T. Son, N.V. Chien, and V.T.K. Thoa (NISF).

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Footnotes

[1]Additional references can be found in the electronic supplemental material. Supplemental material available online

Available freely online through the author-supported open access option.

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Ensure nitrogen remains available to crops when it's needed most. Proximus® backed by Nutri-Guard® Technology is the only naturally sustainable product on the market proven to increase Nitrogen Use Efficiency (NUE) while reducing nitrate leaching. With this innovative technology, farmers can improve their crop performance with less impact on the environment.

Product Label

Product SDS

Ready to reduce nitrogen leaching?

CONTACT US NOW

Works with Natural Soil Processes

Applied with UAN fertilizer, Proximus increases the natural microbial populations within the soil. These microbes synchronize nutrient delivery to the plant and reduce losses through leaching. Its mode of action enhances the naturally-occurring nitrogen cycle, creating an ebb and flow of available nitrogen in the root zone throughout the growing season.

- Increases NUE, enabling greater and more rapid crop uptake
- Promotes beneficial bacteria and natural soil processes
- Naturally-sustainable ingredients
- Safe for all crops when used as labeled

Safe for all crops when used as labeled

SLOW NITRATE LEACHING

Nitrogen loss due to nitrate leaching is a concern many growers and their communities share. Common approaches to compensate for nitrogen loss are higher application rates, additional applications or adding a nitrogen stabilizer. However, adding more nitrogen only increases the risk of leaching and nitrogen stabilizers attack natural soil bacteria that may be beneficial to reducing leaching later in the season.

Proximus ensures nitrogen applications remain available to the crop, eliminating the need to increase rates, reapply or disrupt natural systems. Instead, it helps to gradually release the nitrogen pool back into the soil, allowing crop uptake while minimizing leaching into groundwater.

Proof in the Numbers

UP TO **23%** MORE NITROGEN IN THE CROP

- increased nitrogen availability in multiple field trials

UP TO **15%** HIGHER YIELDS

- resulted in higher yields than when crops were treated with UAN alone

UP TO **69%** LESS LEACHING

- reduced leaching when mixed with UAN fertilizer in trials

BACKED BY RESEARCH

Actagro® utilizes third-party field trials and greenhouses throughout the U.S. and internationally to test performance where it matters. A team of

- increased nitrogen availability in multiple field trials
- resulted in higher yields than when crops were treated with UAN alone
- reduced leaching when mixed with UAN fertilizer in trials

BACKED BY RESEARCH

Actagro® utilizes third-party field trials and greenhouses throughout the U.S. and internationally to test performance where it matters. A team of agronomists and scientists studied Proximus for three years in over 25 studies to produce a formulation that delivers results.

[1]Source: Actagro, 2016. Based on 12 trials across the U.S.
[2]Source: Actagro, 2014, 2016. Based on replicated and on-farm trials across 13 locations.

Nitrogen Use Efficiency Definitions

Google
Nitrogen Use Efficiency

World Nitrogen Use Efficiency for Cereal Production is 33%
Agronomy Journal 91: 357-363

Nitrogen use efficiency and/or fertilizer recovery in crop production systems can be computed using a wide range of methods. Those specifically designated for crop production systems follow. In addition, nitrogen use efficiency has been estimated using world N consumption and crop production, but on macro scales (Agron. J. 91:357-363). Other methods (Difference Method, Isotopic Method (Enriched and Depleted)) are delineated below. The components of Nitrogen Use Efficiency (NUE) are further discussed, as initially reported by Moll et al. (1982). Regardless of the method, almost all result in estimated NUE for cereal production that average between 30 and 35%. Topdress or sidedress N applications in the middle of the season can result in greater NUE's (>50%). Because the risk of N loss is greater when N is applied in the fall, N should be applied in the spring to minimize risk and optimize profitability regardless of tillage system (Vetsch and Randall, 2004).

Keeney 1982 Justification. (reference used in AJ 91:357)

1. Calculating N Use Efficiency using The Difference Method

Difference method

PFR = (NF)-(NC) / R

NF = total crop N uptake (corn, wheat, rice, etc.) from fertilized plots
NC = total crop N uptake (corn, wheat, rice, etc.) from unfertilized plots
R = rate of fertilizer N applied
PFR = percent fertilizer recovery

EXAMPLE below:

Applied N kg/ha	Grain Yield kg/ha	Grain N %	N uptake kg/ha	Fertilizer Recovery (NUE), %
0	1000	2	20	-
50	1300	2.1	27.3	(27.3-20)/50=14.6
100	2000	2.2	44	(44-20)/100=24
150	2000	2.3	46	(46-20)/150=17

2. Macro Calculation of World NUE (method defined)

World Nitrogen Use Efficiency for Cereal Production is 33%, Agronomy Journal 91:357

3. Moll et al. (1982), components of NUE

Moll, R.H., E.J. Kamprath, and W.A. Jackson. 1982. Analysis and interpretation of factors which contribute to efficiency in nitrogen utilization. Agron. J. 74:562-564.

1. Components of NUE (added discussion of Moll et al. (1982)
2. Text, Components of NUE (added discussion)

presence of two primary components of N use efficiency:
efficiency of absorption or uptake (Nt/Ns)
efficiency with which N absorbed is utilized to produce grain (Gw/Nt)
Nt = total N in the plant at maturity (grain + stover)
Ns = nitrogen supply or rate of fertilizer N
Gw = grain weight (all expressed in the same units)

Consideration of additional parameters not discussed in Moll et al. (1982) "plant N loss

- Maximum N accumulation has been found to occur at or near flowering in wheat and corn and not at harvest.
- In order to estimate plant N loss without the use of labeled N forms, the stage of growth where maximum N accumulation is known to occur needs to be identified.
- The amount of N remaining in the grain + straw or stover, is subtracted from the amount at maximum N accumulation to estimate potential plant N loss (difference method).
- Use of difference methods for estimating plant N loss are flawed since continued uptake is known to take place beyond flowering or the point of maximum N accumulation.

Davis, R.L., J.J. Patton, R.K. Teal, Y. Tang, M.T. Humphreys, J. Mosali, K. Girma, J.W. Lawles, S.M. Moges, A. Malapati, J.Si, H. Zhang, S. Deng, G.V. Johnson, R.W. Mullen, and W.R. Raun. 2003. Nitrogen balance in the Magruder Plots following 109 years in continuous winter wheat. J. Plant Nutr. 26(8):1561-1580.

COMPONENTS of NUE (Moll et al., 1982), graphic illustration

4. Nitrogen Use Efficiency (Recovery) Using Isotopic Methods

Enriched 15N:

Materials with a greater than natural concentration of 15N % plant N derived from fertilizer = %15N excess in sample % 15N excess in fertilizer

Depleted 15N:

Materials with a lower than natural concentration of 15N (0.003 - 0.01 atom % 15N) or (< 0.01 atom % 15N)

Use of isotopic 14N

Studies involving residual soil nitrogen are not practical with depleted materials due to the high dilution factor

% plant N derived from the fertilizer =

(Nu - Nt)/(Nu - (Nf/n))
Nu =atom % 15N in unfertilized plants
Nt = atom % 15N in fertilized plants
Nf = atom % 15N in the fertilizer (for example 0.006%)
n = the plant discrimination factor between 14N and 15N.

If it is assumed that there is no discrimination between 14N and 15N, then n = 1.

5. Fertilizer N Recovery (Varvel and Peterson, 1990)

1. Difference method

PFR = (NF)-(NC) / R

Nu =atom % 15N in unfertilized plants
Nt = atom % 15N in fertilized plants
Nf = atom % 15N in the fertilizer (for example 0.006%)
n = the plant discrimination factor between 14N and 15N.

If it is assumed that there is no discrimination between 14N and 15N, then n = 1.

5. Fertilizer N Recovery (Varvel and Peterson, 1990)

1. Difference method

PFR = (NF)-(NC) / R

NF = total N uptake in corn from N fertilized plots
NC = total N uptake in corn from unfertilized plots
R = rate of fertilizer N applied
PFR = percent fertilizer recovery

2. Isotopic method (Depleted material)

PFR = ((NF) x (C-B)/D) / R

NF = total N uptake in corn from N fertilized plots
B = atom % 15N of plant tissue from N fertilized plots
C = atom % 15N of plant tissue from unfertilized plots (0.366%)
D = depleted atom % 15N in applied N fertilizer
R = rate of applied 15N-labeled fertilizer

3. Isotopic method (Enriched material, Sanchez et al., 1987)

F = As-Ar/Af-Ar
F= fraction of total N uptake derived from 15N enriched fertilizer
As = atom % 15N measured in the harvested plant sample
Af = atom % 15N in the enriched fertilizer
Ar = atom % 15N of the reference harvested plant material from non 15N enriched fertilizer treatments

Ef = F x total N uptake
Ef = uptake of 15N enriched fertilizer

Shearer and Legg (1975) found that d15N of wheat plants decreased as the N application rate increased.

d15N = atom % 15N (sample) - atom % 15N (standard) x 1000 / atom % 15 N (standard)

15N composition of the total N of grain and leaf samples of corn (Zea mays L.) decreased systematically as N fertilizer rates increased (Kohl et al., 1973). This result was considered to be consistent with increasing contributions of fertilizer N to plants as the rate of applied N increased.

Hauck and Bremner, 1976

percent nitrogen recovered (plant or soil) =

= 100P (c-b) / f(a-b)

P = total N in the plant part or soil in kg ha-1
f = rate of 15N fertilizer applied
a = atom percent 15N in the labeled fertilizer
b = atom percent 15N in the plant part or soil receiving no 15N
c = atom percent 15N in the plant part or soil that did receive 15N

unlabeled N uptake = (total N uptake in grain and straw) -

[N rate(% recovery of 15N in grain and straw)]

6. Fertilizer N Recovery, Mass Balance (Davis et al., 2003)

Davis, R.L., J.J. Patton, R.K. Teal, Y. Tang, M.T. Humphreys, J. Mosali, K. Girma, J.W. Lawles, S.M. Moges, A. Malapati, J.Si, H. Zhang, S. Deng, G.V. Johnson, R.W. Mullen, and W.R. Raun. 2003. Nitrogen balance in the Magruder Plots following 109 years in continuous winter wheat. J. Plant Nutr. 26(8):1561-1580.

The Magruder Plots are the oldest continuous soil fertility wheat research plots in the Great Plains region, and are one of the oldest continuous soil fertility wheat plots in the world.

They were initiated in 1892 by Alexander C. Magruder who was interested in the productivity of native prairie soils when sown continuously to winter wheat.

Simple estimate of nitrogen (N) balance
1. account for N applied.
2. account for N removed in the grain
3. account for estimated plant N loss, denitrification, nitrate leaching
4. account for non-symbiotic N fixation, N applied in the rainfall.
5. have an estimate of total soil N (0-30 cm) at the beginning of the experiment
6. have an estimate of total soil N (0-30 cm) at the end of the experiment

Manure plots: total soil N decreased from 6890 kg N ha-1 in the surface 0-30 cm in 1892, to 3198 kg N ha-1 in 2002.

Check plots (no nutrients applied for 109 years) only 2411 kg N ha-1 or 35% of the original total soil organic N remains.

Nitrogen removed in the grain averaged 38.4 kg N ha-1yr-1
N additions (manure, N in rainfall, N via symbiotic N fixation) averaged 44.5 kg N ha-1 yr-1 in the Manure plots.

Following 109 years, unaccounted N ranged from 229 to 1395 kg N ha-1.
By year basis, translates into 2 to 13 kg N ha-1yr-1 that were unaccounted
Manure plots, estimate of nitrogen use efficiency (NUE) (N removed in the grain, minus N removed in the grain of the check plots, divided by the rate of N applied) was 32.8%

Similar to the 33% NUE for world cereal production reported in 1999.
World Nitrogen Use Efficiency for Cereal Production is 33%
Agronomy Journal, 91:357-363

EHAG 17

References (Papers showing that NUE is between 30 and 40%)

Olson, R.V. and C.W. Swallow. 1984. Fate of labeled nitrogen fertilizer applied to winter wheat for five years. Soil Sci. Soc. Am. J. 48:583-586.

NUE: 27-33%

Davis, R.L., J.J. Patton, R.K. Teal, Y. Tang, M.T. Humphreys, J. Mosali, K. Girma, J.W. Lawles, S.M. Moges, A. Malapati, J.Si, H. Zhang, S. Deng, G.V. Johnson, R.W. Mullen, and W.R. Raun. 2003. Nitrogen balance in the Magruder Plots following 109 years in continuous winter wheat. J. Plant Nutr. 26(8):1561-1580.

NUE: 32.8%

Raun, W.R. and G.V. Johnson. 1999. Improving Nitrogen Use Efficiency for Cereal Production. Agron. J. 91:357-363.

NUE: 33%
(maize, rice, barley, sorghum, millet, oat, and rye)

Moll, R.H., E.J. Kamprath, and W.A. Jackson. 1982. Analysis and interpretation of factors which contribute to efficiency to nitrogen utilization. Agron. J. 74:562-564.

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Raun, W.R., Solie, J.B., Johnson, G.V., Stone, M.L., Mullen, R.W., Freeman, K.W., Thomason, W.E., and Lukina, E.V. (2002) Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agronomy Journal, 94: 815 to 820.

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NEW N Management Strategy for Corn and Wheat

PDF version from Agronomy Journal (91:357-363)

NUE Flow Chart (OSU discussion)

Components of Nitrogen Use Efficiency (added discussion of the Moll et al. 1982) manuscript

Nitrogen Cycle Page.

Technical Paper 01/2015

Position Paper
Nitrogen Use Efficiency and Nutrient Performance Indicators

A publication of the
Global Partnership on Nutrient Management

Lead authors:
Rob Norton, Eric Davidson, and Terry Roberts

2015

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About the Global Partnership on Nutrient Management

The Global Partnership on Nutrient Management (GPNM) is a multi-stakeholder partnership comprising of governments, private sector, scientific community, civil society organizations and UN agencies committed to promote effective nutrient management to achieve the twin goals of food security through increased productivity and conservation of natural resources and the environment. The United Nations Environment Programme (UNEP), through the Coordination of Office of the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA), provides the Secretariat of GPNM.

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Foreword

This paper offers the technical basis and supporting research for using Nitrogen Use Efficiency (NUE) as a performance indicator to improve global food production and control the potential harmful environmental impacts of excess nitrogen-based compounds from manufactured and animal waste fertilizers. NUE implies a more precise application of nutrients that is based on current agronomic principles in combination with other factors like soil health, water availability, climate, and type of crop.

Since the NUE indicator can be quantified, countries now have an opportunity to evaluate the effectiveness of their own nutrient policies and, at the same time, farmers have the ability to assess the efficiency of their farming practices and nutrient use to increase production and reduce environmental damage. The GPNM recommends NUE as a performance indicator to address nutrient losses within developing and existing global agreements that focus on sustainable development, oceans, climate change, biodiversity, water quality, air quality and soil health.

Greg Crosby
Chair, GPNM
USDA National Institute of Food and Agriculture

Nitrogen use efficiency and nutrient performance indicators. GPNM Task Team Report and Recommendations[1]

Rob Norton, Eric Davidson, and Terry Roberts

Summary

The Task Team recommends using Nitrogen Use Efficiency (NUE) to describe partial nutrient balance (also referred to as removal/use or output/input ratio) and note that it can be configured in different ways to show the current starting point (benchmark) from which future improvements can be assessed (progress indicator). NUE can be expressed at different scales from the farm to the country level. Neither a high nor a low NUE is an implicit target, but raising low values, which usually indicate inefficient use of added nitrogen, and lowering very high values, which usually indicates mining of soil nitrogen, will require appropriate interventions at the farm level, so that the farmer engagement is important in achieving progress. The task team recognizes that NUE relates to production and soil health, so it needs to be put in context to other indicators. We also note that significant lags between improvements in NUE and reductions in N pollution of groundwater and surface waters may occur, but nevertheless, increases in NUE and reductions of surplus N in agriculture should eventually lead to lower N pollution.

PREAMBLE

The efficient and effective use of nutrients underpins food security and reduces losses of nutrients to the environment. While balanced nutrition is important, nitrogen in particular is fundamental to raising crops and animals to feed the world now and in the future. Much of the increase in food production over the past half century can be attributed to the use of synthetic nitrogen fertilizers. However, when used at the wrong time, or the wrong rate, or in the wrong form and put in the wrong place, adverse impacts can occur as nitrogen flows through the environment.

The importance of reconciling nutrient removal with nutrient additions has been recognized through the United Nations Environmental Program's view that there is a need to define and then assess trends in nutrient performance. The Sustainable Development Solutions Network has also proposed that crop nitrogen use efficiency should be an indicator of progress towards a goal to end hunger, achieve food security, improve nutrition, reduce pollution, and promote sustainable agriculture. Science and industry have supported the development of appropriate indicators to represent the balance between underuse of nitrogen that can lead to low production and the depletion of soil fertility, with excess nitrogen that can lead to adverse environmental impacts. Using nitrogen use efficiency estimation is consistent with the indicators proposed by other agencies and the fertilizer industry.

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[1] Revised April 8, 2015

The focus of this report is nitrogen and similar principles could be applied to estimating phosphorus, potassium or sulfur nutrient use efficiencies.

DEFINING NITROGEN USE EFFICIENCY

Nitrogen use efficiency (NUE) can be defined in many ways depending on the purpose to which the indicator will be put. Agronomic efficiency or apparent recovery efficiency are appropriate performance indicators, especially in the selection of more efficient genotypes for nutrient uptake or to assess nutrient transfers among soil pools, but both of these measures require a nil fertilizer application treatment to estimate the extra yield due to the added fertilizer. Such measures are normally only available on research plots limiting their usefulness in non-research settings. We recommend using partial nutrient balance to measure NUE. Also called the removal/use ratio or the output/input ratio, this indicator is derived from the sum of N in all of the products removed from the field (i.e., the harvested crop or livestock product and any stover or other material removed) and the sum of all inputs of N to the field, farm or region (i.e., fertilizer, imported animal manure, compost, green manure or other soil amendments, imported animal feed, and biological N fixation; note that atmospheric N deposition is usually ignored because it is usually small relative to agricultural inputs, but it could be included where deemed important). As such, NUE reflects the proportion of nutrient recovered in produce, within the boundary of the system described, relative to the amount of N entering the site:

NUE = sum-of-outputs/ sum-of-inputs

NUE does not describe pathways of internal N transformation within a system (e.g., N mineralization or nitrification), nor is it necessarily a direct quantitative estimate of N loss from the system, because N not removed in the harvest might remain on site in the soil. Over the long term, however, changes in soil N stocks are usually low relative to inputs and outputs, and therefore, low NUE values over multiple years are reasonably reliable indirect indicators of probable significant N loss to the environment.

An important advantage of this definition of NUE is that the data are generally available at both the farm level and the national accounting level. On the farm, fertilizer (and imported manure) amounts are usually known, as is the harvest volume or mass (e.g. bushels/acre or tonnes/hectare). The concentrations of N for manure and harvest products are often not known for specific farms, but they can be estimated from regional literature values. At the national and sub-national level, data on production by commodity type (e.g., maize, wheat, rice, other crops, dairy products, and meat) are estimated by governments and the FAO when real data are not available. The FAO also gives data on the total apparent fertilizer consumption by country, but these data are not disaggregated by crop or region. Attempts have been made in the scientific community to disaggregate national data to crop specific application rates on agricultural areas (e.g. Potter et al., 2011), that could be used as baselines or reference values. IFA has released two reports on fertilizer use by crop by country from collected data (Heffer 2009, 2013), but these do not cover all countries.

Although there are some data limitations and uncertainties, both inputs and outputs can be estimated locally and nationally, and from those estimates, NUE can be derived.

A disadvantage of NUE is that it, alone, is often inadequate for assessing agricultural sustainability, so that NUE data must be interpreted in the context of other data. Different crop types are likely to have different NUE, and national and regional NUE values may reflect the particular mix of farming systems within those areas. Maize generally has lower NUE than wheat, and so a country or farmer growing a lot of wheat may report relatively high NUE, not necessarily because of particularly efficient nutrient management practices, but because of the type of crop that the soils and climate best support. Table 1 gives examples of annual NUE for different crops from selected countries.

Table 1. An example of NUE by country and crop. Data were derived from FAOSTAT (Crop production and area sown), IFA (Fertilizer use by crop) and IPNI (Crop product nutrient concentrations). Neither biological N fixation nor manure applications are considered in this example and crop removal is estimated using mean values rather than regionally relevant data.

Country	Wheat	Maize	Rice	Other Cereals	All Cereals	Soybean*	Palm	Other Oilseeds	Sugar
Argentina	1.28	0.99	2.26	1.67	1.21	1.20	-	3.23	2.17
Australia	1.10	1.06	2.60	0.86	1.02	-	-	0.63	0.93
Bangladesh	1.27	1.06	0.56	-	0.57	-	-	1.01	0.89
Brazil	0.99	0.85	0.97	0.87	0.88	1.20	0.55	1.02	1.83
Canada	0.86	0.70	-	1.05	0.89	1.18	-	0.94	-
Chile	0.63	0.51	0.83	0.81	0.63	-	-	1.08	-
China	0.54	0.40	0.47	0.66	0.47	0.80	0.32	0.41	0.38
Egypt	0.59	0.26	0.53	0.64	0.45	0.74	-	0.19	0.44
EU-27	0.96	0.53	0.86	1.09	0.90	1.13	-	0.95	-
India	0.46	0.36	0.40	0.50	0.43	0.90	-	0.49	0.64
Indonesia	-	0.43	0.65	-	0.59	0.94	0.86	0.00	1.07
Iran	0.78	0.46	0.48	0.79	0.71	1.05	-	0.43	0.26
Malaysia	-	0.38	0.37	-	0.37	-	0.69	11.68	1.07
Mexico	1.22	0.39	0.60	5.12	0.62	-	0.08	0.94	1.29
Morocco	1.78	0.53	0.55	1.30	1.52	-	-	0.33	0.13
Pakistan	0.40	0.30	0.34	0.53	0.38	-	-	1.26	0.39
Philippines	-	0.75	0.97	-	0.90	-	0.46	0.05	2.08
Russia	1.63	0.46	0.71	2.79	1.78	1.08	-	4.87	-
South Africa	1.46	0.54	-	1.70	0.66	1.20	-	1.25	0.79
Thailand	-	0.64	0.94	0.88	0.90	1.12	0.71	0.26	1.20
Turkey	0.73	0.46	0.84	1.30	0.81	0.93	-	0.55	-
USA	0.73	0.61	0.55	0.77	0.64	1.22	-	0.60	0.43
Vietnam	-	0.36	0.65	-	0.60	0.74	-	0.05	0.62
World	0.77	0.55	0.56	1.26	0.68	1.15	0.81	0.73	0.89

* Soybean N balance was estimated as the N removed divided by the sum of N applied plus fixed N. The amount of fixed N was estimated as 0.8 of the N removed.

A second complication of NUE estimates is the consideration of crop rotations. Where maize and soybeans are rotated on the same field annually, for example, NUE would have to be calculated for a two-year rotation cycle in order to account for the N inputs from soybeans in one year that could remain as inputs to the maize crop the follow year. Where longer and more complex crop rotations are employed NUE estimates would need to consider the whole crop cycle and not just crops in isolation.

Biological N fixation (BNF) by soybeans, pulses, and other leguminous crops presents a third complication. Assumptions must be made regarding the fraction of N within the plants that is from BNF and the fraction of total plant N that is removed. An estimate of total plant N times the fraction from BNF must be included in the input term to calculate NUE. Such estimates are available in the agronomic literature (e.g. Salvagotti et al., 2008; Peoples et al., 2009) and can be provided in simple look-up tables for use by farmers or by national agronomic policy analysts, similar to look-up terms now in use for calculating greenhouse gas emissions for IPCC accounting requirements.

A fourth potential complication involves the more complex accounting that is needed to estimate NUE in mixed crop-livestock operations. Outputs could include some crop products if they are exported and not used entirely within the farm for feed, as well as the dairy or animal products, including any manure that might be exported to another farm rather than being used internally. Inputs would include fertilizers and feed supplements. Again, these are not insurmountable problems, but do add a layer of complexity to the needed accounting.

A fifth issue is that NUE is best interpreted in terms of a trend of changing NUE over time, rather than attempting to interpret a single snapshot of a single year's estimate for a farm or a nation. As mentioned above, a single estimate of NUE is strongly influenced by the crop or animal production system, and it is difficult to define whether a single estimated value of NUE is inherently good or bad. If repeated over time, however, a trajectory of NUE values can provide a very useful indicator of whether progress is being made to improve NUE within a given cropping system within the context of the climate, soils, and commerce of the region.

Despite these challenges, the inclusion of all the input and output components in estimating NUE is essential to assess if there is sufficient nutrient supply for high yields and to maintain or even improve soil health. Using animal manure, recycling plant material (e.g. composts, processing waste streams) and integrating legumes into cropping systems are all important strategies to increase soil organic matter and improve soil structure, leading to synergies between organic and mineral fertilizers and improving NUE.

DERIVING NUE

We envision an accounting system similar to the IPCC system for calculating greenhouse gas emissions, but designed to facilitate estimating NUE at a variety of scales, from the farm to the nation. Where site-specific data are not available on N concentrations of crops and manures and for BNF contributions, simple lookup tables could be provided. For example, a farmer who has produced X tonnes per hectare of maize could look up the N concentration of grain in that region (Y %N) and estimate the output term as:

Output N = X * Y/ 100.

If the harvested products were analyzed for N concentration, that value could be used in lieu of those from lookup tables.

Most commercial fertilizers come with an estimate of N concentration, so the input is simply the application rate in kilograms of product per hectare multiplied by the concentration of N in the product. Nutrient concentrations of manures, however, are more variable. If concentration data are available for a specific manure source, they could be used, but when specific concentration data are not available, a regionally pertinent lookup table (e.g. showing the average N concentration of chicken manure in the mid-Atlantic states of the USA) could be provided to the farmer.

Inputs of BNF by leguminous crops would require regionally appropriate estimates of the total amount of N in the crop (crop mass multiplied by the N concentration of the mass), multiplied by the fraction of N provided by BNF (usually 60-80%, e.g. Peoples et al., 2009). Not all the BNF remains in the field, so the proportion of the N removed from the site in grain or other crop products (harvest fraction) needs to be considered.

BNF inputs =
crop mass produced X % N of the crop mass X BNF fraction X (1-harvest fraction)

Data for fertilizer use can be derived from existing sources, such as sub-national agricultural extension and research stations for farm-level operations. For national accounting, data are currently available from IPNI for average nutrient concentrations (IPNI 2012), FAO for production (FAOSTAT 2014), and IFA for fertilizer use (IFA, 2015; Heffer 2009, 2013).

Input N = Applied manure N + BNF + Applied fertilizer N

NUE can be derived at a range of scales, but downscaling from national to regional data will require additional qualification of the input and output. It is also appropriate to investigate upscaling of farm level nutrient balances to validate downscaled national data.

INTERPRETING NUE ESTIMATES

When NUE = 1, the amount of nutrient removed equals the input of N. When NUE < 1, more N is being applied than is being removed, and the N not removed could either be stored in the soil and/or flow through to the environment causing ecosystem degradation. When

NUE > 1, more N is being removed than is being supplied, which indicates that the soil is being mined of nutrients, eventually depleting soil fertility.

While NUE is the ratio of outputs/inputs, "N surplus" is defined as the difference (inputs-outputs). When NUE <1, the surplus is positive, indicating the likelihood of loss of N to the environment.

No biological systems, including crop and animal production systems, can be 100% efficient, so a goal of NUE = 1 and a surplus of zero is unrealistic. Nor do we know how efficient (how close to an NUE of 1) cropping systems could become and still maintain productivity. It is desirable however to approach NUE =1 for long term system sustainability. In general, animal production systems are less efficient than cropping systems because animals inherently produce N-rich wastes in urine and feces, which are challenging to recycle with high efficiency. While it is very difficult to establish hard and fast NUE goals, we can generalize that when NUE < 0.5, there is probably a large opportunity for improving NUE. At the other extreme, when NUE > 0.9, it is likely that efficiency cannot be improved further without risking mining of soil nutrients.

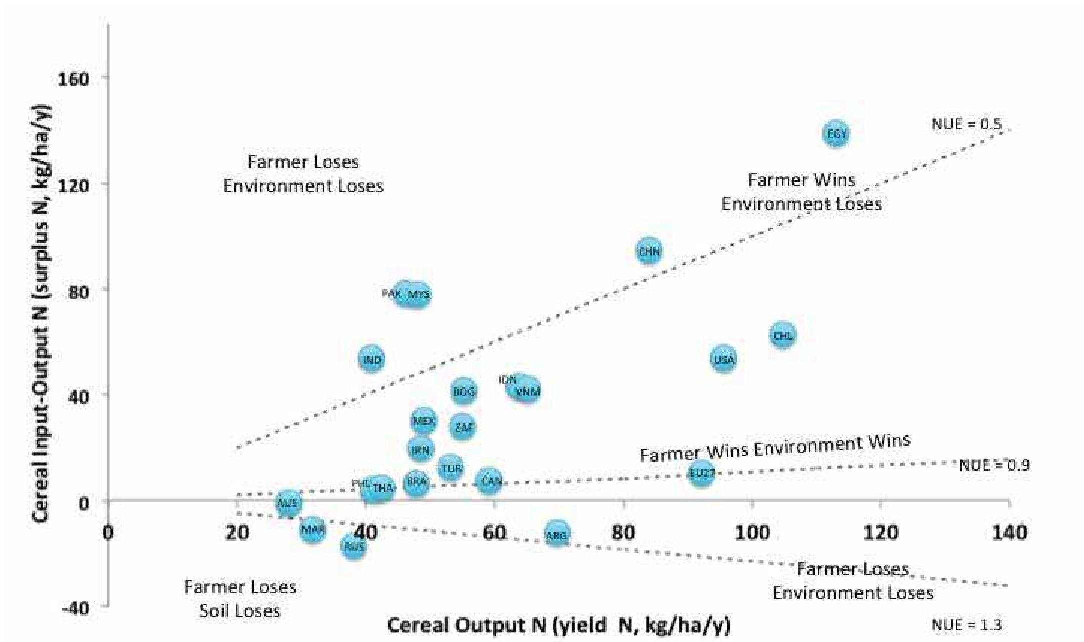

Figure 1: NUE for cereals, graphed as the surplus of N (inputs minus outputs) versus removal (output) of N. The dotted lines show values of NUE according to the relation between inputs and outputs. Biological N fixation and manure use are not considered in this example. Each circle represents a country indicated by UN Country 3 letter code.

However, this should not imply that NUE values between 0.5 and 0.9 are necessarily acceptable, because, as already noted, an NUE value of, say 0.7, may be good for some systems in some places and not so good for other systems in other places. For example, many of the countries that fall between the 0.5 and 0.9 NUE lines in Figure 1 are likely to have potential for further improvements, and the differences among countries may reflect differences in the crop grown, the use of manures and the importance of legume based rotations, as much as differences in nutrient management practices. Figure 1 is shown as an example of NUE for cereals only, where Output-N is plotted on the X axis and N surplus (Input-N minus Output-N), on the Y axis, and the dotted lines show values on the X and Y axes that are consistent with a specific NUE value, which is a mathematical outcome of the definitions of N surplus and NUE. Any number of lines could be drawn, but the figure here shows only three – NUE = 0.5, 0.9, or 1.3 – as benchmarks. The data to produce this figure are shown in the Appendix table and are pre-Tier 1 values as they do not contain estimates of BNF or manure inputs, and N contents were averages not regionally specific.

Rather than the snapshot comparison shown in the example in Figure 1, it is best to use an indicator based on a trajectory of NUE values over time to demonstrate if progress on improving NUE is being made or if an upper efficiency limit is being approached. Figure 2 shows a hypothetical example of a farm growing maize in the mid-western region of the USA (Davidson et al. 2015). It could represent a single farm or an average for the region or nation. The square shows a one-time estimate of NUE of 0.67. The arrows show the trajectory that would be consistent with improved NUE over time. Hence, the initial point is a benchmark by which progress can be demonstrated. We believe that this type of figure could be generated easily through an appropriate canned algorithm (such as a pre-formatted Excel spreadsheet or a customized user-friendly software package) that would require only very simple data inputs. As each year's data is entered, the trajectory for the farmer or for the nation could be tracked.

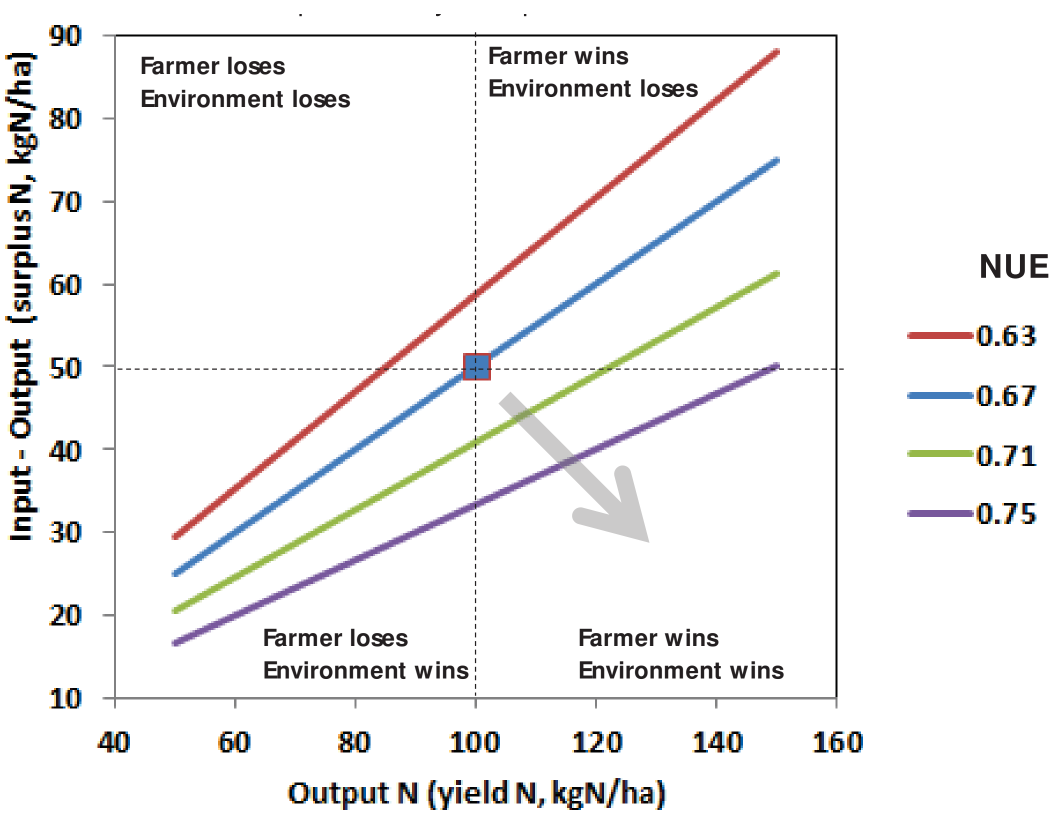

Figure 2. Diagram of how NUE can improve relative to an initial benchmark value and who wins when the trajectory over time is to the right or left, up or down in the plotted

parameter space. A win-win situation for both the farmer and the environment occurs when NUE increases, N surplus decreases, and crop yield (Output N) increases as plotted values on this graph move from the benchmark value to the lower right (after Davidson et al 2015.)

The example in Figure 2 applies to the high yielding regions of the world, where N surpluses are often positive and environmental pollution associated with excess N is a societal concern. In contrast, parts of the developing world face a problem of too little N input to agriculture due to unfavorable crop/fertilizer price ratios or lack of availability of fertilizers or other sources of N inputs. Figure 3 extends the range of surplus N values shown in Figure 2 to negative values on the Y axis, which illustrate mining of soil N, because N removed in harvest exceeds N inputs. In this case, the win-win option for farmers and the environment results from movement toward the upper right of the graph, where crop yields increase, N mining decreases (i.e. NUE declines below 1), and N surplus remains relatively small. However, how far to the upper right is desirable before risking significant and damaging loss of N to the environment is difficult to specify.

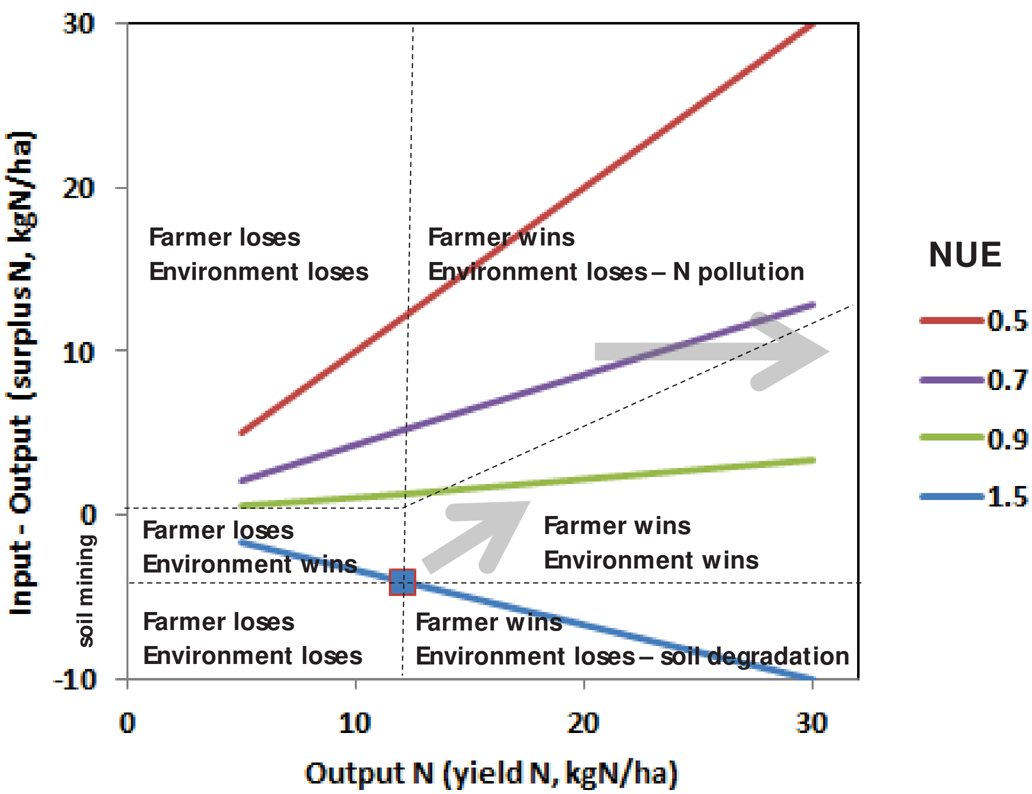

Figure 3. Application of the concepts shown in Figure 2 to a lower yielding or less developed country where mining of soil N is occurring due to NUE >1 and N surplus < 0. While the farmers in high yielding environments should move to the lower right to improve

NUE, farmers in low yielding environments farmer should move toward the upper right, at least initially.

A TIERED APPROACH TO NUE ACCOUNTING

Because the availability and quality of data on N inputs and outputs vary regionally, we envision a tiered system for reporting NUE estimates, patterned after the IPCC system:

<u>Tier I</u>: A system of global default values provided in lookup tables for N concentrations of crop products, fertilizers, manures, other soil amendments, and BNF inputs. Simple mathematical equations would be provided, demonstrating how these default values would be combined with local or national "activity data", which in this case, would be yield data (e.g., bushels/acre, tons/hectare, liters of milk/cow, etc.) and input rates (e.g., fertilizer application rates, manure application rates, daily feed supplement rates, etc.) to derive estimates of farm-level or national-level inputs of N, outputs of N, N surplus (inputs minus outputs), and NUE (outputs/inputs).

<u>Tier II</u>: Where data on N concentrations are available at the site, regional, or national level that can be demonstrated to be more specific to the application area, and hence likely to be more geographically and systems specific, these data may be substituted for the global default values recommended for the Tier I approach. The equations would be the same as in Tier I.

<u>Tier III</u>: It is possible to model agronomic inputs and outputs of N in response to factors such as economic conditions, commerce, soils, climate, crop performance characteristics, and available technology. Where such models have been developed and validated at the farm scale or larger scales, such as by survey or nutrient audits, they could be used to estimate NUE and N surplus. Indeed, models of N input-output have been developed at the global scale (Bouwman et al., 2011).

At present, the publication of FAO production data is about two calendar years behind the present. IFA fertilizer consumption statistics are also released two years after completion of the campaign. The IFA fertilizer-use-by-crop data are available only for three periods, and the degree of temporal variation in product nutrient concentration is not available. It would seem unlikely that with the current procedures that country-level NUE could be reported annually, and within one year of the data period. Aggregated moving means of triennial NUE values may best serve the purpose of a moderate cost for data collection balanced with a reliable estimate. Furthermore, year-on-year changes are likely to be minimal so that triennial monitoring may be sufficient.

NUE AS A NUTRIENT PERFORMANCE INDICATOR

The purposes for the application of these performance metrics are as indicators of the outcome of management and as statements of accountability. They do not prescribe interventions, but can be used as benchmarks of current performance and can be used then to set targets for future performance against which progress can be assessed. The actual critical values for NUE and the targets to be established are aspects of policy, and are likely to vary from region to region and between farming systems.

An increase in NUE does not always guarantee lower N pollution, but it is an essential step for reducing N loss to the environment while maintaining high agricultural productivity. Our recommendation is based on the premise that using NUE as an indicator will likely reduce N losses to the environment, which will be followed in time by improved indicators of environmental quality, albeit with lags in the system. Hence, NUE should be viewed not as a final indicator of success, but rather an important and essential indicator of progress in the agricultural sector.

While NUE can be estimated using existing data and applied at a range of scales, it is a ratio and so does not provide a link to either productivity or soil health, both of which are critically important for current and future food security. In assessing progress to improved nutrient performance, both productivity (such as yield) and soil health (such as soil test values) should be considered as part of a suite of outcome indicators. Additionally, other indicators of the development of the support for and the adoption of sustainable crop nutrition (e.g. outreach to farmers) could extend the range of metrics appropriate to nutrient stewardship.

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Appendix Table: Cereal production NUE by country. Data were derived from FAOSTAT (Crop production and area sown), IFA (Fertilizer use by crop) and IPNI (Crop product nutrient concentrations). Neither biological N fixation nor manure applications are considered in this example and crop removal is estimated using mean values rather than regionally relevant data.

Country	Cereal area (Mha)	Cereal production (Mt)	Mean cereal yield (t/ha)	NUE (kg N grain/kg N fert)	Output (kg N/ha)	Input (kg N/ha)	Surplus (kg N/ha)
Argentina	9.24	40.68	4.37	1.21	69.6	57.7	-12
Australia	18.37	26.45	1.39	1.02	27.9	27.4	-1
Bangladesh	11.18	46.95	4.02	0.57	55.1	96.6	41
Brazil	18.42	67.16	3.63	0.88	47.8	54.3	7
Canada	15.95	47.11	3.26	0.89	59.0	66.4	7
Chile	0.59	3.58	6.41	0.63	104.6	167.4	63
China	83.14	473.94	5.48	0.47	83.9	178.9	95
Egypt	2.99	20.98	7.01	0.45	113.0	252.1	139
EU-27	58.04	277.82	4.85	0.90	92.1	102.5	10
India	99.24	255.31	2.56	0.43	40.8	95.0	54
Indonesia	15.13	75.43	4.62	0.59	63.8	107.3	44
Iran	8.70	22.33	2.47	0.71	48.5	68.3	20
Malaysia	0.67	2.39	3.52	0.37	46.3	124.6	78
Mexico	10.01	33.54	3.36	0.62	48.9	79.3	30
Morocco	5.59	8.54	1.60	1.52	31.6	20.7	-11
Pakistan	12.93	33.92	2.58	0.38	47.9	126.0	78
Philippines	6.73	21.78	3.21	0.90	41.1	45.7	5
Russia	40.54	68.06	1.87	1.78	38.2	21.4	-17
South Africa	2.99	12.07	3.65	0.66	54.9	83.3	28
Thailand	11.32	37.27	3.00	0.90	42.5	47.4	5
Turkey	13.04	33.70	2.68	0.81	53.2	65.7	13
USA	52.86	370.00	6.69	0.64	95.6	149.8	54
Vietnam	8.36	42.16	4.96	0.60	65.1	107.6	43
World	679.08	2,355.31	3.43	0.68	55.7	81.4	26

A Powerful Tool to Improve Nitrogen Use Efficiency

CENTURO

Efficiently using resources and good crop management go hand-in-hand on any successful farming operation. This is no trade secret — you want to minimize the inputs needed to produce the highest yield possible. That's why optimizing your nitrogen use efficiency (NUE) is critical to getting the most out of your fertilizer investment and ultimately, a better bottom line.

What is NUE? In short, NUE is the amount of nitrogen taken up by crops compared to the amount of fertilizer applied to the field. The higher your NUE, the greater your ability is to optimize every pound of nitrogen you apply.

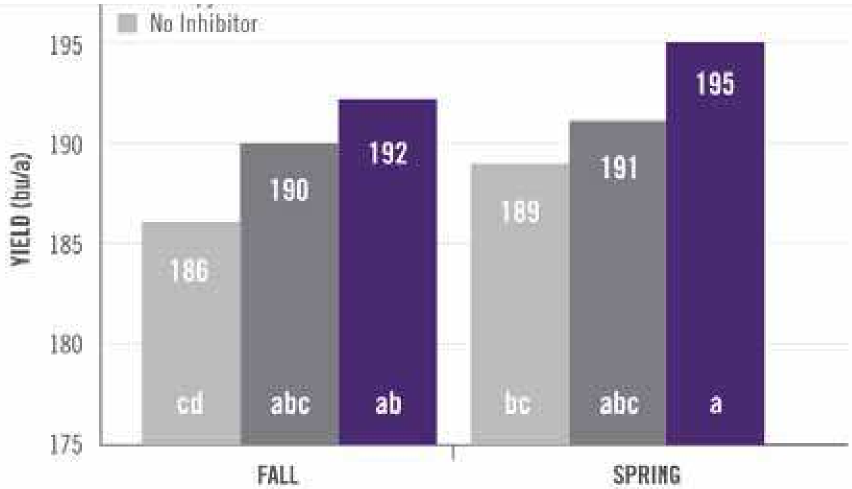
In any given field, there are two sources of nitrogen for crops: nitrogen that is applied by you, and organic nitrogen that comes from biological processes within the soil. While many factors such as pH and residue can contribute to organic nitrogen's availability, you have the power to protect the availability of the nutrients you apply.

KEEP YOUR NITROGEN WHERE YOU NEED IT

Nitrate leaching and denitrification are two forms of nitrogen loss that can significantly reduce the efficiency of your anhydrous ammonia fertilizer investment. CENTURO™ nitrogen stabilizer from Koch Agronomic Services is a next-generation nitrification inhibitor designed to maximize the anhydrous you apply. With a newly patented active ingredient, CENTURO offers highly effective below-ground protection against loss and improved NUE.

A nitrification inhibitor, like CENTURO, is an important tool for protecting nitrogen and keeping the valuable nutrient available in the root zone — where you want it to be. This leads to more of the applied nitrogen being used by the plant.

"Inhibitors provide more nitrogen to the plant by keeping it in an ammonium form," said Dr. Kelly Nelson, professor of agronomy in the Division of Plant Sciences at the University of Missouri. "If we can keep it in the ammonium form, that leaves it less susceptible to loss mechanisms such as denitrification and leaching."



N rate for all bars is 70% recommended rate. Bars with same letter are not significantly different (p<0.10)

In the first two years of an ongoing study conducted at Iowa State University, CENTURO reduced nitrate leaching by 44% in fall-applied ammonia compared to untreated ammonia.[1] In eight replicated trials conducted across four site locations in Illinois, Missouri and Nebraska from 2016-2018, ammonia treated with CENTURO improved NUE by up to 25% and **increased corn yield by an average of 6 bushels per acre compared to untreated ammonia.**[2]

The results are clear. When you protect your nitrogen and increase your NUE, you can minimize the fertilizer inputs needed to optimize your yield potential. As the first nitrification inhibitor for anhydrous ammonia to be registered by the EPA in 40 years, CENTURO is the proven tool you can trust to protect your nutrient investment.

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CENTURO is not registered for sale or use in all states. Contact your state pesticide regulatory agency to determine if a product is registered for sale or use in your state. [2] The underlying data was provided by University of Nebraska, University of Missouri, and the Illinois Fertilizer and Chemical Association under Research Trial Financial Support Agreements with Koch Agronomic Services, LLC. Neither the universities or institutions nor the individual researchers referenced, endorse or recommend any product or service. Improvements in nutrient use efficiency, yield and nitrate leaching may not be observed in all cases. CENTURO™ and the CENTURO logo are trademarks of Koch Agronomic Services, LLC. Koch and the Koch logo are trademarks of Koch Industries, Inc. © 2019 Koch Agronomic Services, LLC.

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Nitrogen Use Efficiency

Plants need nitrogen to grow, develop and produce usable products. Since plants get their nitrogen from the soil, farmers must replenish nitrogen to ensure successful growth and to replace nitrogen removed in the harvested crop. Nitrogen is generally applied to the soil through various types of fertilizers. Due to the substantial yield increases resulting from fertilization, farmers have steadily increased the amount of fertilizer added per unit of land area.

What happens if plants don't have enough nitrogen?
When plants are not provided with sufficient nitrogen, they become nitrogen deficient. Plants with nitrogen deficiency often have spindly stems and their growth is stunted.

What is nitrogen use efficiency?
Nitrogen use efficiency (NUE) is the fraction of applied nitrogen that is absorbed and used by the plant. Improving a plant's ability to utilize nitrogen is a key component in enhancing environmental sustainability. Today, improved plant breeding through the use of genetic engineering has the greatest potential to produce plants that will utilize fertilizer more efficiently than conventional varieties.

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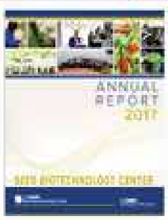

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Agronomy Journal - Agronomy, Soils and Environmental Quality

Impacts of Nitrogen Rate and Landscape Position on Soils and Switchgrass Root Growth Parameters

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doi:10.2134/agronj2018.08.0483

Core Ideas:

- Nitrogen rate did not affect soil properties for Oklahoma, South Dakota, and Virginia.
- Landscape position affected soil properties under higher slope.
- Nitrogen rate affected root N, surface area, and weight for the total profile.
- Landscape position affected the root C and N.
- Switchgrass roots can increase C accumulation and reduce risk of N loss in soils.

Abstract

Switchgrass (*Panicum virgatum* L.) has been recognized as a potential bioenergy feedstock, and can positively impact soils and the environment. The experimental sites were established in 2008 at three locations with each in Oklahoma (OK), South Dakota (SD), and Virginia (VA) to assess the impacts of N fertilization rate (N rate, low, 0 kg ha^{-1}, high, 112 kg ha^{-1}) and landscape position (shoulder, backslope, and footslope) on select soil properties and root growth parameters. Data indicate that N rate did not affect soil bulk density (BD), pH, electrical conductivity (EC), soil organic carbon (SOC), and total nitrogen (TN) for any of five depths. Landscape position impacted some of these properties by depth, depending on location. The N rate influenced root weight (RW), root surface area (RSA), and root total nitrogen (RTN) for the total profile (0–100-cm depth) depending on local site conditions. The landscape position impacted RW, root total carbon (RTC), and RTN for total profile according to different site conditions. The interactions of landscape position by N rate on switchgrass root parameters were significant. The findings in this study indicate that the root system of switchgrass could improve soils and increase C accumulation and reduce the risk of N loss to benefit the environment.

Abbreviations

BD, bulk density; EC, electrical conductivity; LD01, root length density between 0 to 1 mm; LD12, root length density between 1 to 2 mm; LDg2, root length density >2mm diameter; NUE, nitrogen use efficiency; OK, Oklahoma; RSA, root surface area; RTC, root total carbon; RTN, root total nitrogen; RW, root weight; SA01, surface area between 0 to 1 mm; SA12, surface area between 1 to 2 mm; SAg2, root surface area >2 mm diameter; SD, South Dakota; SOC, soil organic carbon; SOM, soil organic matter; TLD, total root length density; TN, total nitrogen; TSA, total surface area; VA, Virginia

Switchgrass, a perennial warm-season C_4 grass native to North America (Lewandowski et al., 2003), has high water and nutrient use efficiency. Switchgrass has been recognized as a bioenergy feedstock since the early 1990s in the United States (Lee et al., 2012) because the species requires relatively low inputs (Fike et al., 2017), can grow across diverse climatic conditions, soils, and landscapes, and is suitable for use on marginal lands (Sanderson et al., 2006; Wright and Turhollow, 2010). In addition, switchgrass can positively impact soils and the environment by enhancing SOC (Frank et al., 2004; Lemus and Lal, 2005), and by reducing soil erosion (Williams et al., 2009) and greenhouse gas (GHG) emissions (Lai et al., 2018a).

A plant acquires resources such as water, nutrients, and C from the environment to construct leaves, stems, and roots, and this growth assists in additional acquisition (Bloom et al., 1985). Roots, especially, play a key role in ecosystem C, nutrient, and water cycling (Pritchard and Rogers, 2000). Fine roots (<2 mm in diameter) represent ~33% of global net primary productivity (NPP) (Jackson et al., 1997) and the majority of C accumulation in the soil is the result of fine root production and turnover (Haynes and Gower, 1995). Carbon in this global fine root pool may be 5% of the size of the atmospheric C pool (Jackson et al., 1997). Therefore, it is important to better understand root production and how it influences C sequestration (Gill and Jackson, 2000). Root size (i.e., mass, length, or area) and architecture drive the plant's capacity to access N and other nutrients. The architecture of the root is determined by the pattern of root branching and strongly influenced by a wide range of physical, chemical, and biological factors (Miller and Cramer, 2005) such as soil nutrients and properties (e.g., SOC, TN, soil BD, pH, and EC), carbon dioxide (CO_2), water, and fluctuations in weather (Eissenstat et al., 2000). In field settings, switchgrass had significantly higher root production than two annual cropping systems (corn [*Zea mays* L.] and triticale [× *Triticosecale* Wittm.]/sorghum [*Sorghum bicolor* L. Moench]), and produced twice as much root biomass as continuous corn system in Iowa (Ontl et al., 2013). Switchgrass also produces more fine roots (1.26 g m^{-2} day^{-1}) than the miscanthus (*Miscanthus* × *giganteus*) (1.18 g m^{-2} day^{-1}), and hybrid poplar (*Populus nigra* × *P. maximowiczii* 'NM6') (1.10 g m^{-2} day^{-1}) (Sprunger et al. (2017). Switchgrass roots can extend to more than 3-m soil depth (Ma et al., 2000; Weaver, 1968). Deep root systems of perennial plants such as switchgrass contribute organic matter to

Vol. 111 No. 3, p. 1046-1059
OPEN ACCESS

Received: Aug 03, 2018
Accepted: Jan 18, 2019
Published: May 3, 2019

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Nitrogen fertilization rate (N rate), a key input that strongly influences switchgrass production, impacts both soil properties and root growth parameters. Nitrogen fertilizer is important for switchgrass land management (Hong et al., 2014; Owens et al., 2013), although the response to applied N is affected by soil conditions ([Kering, 2012] no. 3310; [Fike, 2017] no. 688). An optimum N rate may result in increased SOC and soil fertility (Bowman and Halvorson, 1998), but excessive N application over prolonged periods can degrade soils by increasing acidity and lowering nutrient availability (Chen et al., 2009). In some previous studies of switchgrass, fertilization rate had no effect on SOC, TN, BD, and pH (e.g., Jung and Lal, 2011; Kibet et al., 2016), but others have reported decreased pH with the increasing rates of N fertilization (Gelssler and Scow, 2014). Varied responses of switchgrass root biomass to increased fertilization rates also have been reported (Heggenstaller et al., 2009; Ma et al., 2001; Sanderson and Reed, 2000).

Landscape position also may play a key role in the C sequestration potential of switchgrass. Soil properties can vary dramatically by hillslope (Jackson-Gilbert et al., 2015), with significant impacts on root growth. Earlier studies by Bronson et al. (2003) and Guzman and Al-Kaisi (2011) emphasized the major influence that topographic positions in different landscapes have on soil properties. Ontl et al. (2013) found that mean root productivity of switchgrass at the backslope positions was lower than that observed on the summit, shoulder, and footslope positions. However, studies assessing the combined effects of N rate and landscape position on soil properties and switchgrass root characteristics at multiple locations and environments are lacking. In particular, the scientific knowledge of variability in soils and root productivity over heterogeneous environmental conditions is not well developed.

Because root production can be influenced both by soil fertility and climate (Eissenstat et al., 2000; Leuschner et al., 2004; Sprunger et al., 2017), we contrasted soil and switchgrass root responses to N and landscape at three different locations (OK, SD, and VA) that were marginally productive for agricultural crops. A comprehensive understanding of how switchgrass roots respond to topographic and soil heterogeneity is a prerequisite for developing cellulosic bioenergy systems that meet the dual goals of high energy output and greater environmental sustainability (Taubert et al., 2012). Therefore, specific objectives of this study were to (i) assess the influence of N rate and landscape position on SOC, BD, pH, EC, and TN, and to (ii) evaluate the impacts of N rate and landscape position on RW, root length density (LD), RSA, RTC, and RTN.

MATERIALS AND METHODS

Experimental Sites and Design

Three sites were used for this study as part of a larger bioenergy production study that measured switchgrass response to N on marginal lands conducted at field scale (Fike et al., 2017). The sites, located in OK, SD, and VA, were planted to switchgrass in 2008. Individual plots (ranging from 0.4–0.8 ha) were sufficiently large to allow the use of conventional agricultural equipment. Descriptions of the soils, slopes, prior management, initial TN, 30-yr (1986–2015) mean annual precipitation (MAP) and daily temperature (MDT), and cultivar and planting dates are presented in Table 1.

Table 1. View Full Table | Close Full View

Site, soil series, slope, previous management, initial total nitrogen (TN), slope, 30-yr (1986–2015) mean annual precipitation (MAP) and daily temperature (MDT), and switchgrass cultivar and planting date used in a long-term, field-scale bioenergy production study

Site and GPS coordinates	
Haskell, OK (35°44′32.9994″ N 95°38′21.12″ W)	Parsons-Carytown (fine, mixed,
Bristol, SD (45°16′24.55″ N 97°50′13.34″W)	Nutley-Sinai (silty c
Gretna, VA (36°55′56.2656″ N 79°11′23.8842″ W)	Mayodan (fine sandy loa

†Data were measured in 2008 at the three sites and extracted from Owens et al. (2013).
‡Data taken from Fike et al. (2017).
§At all sites, switchgrass was seeded at 11.2 kg pure live seed ha^{-1} using a no-till drill.

Switchgrass stands were allowed to establish in the planting (2008) season, and N treatment applications began in 2009. Treatment rates were 0, 56, and 112 kg N ha^{-1} and these fertility inputs continued annually for the duration of the experiment. Fertilizer (urea in OK and SD and ammonium sulfate in VA) was applied between late May and early June each year. Switchgrass plots were harvested annually following a killing frost. In OK and SD, the harvest occurred in late fall, but in VA harvests typically occurred in January. In 2014, wet soil conditions delayed the VA harvest to 1 April.

Soil Sampling and Analysis

Soil samples were collected in May 2014 before application of N fertilizer at the 0- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 100-cm soil depths by using a hydraulic push probe (4 cm diam.). Four replicated samples from each plot were extracted and mixed together to make a composite sample to represent the plot. Later, visible plant residue and roots were removed, and soil samples were sieved using an 8-mm screen and dried in a forced-air oven at 40°C until consistent mass was attained. Dried soil samples were then ground to pass a 2-mm screen for further analysis. Soil BD was determined by the core method as the weight of the intact air-dried soil over the corresponding core volume (Grossman and Reinsch, 2002). Soil pH (1:1 soil:water) was determined using the procedure given by McLean (1982). Soil pH

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Root Sampling and Analysis

Root samples were collected in August 2014 from the 0- to 100-cm soil depth and were separated into the 0- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 100-cm depth increments at three sites using a tractor-mounted hydraulic soil probe. Four replicated samples from each plot were extracted. Subsequently, roots were washed with water to remove soil particles. Root length density and surface area by the three diameter classes (0–1, 1–2, >2 mm) for each depth were determined using a flatbed scanner assisted with computer software (WinRhizo 2003b, Regent Instruments, Inc., Montreal, QC, Canada). Root length density and surface area were expressed in cm 100 cm^{-3} and cm^2 100 cm^{-3}, respectively, using the base of the soil core volume [pi × (core radius)^2 × depth from which roots were extracted]. After scanning, each root sample was dried at 70◦C for 48 h and then immediately weighed to determine RW expressed in g 100 cm^{-3}. Then, dried roots were ground to obtain a powder that was used for analyzing the RTC and RTN using a Vario Max CNS elemental analyzer (Elementar Instrument, Mt. Laurel, NJ). The details were described in our previous study (Kumar et al., 2010).

Statistical Analysis

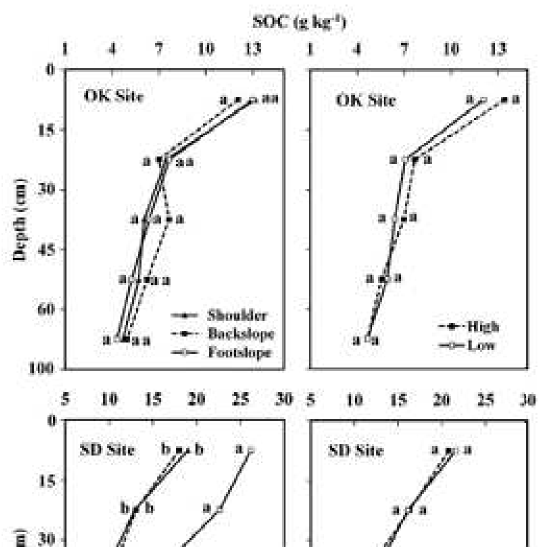
The experimental design was a split-plot design comprised of three N rates as whole plots and the three positions (shoulder, backslope, and footslope) as subplots with four replications. The VA location is rolling but did not have clearly delineated landscape position differences to test, so this was not a factor in the model for that site.

The statistical analysis of N rate and landscape position effects on soil BD, pH, EC, SOC, TN, RW, LD, SA, RTC, and RTN for the 0- to 100-cm depth for OK and SD sites were obtained using the pairwise differences method to compare least-squares means estimated by mixed models using the GLIMMIX procedure in SAS9.4 (SAS Institute, 2013). Nitrogen rate, slope position, soil depth, N rate × position (N × P), N rate × depth, position × depth, and N rate × position × depth were considered fixed effects, and replication, replication × N rate, and replication × N rate × depth were treated as random effects. For each depth, the mixed models included that the N rate, position, and N rate × position were considered as fixed effects and replication and replication × N rate as random effects. At the VA site, because of no position factor, the model included only N rate, depth (data for the 0–100-cm depth), and N rate × depth as fixed effects and replication and replication × N rate as random effects. For each depth data, the mixed models included the N rate as fixed effect and replication as a random effect. The ANOVA was used to test the fixed effects of the N rate, position, and depth on the parameters based on the mixed models. If the effects of interaction were significant, the data were separately analyzed for each N rate and position. The data were transformed when necessary, and the transformation was determined using the Box–Cox method (Box and Cox, 1964, 1981). Treatments were considered significant at $\alpha \le 0.05$.

RESULTS

Nitrogen Rate and Position Impacts on Soil Properties

For OK site, N rate and position did not significantly influence SOC, BD, pH, and TN at all five depths (Fig. 1 and Supplemental Table S1). Mean EC values were higher under high N rate than the low N rate for all five depths, and EC varied by slope position (Supplemental Table S1). At the 0- to 15-cm depth, mean EC values at the shoulder (0.156 dS m^{-1}) and backslope (0.147 dS m^{-1}) positions were significantly higher than that for the footslope (0.107 dS m^{-1}). At the 15- to 30-cm depth, the effect of interaction between the N rate and position on EC was significant (Supplemental Table S1). Under high N rate, the EC at the shoulder was significantly higher than that for the backslope and footslope positions. At the shoulder, the EC under high N rate was significantly higher than that at low N rate (note in Supplemental Table S1).



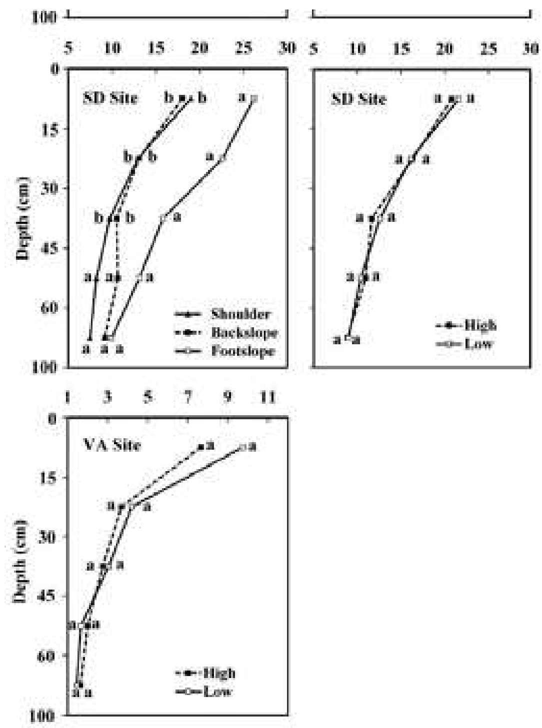


Fig. 1.

Mean soil organic carbon (SOC, g kg^{-1}) in switchgrass field for the 0- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 100-cm depths in 2014 under high and low N fertilization rates at the shoulder, backslope, and footslope positions at the three sites in Oklahoma (OK), South Dakota (SD), and Virginia (VA). Note: Means within the same depth followed by different small letters are significantly different at $P < 0.05$ for the N rate and landscape position.

Soils at backslopes had highest pH values, followed by shoulder and footslope for all five depths. Similar slope effects were observed for SOC and TN, which also were higher under high N rate at the first three depths. Soil pH increased with depth while SOC and TN decreased; soil BD also decreased to 45 cm. Mean SOC, BD, pH, EC, and TN under two N rates and three positions for all the five depths ranged from 4.32 to 13.41 g kg^{-1}, 1.27 to 1.39 Mg m^{-3}, 5.04 to 6.77, 0.065 to 0.194 dS m^{-1}, and 0.35 to 1.26 g kg^{-1} respectively (Fig. 1 and Supplemental Table S1).

For the SD site, N rate did not impact SOC, BD, pH, EC, and TN at any depth, whereas the landscape position significantly influenced these properties at different depths (Fig. 1 and Supplemental Table S2). Soil BD was lower at the footslope than at the backslope and shoulder positions for the 0- to 15-, 15- to 30-, 30- to 45-, and 45- to 60-cm depths (BD values at the 60–100-cm depth were missing). Higher pH was noticed under shoulder and backslope positions than the footslope for all five depths. Mean EC at the footslope was greater than at shoulder and backslope positions at the 0- to 15-cm depth only (Supplemental Table S2). The SOC at the 0- to 15-, 15- to 30-, and 30- to 45-cm depths for the footslope were significantly higher compared with the shoulder and backslope positions (Fig. 1), and TN followed a similar trend for all five soil depths (Supplemental Table S2). The impact of N × P on soil BD at 15- to 30-cm depth was significant (Supplemental Table S2). Further, under high N rate, mean BD at the backslope was significantly higher than that at shoulder and footslope positions. Under low N rate, mean BD at the footslope was significantly lower than that at shoulder and backslope positions. At shoulder position, mean BD under high N rate was significantly lower than for the low N rate (note in Supplemental Table S2).

At the 0- to 15-cm depth, soil pH with the low N rate was greatest at the shoulder and declined at the backslope and footslope positions. The effect of N × P on soil pH was significant at the 0–15 cm depth (Supplemental Table S2). Mean pH with low N rate at the shoulder was significantly higher than that at the backslope, which was significantly higher than the footslope. The mean pH under the high N rate at the shoulder position was significantly lower than that for low N rate (note in Supplemental Table S2). Mean BD and pH generally increased while EC, SOC, and TN decreased as soil depth increased (Supplemental Table S2). Mean SOC, BD, pH, EC, and TN under the two N rates and three positions for all the five depths ranged from 5.21 to 26.19 g kg^{-1}, 1.13 to 1.47 Mg m^{-3} (values at the 60–100-cm depth were missing), 7.04 to 8.03, 0.129 to 0.205 dS m^{-1}, and 0.27 to 2.12 g kg^{-1}, respectively (Fig. 1 and Supplemental Table S2).

For VA site, the N rate did not impact soil pH or BD for any depth. Mean SOC, EC, and TN generally reduced as the depth increased. The mean SOC, BD, pH, EC, and TN under two N rates for all the five depths ranged from 1.45 to 9.73 g kg^{-1}, 1.37 to 1.60 Mg m^{-3}, 4.41 to 5.28, 0.033 to 0.16 dS m^{-1}, and 0.11 to 0.70 g kg^{-1}, respectively (Fig. 1 and Supplemental Table S3).

Nitrogen Rate and Position Impacts on Root Growth Parameters

For the OK site, data on root growth parameters as influenced by the N rate and landscape position are presented in Tables 1 and Supplemental Tables S4 to S6. The mean values of total root length density (TLD), total surface area (TSA), root length density and surface area between 0 to 1 mm (LD01 and SA01) and 1 to 2 mm (LD12 and SA12) diameter were significantly higher under low N rate as compared to high N application for the 0- to 100-cm soil depth. However, landscape position did not impact these root growth parameters (Table 2). The effects of interaction between the N rate and position on RW, TLD, LD01, LD12, root length density >2 mm diam. (LDg2), TSA, SA01, SA12, and RTN were significant (Table 2), thereby the data were separately analyzed for each N rate and position (Supplemental Table

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Table 2. View Full Table | Close Full View

Mean root dry weight, root length density and surface area of switchgrass for the 0- to 100-cm depth in 2014 under the high and low N fertilization rates at the shoulder, backslope, and footslope positions at Oklahoma (OK) site.

				0–1 mm	
Treatments	RW†	TLD	TSA	LD	RS
	g 100 cm^{-3}	cm 100 cm^{-3}	cm^2 100 cm^{-3}	cm 100 cm^{-3}	cm^2 100
N Rate (N)					
High	0.109a‡	132.45b	22.65b	114.37b	12.61b
Low	0.086a	166.90a	30.86a	140.46a	16.72a
Position (P)					
Shoulder	0.098a	159.48a	28.06a	136.18a	15.53a
Backslope	0.100a	146.74a	26.49a	124.79a	14.41a
Footslope	0.094a	142.95a	25.77a	121.36a	14.07a
					Ana
N	0.13	0.014	0.014	0.013	0.011
P	0.13	0.06	0.096	0.07	0.102
Depth (D)	<0.001	<0.001	<0.001	<0.001	<0.001
N × P	0.009§	0.003§	0.004§	0.004§	0.008§
N × D	0.56	0.75	0.74	0.71	0.62
P × D	0.44	0.34	0.47	0.28	0.27
N × P × D	0.98	0.77	0.34	0.87	0.39

† RW, root dry weight; TLD, total length density; TSA, total surface area; LD, length density; RSA, root surface area; RTC, root total carbon; RTN, root total nitrogen.
‡ Means within the same column followed by different small letters are significantly different at P = 0.05 for the N rate and landscape position.
§ The effects of N rate × Position were significant, thereby, the data were analyzed separately for each N rate and position (Supplemental Table S2).

For OK site, RTC was not significantly impacted by the N rate and landscape position at the 0- to 100-cm depth, whereas but the mean RTN with the low N rate was significantly lower than that under the high N rate for the total profile, and mean RNT at the footslope position was significantly higher than the shoulder position (Table 2). The effect of interaction between the N rate and position on the RTN was significant (Table 2), and the separate analysis showed that at each of the three positions, the mean RTN under the high N rate was significantly higher than those for the low N rate. Under the high N rate, the mean RTN at the footslope was significantly higher than for the shoulder and backslope positions (Supplemental Table S4). The RTC and RTN data were further analyzed for each depth. At the 0- to 15-, 45- to 60-, and 60- to 100-cm depths, the RTC and RTN were not impacted by the N rate and landscape

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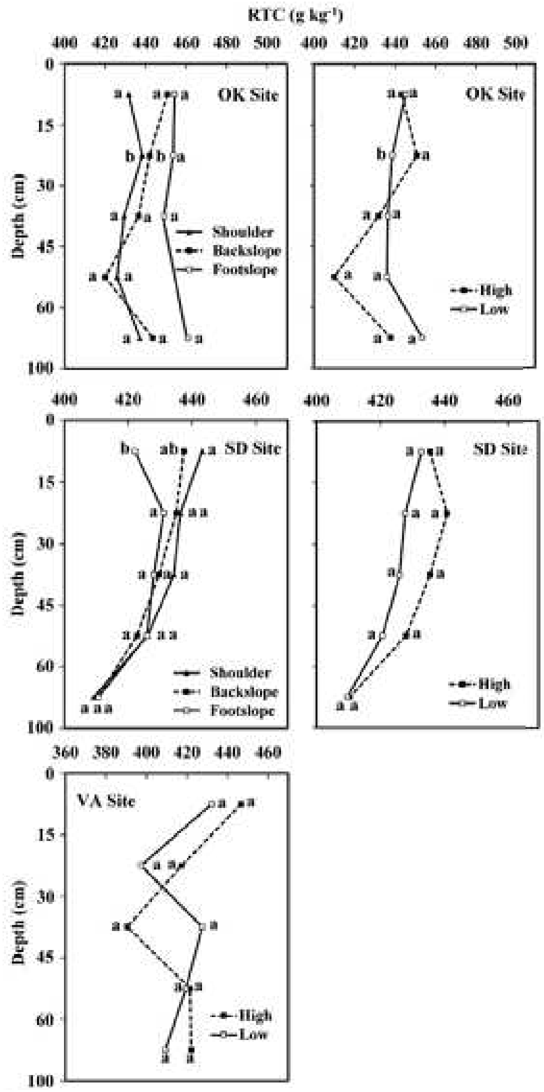

Fig. 2.

Mean root total carbon (RTC) of switchgrass for the 0- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 100-cm depths in 2014 under the high and low N fertilization rates at the shoulder, backslope, and footslope positions at the Oklahoma (OK), South Dakota (SD), and Virginia (VA) sites. Note: (i) The effect of N rate × Position on RTC at the 15- to 30-cm depth at the OK site was significant. The separate analysis results for each N rate and position (data not shown) showed that, at the shoulder position, the mean RTC under the high N rate was significantly higher than that for the low N rate. Under the high N rate, the mean RTC at the shoulder position was significantly higher than that for the backslope position. Under the low N rate, the mean RTC at the footslope position was significantly higher than that for the backslope and shoulder positions. (ii) Means within the same depth followed by different small letters are significantly different at $P < 0.05$ for the N rate and landscape position.

backslope position. Under the low N rate, the mean RTC at the footslope position was significantly higher than that for the backslope and shoulder positions. (ii) Means within the same depth followed by different small letters are significantly different at $P < 0.05$ for the N rate and landscape position.

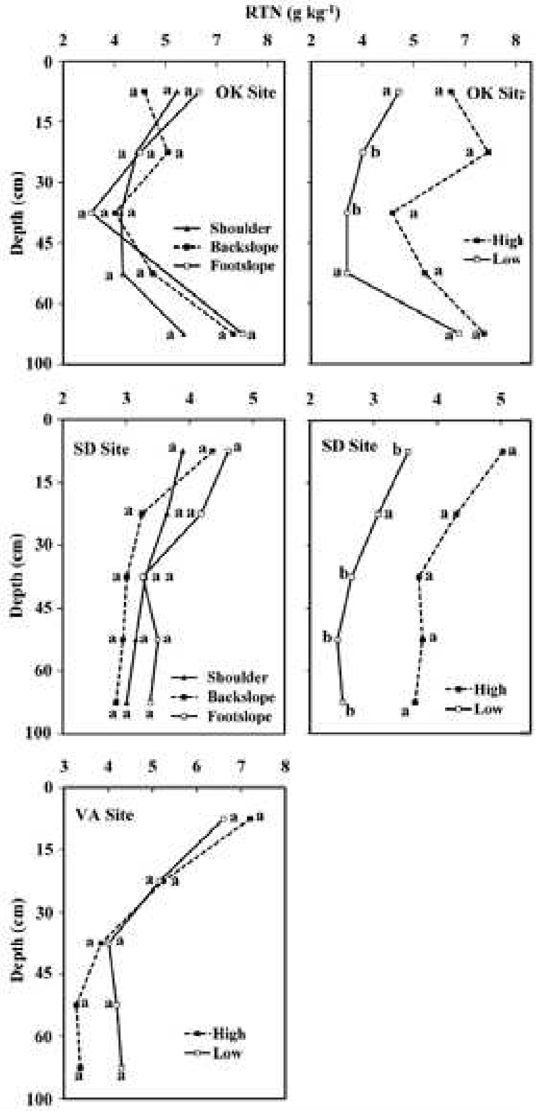

Fig. 3.

Mean root total nitrogen (RTN) of switchgrass for the 0- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 100-cm depths in 2014 under the high and low N fertilization rates at the shoulder, backslope, and footslope positions at the Oklahoma (OK), South Dakota (SD), and Virginia (VA) sites. Note: (i) The effect of N rate × Position on RTN at the 0- to 15-cm depth at the SD site was significant and the separate analysis results for each N rate and position (data not shown) showed that under the low N rate, the mean RTN at the footslope was significantly higher than that for the shoulder and backslope positions. At the shoulder and backslope positions, the RTN under the high N rate was significantly higher than that for the low N rate. (ii) The effect of N rate × Position on RTN at the 30- to 45-cm depth at the SD site was significant (data not shown), and the results showed that at the shoulder position, the RTN under the high N rate was significantly higher than that for the low N rate. (iii) Means within the same depth followed by different small letters are significantly different at $P < 0.05$ for the N rate and landscape position.

For SD site, effects of the N rate and landscape position on root parameters such as RW, TLD, TSA, LD01, SA01, LD12, SA12, LDg2, and SAg2 were not significant at the 0- to 100-cm depth in 2014. However, the effects of interaction between N rate and position on RW, TLD, TSA, LD01, SA01, LDg2, and SAg2 were significant (Table 3), thereby the data were separately analyzed for each N rate and position (Supplemental Table S7). At the shoulder position, the mean RW under the low N rate was significantly lower than that for the high N rate. At the footslope position, the mean TLD, LD01, SA01, LDg2, and SAg2 under the low N rate were significantly higher than that for the high N rate. Under the high N rate, the mean RW, TSA, and SA01 at the backslope position were significantly higher than that for the shoulder and footslope positions, and the mean TLD and LD01 at the backslope position were significantly higher than that for the footslope position (Supplemental Table S7). The depth effects on the selected soil properties were significant at the 0- to 100-cm depth in 2014 (Table 3), and the data were separately analyzed for each depth (Supplemental Table S8). At the 0- to 15-cm depth, the N rate did not impact the RW, TLD, TSA, LD01, SA01, LD12, SA12, LDg2, and SAg2, but the position significantly impacted the LD12 (mean LD12 at the backslope is significantly higher than the shoulder and footslope positions). For the 15- to 30- and 60- to 100-cm depths, both the N rate and the position did not impact these root parameters. At the 30- to 45-cm depth, the interaction effects of N rate × position on the LDg2 and SAg2 were significant (Supplemental Table S8). At the footslope, the LDg2 and SAg2 shoulder and footslope positions, and the mean TLD and LD01 at the backslope position were significantly higher than that for the footslope position (Supplemental Table S7). The depth effects on the selected soil properties were significant at the 0- to 100-cm depth in 2014 (Table 3), and the data were separately analyzed for each depth (Supplemental Table S8). At the 0- to 15-cm depth, the N rate did not impact the RW, TLD, TSA, LD01, SA01, LD12, SA12, LDg2, and SAg2, but the position significantly impacted the LD12 (mean LD12 at the backslope is significantly higher than the shoulder and footslope positions). For the 15- to 30- and 60- to 100-cm depths, both the N rate and the position did not impact these root parameters. At the 30- to 45-cm depth, the interaction effects of N rate × position on the LDg2 and SAg2 were significant (Supplemental Table S8). At the footslope, the LDg2 and SAg2 under the high N rate were significantly lower than that for the low N rate (note in Supplemental Table S8). At the 45- to 60-cm depth, the interaction effects of N rate × position were significant (Supplemental Table S8). At the backslope position, under the high N rate, the TLD, TSA, LD01, and SA01 observed significantly higher values compared to the low N rate. The footslope position under high N rate exhibited significantly higher mean TSA compared with the backslope. The mean LD01 and SA01 at the backslope position was significantly higher than that for the shoulder and footslope positions. Under the low N rate, significantly higher mean TLD and LD01 were recorded under the footslope position compared to the backslope (Supplemental Table S9). Moreover, with increasing soil depth, higher values of mean LD12 and SA12 were recorded with high N rate (Supplemental Table S8). The mean values of RW, TLD, TSA, LD01, SA01, LD12, SA12, LDg2, and SAg2 under the two N rates and three positions for all five depths in 2014 ranged from 0.052 to 0.196 g 100 cm^{-3}, 79.12 to 213.0 cm 100 cm^{-3}, 12.94 to 33.78 cm^2 100 cm^{-3}, 68.77 to 185.8 cm 100 cm^{-3}, 7.86 to 21.42 cm^2 100 cm^{-3}, 9.07 to 33.57 cm 100 cm^{-3}, 3.87 to 13.77 cm^2 100 cm^{-3}, 0.29 to 2.11 cm 100 cm^{-3}, and 0.21 to 1.85 cm^2 100 cm^{-3}, respectively (Supplemental Table S8).

Table 3. View Full Table | Close Full View

Mean root dry weight, root length density, and surface area, and root C and N of switchgrass for the 0- to 100-cm depth in 2014 under the high and low N fertilization rates at the shoulder, backslope, and footslope positions at the South Dakota (SD) site

				0–1 mm	
Treatments	RW†	TLD	TSA	LD	RSA
	g 100 cm^{-3}	cm 100 cm^{-3}	cm^2 100 cm^{-3}	cm 100 cm^{-3}	cm^2 100
N Rate (N)					
High	0.104a‡	125.5a	22.44a	105.5a	12.12a
Low	0.092a	135.7a	21.51a	119.7a	12.70a
Position (P)					
Shoulder	0.102a	125.8a	21.58a	108.0a	12.06a
Backslope	0.105a	132.7a	23.41a	113.4a	13.51a
Footslope	0.089b	133.0a	20.94a	115.9a	11.61a
					Analys
N	0.94	0.36	0.85	0.22	0.36
P	<0.001	0.55	0.051	0.66	0.03
Depth (D)	<0.001	<0.001	<0.001	<0.001	<0.001
N × P	0.03§	0.02§	0.008§	0.034§	0.006§
N × D	0.61	0.21	0.34	0.18	0.22
P × D	0.98	0.63	0.95	0.4	0.49
N × P × D	0.88	0.88	0.94	0.82	0.7

† RW, root dry weight; TLD, total length density; TSA, total surface area; LD, length density; RSA, root surface area; RTC, root total carbon; RTN, root total nitrogen.

‡ Means within the same column followed by different small letters are significantly different at P < 0.05 for the N rate and landscape position.

§ The effects of N rate × Position were significant, thereby, the data were analyzed separately for each N rate and position (Supplemental Table S8).

For SD site, RTC was significantly impacted by the landscape position at the 0- to 100-cm depth (mean RTC at the shoulder > footslope), but RTN was significantly influenced by the N rate (mean RTN under the high N rate > low N rate) and landscape position (mean RTN at the footslope > shoulder and backslope) (Table 3). The effect of interaction between the N rate and position on the RTN was significant (Table 3), and the separate analysis showed that at the shoulder and backslope positions, the mean RTN under the low N rate was significantly lower than that for the high N rate. Under the low N rate, the mean RTN at the footslope position was significantly higher than that for the shoulder and backslope positions (Supplemental Table S7). The effect of depth on the RTC and RTN was significant (Table 3), and thereby the data were separately analyzed for each depth. At the 0- to 15-cm depth, mean RTC at the shoulder position (443.1 g kg^{-1}) was significantly higher than that for the footslope (422.0 g kg^{-1}). For the other four depths, the N rate and position did not significantly impact the RTC. In general, the RTC reduced as the depth increased (Fig. 2). At the 0- to 15-, 30- to 45-, 45- to 60-, and 60- to 100-cm depths, the mean RTN under the high N rate (4.53, 3.21, 3.27, and 3.15 g kg^{-1}, respectively) was significantly higher than that for the low N rate (3.04, 2.15, 1.93, and 2.01 g kg^{-1}, respectively) (Fig. 3). At the 0- to 15-cm depth, the effect of interaction between the N rate and position on RTN was significant (Fig. 3). The separate analysis results for each N rate and position (data not shown) showed that under the low N rate, the mean RTN at the footslope was significantly higher than that for the shoulder and backslope positions. At the shoulder and backslope positions, the RTN under the high N rate was significantly higher than that for the low N rate (note in Fig. 3). At the 30- to 45-cm depth, the effect of interaction between the N rate and position on RTN was also significant (Fig. 3). At the shoulder position, the RTN under the high N rate was significantly higher than that for the low N rate (note in Fig. 3). The position did not significantly impact the RTN. Generally, the RTN reduced as the depth increased (Fig. 3).

For the VA site, root parameters (i.e., RW, TLD, TSA, LD01, SA01, LD12, SA12, LDg2, and SAg2) were not significantly influenced by N rate for the 0- to 100-cm depth (Table 4). Higher values of RW, TLD, TSA, LD01, SA01, LD12, and SA12 were recorded with low N rate compared with high N rate. Greater mean values were recorded for both the LDg2 and SAg2 within the high N rate when compared to the low N rate values. However, the depth significantly impacted these parameters (Table 4). The mean RW under the low N rate (1.35 g 100 cm^{-2}) was significantly higher than that for the high N rate (0.76 g 100 cm^{-2}) at the 0- to 15-cm depth only, but other four depths had the same trend for the RW, that is, mean RW

RTN reduced as the depth increased (Fig. 3).

For the VA site, root parameters (i.e., RW, TLD, TSA, LD01, SA01, LD12, SA12, LDg2, and SAg2) were not significantly influenced by N rate for the 0- to 100-cm depth (Table 4). Higher values of RW, TLD, TSA, LD01, SA01, LD12, and SA12 were recorded with low N rate compared with high N rate. Greater mean values were recorded for both the LDg2 and SAg2 within the high N rate when compared to the low N rate values. However, the depth significantly impacted these parameters (Table 4). The mean RW under the low N rate (1.35 g 100 cm^{-3}) was significantly higher than that for the high N rate (0.76 g 100 cm^{-3}) at the 0- to 15-cm depth only, but other four depths had the same trend for the RW, that is, mean RW under the low N rate > the high N rate (Supplemental Table S10). Other root parameters (TLD, TSA, LD01, SA01, LD12, SA12, LDg2, and SAg2) were not impacted by the N rate for each depth (Supplemental Table S10). The mean values of RW, TLD, TSA, LD01, SA01, LD12, SA12, LDg2, and SAg2 at the two N rates for all five depths ranged from 0.15 to 1.35 g 100 cm^{-3}, 62.5 to 212.6 cm 100 cm^{-3}, 16.76 to 61.96 cm^2 100 cm^{-3}, 38.38 to 164.8 cm 100 cm^{-3}, 5.14 to 20.09 cm^2 100 cm^{-3}, 8.21 to 38.34 cm 100 cm^{-3}, 3.25 to 17.17 cm^2 100 cm^{-3}, 0.31 to 11.27 cm 100 cm^{-3} and 0.24 to 8.78 cm^2 100 cm^{-3}, respectively (Supplemental Table S10).

Table 4. View Full Table | Close Full View

Mean root length density, root surface area, and root C and N of switchgrass for the 0- to 100-cm depth in 2014 under the high and low N fertilization rates at the Virginia (VA) site

Treatments	RW†	TLD	TSA	0–1 mm	
				LD	RSA
	g 100 cm^{-3}	cm 100 cm^{-3}	cm^2 100 cm^{-3}	cm 100 cm^{-3}	cm^2 100
N Rate (N)					
High	0.40a‡	107.5a	25.73a	82.01a	10.71a
Low	0.63a	134.5a	33.79a	101.8a	13.33a
					Analysi
N	0.22	0.37	0.38	0.36	0.52
Depth (D)	<0.001	<0.001	<0.001	<0.001	0.001
N × D	0.72	0.64	0.68	0.38	0.37

† RW, root dry weight; TLD, total length density; TSA, total surface area; LD, length density; RSA, root surface area; RTC, root total carbon; RTN, root total nitrogen.
‡ Means within the same column followed by different small letters are significantly different at $P <$ 0.05 for the N rate.

For the VA site, the RTC and RTN were not impacted by the N rate but significantly influenced by the depth at the 0- to 100-cm depth (Table 4). The N rate did not impact RTC for each depth but significantly impacted the RTN at the 45- to 60- and 60- to 100-cm depths (the RTN under the high N rate < the low N rate). The RTC did not have an observed trend as the depth increased, but the RTN had a decreasing trend with an increase in the depth. The mean values of RTC and RTN under the two N rates for all the five depths ranged from 390.5 to 446.7 and 3.28 to 7.21 g kg^{-1}, respectively (Fig. 2 and 3).

DISCUSSION

Impacts of N Rate on Soil Properties

The observations from this experiment showed that the N rate did not significantly impact soil SOC, BD, pH, EC, and TN for each depth in switchgrass fields after 5 yr of continuous N application in OK, SD, and VA (Fig. 1 and Supplemental Tables S1–S3). Some studies have also reported no significant differences in SOC, TN, BD, aggregate stability, and pH among different fertilization rates (e.g., Jung and Lal, 2011; Kibet et al., 2016). Given slope differences within sites, water movement through runoff and leaching due to precipitation may have disturbed, mixed, or redistributed the N fertilizers applied. Moreover, water erosion can move surface soils and mix topsoil and subsoil, resulting in the redistribution in SOC in the eroded soils (Martínez-Mena et al., 2012) and reducing the effects of N rate on the soil properties.

Soil pH and EC in response to N rate differed among the three experimental sites (Supplemental Tables S1–S3) but generally differed from Geisseler and Scow (2014), who reported that pH decreased with increasing rates of N fertilization. Our data also questions the assertion that the N fertilizer application increases salinity (NRCS, 2016), but likely reflects differences in rainfall and soil types among sites (Fike et al. 2017). Nitrogen in soils influences soil pH in two ways: (i) N inputs from fertilizers can acidify the soil directly, and (ii) nitrate-N (along with sulfate-S) can be taken up and assimilated by crops to release alkalinity from their roots (Barak et al., 1997). Mean nitrogen use efficiency (NUE) at the OK site (4.91 kg kg^{-1}) was much lower than NUE at the SD site (15.49 kg kg^{-1}) (Owens et al., 2013), indicating the greater numerical differences in N removal were observed in SD than OK. Therefore, at the OK site, the alkalinity from the dense roots of switchgrass could be lower than the acidifying effect of N fertilizers, thus the pH value was lower under the high N rate than the low N rate (Supplemental Table S1). In SD, however, high N fertilization had less of an acidifying effect than in OK, resulting in a higher pH value compared with the low N rate (Supplemental Table S2). Differences in cultivar between sites may also have affected these results (e.g., by differences in root exudates), but this was not explored. Soil EC, a measure of the ability of the solution to conduct electricity, indicates the presence or absence of salts. Factors affecting soil EC include the inherent elements such as soil minerals, climate, and soil texture, and the environmental conditions such as cropping, irrigation, land use, and application of fertilizers (NRCS, 2016). Precipitation amounts and intensity (not measured), along with slope differences among the three sites may also have affected runoff and salt movement (NRCS, 2016), potentially observed patterns for EC at the different sites.

Impacts of Nitrogen Rate on Root Parameters

The findings of this study showed that the TLD, TSA, LD01, SA01, LD12, and SA12 were significantly impacted by the N rate in the total profile at the OK site (high N rate < low N rate), whereas at the SD and VA sites, the N rate did not influence these parameters (Tables 2-4). Previous experiments also found inconsistent results for the effects of N rate on switchgrass root. For example, switchgrass root biomass is increased (Sanderson and Reed, 2000), unchanged (Ma et al., 2001), or a complex manner (Heggenstaller et al., 2009) with the increase in fertilization rates (Garten, Jr. et al., 2011). The mixed results were also reported by Jung and Lal (2011) and Kibet et al. (2016). This is mostly because switchgrass can still grow well at a low soil N level (Lemus et al., 2008) and different soil N levels in switchgrass fields at

The findings of this study showed that the TLD, TSA, LD01, SA01, LD12, and SA12 were significantly impacted by the N rate in the total profile at the OK site (high N rate < low N rate), whereas at the SD and VA sites, the N rate did not influence these parameters (Tables 2–4). Previous experiments also found inconsistent results for the effects of N rate on switchgrass root. For example, switchgrass root biomass is increased (Sanderson and Reed, 2000), unchanged (Ma et al., 2001), or a complex manner (Heggenstaller et al., 2009) with the increase in fertilization rates (Garten, Jr. et al., 2011). The mixed results were also reported by Jung and Lal (2011) and Kibet et al. (2016). This is mostly because switchgrass can still grow well at a low soil N level (Lemus et al., 2008) and different soil N levels in switchgrass fields at the three sites. Within switchgrass fields, mineralization of N from soil organic matter (SOM) can make substantial amounts of N available for plants due to switchgrass rapidly growing after soils are fully warmed (Stout, 1995). Rhizosphere microbes in switchgrass fields can also fix N_2 that could turn into available N (Brejda et al., 1994; Welbaum et al., 2004). In addition, atmospheric deposition of N can provide more available N (NO_3^- and NH_4^+) (Coulston et al., 2004). These available N forms can certainly account for the slight N input response by switchgrass. Therefore, the available N forms can lower the efficiency of N recovery (Stout and Jung, 1995), i.e., "compete" with added N such as N fertilizers (Parrish and Fike, 2005), resulting in little N response even after 3 or more years of biomass removal (Thomason et al., 2005). Therefore, the findings of this experiment that LD and RSA parameters under the low N rate were higher, compared with the high N rate at some sites, and could be reasonable. In specifically, the nitrogen use efficiency (NUE) at the OK site was the lowest among the three sites (NUE at the OK, SD, and VA sites were 4.91, 15.49, and 32.79 kg kg^{-1}, respectively [Owens et al., 2013]), indicating that there was more N fertilizer in the OK field, which, as stated previously, resulted in that the pH value was lower under the high N rate than the low N rate (Supplemental Table S1). Also, the pH at the OK site < 6 at the 0- to 30-cm depth and < 7 at the 30- to 100-cm depth (Supplemental Table S1), and the lower pH under the high N rate in acidic soils could restrict switchgrass root growth (Clark et al., 1999; Pinkerton and Simpson, 1986), likely resulting in root length and area under the high N rate to be significantly lower than for the low N rate (Table 2).

The RTC, in general, was not impacted by the N rate at the three sites. However, the N rate significantly increased RTN at the OK and SD sites but did not impact the RTN for the VA site (Tables 2–4). This is primarily because N in the switchgrass can naturally recycle from shoots to roots under different conditions (Beaty et al., 1978; Heckathorn and DeLucia, 1994). The capacity of a plant to accumulate soil N depends more on the physiological parameters (e.g., transporters and assimilatory proteins) for regulating N uptake (Glass, 2003). The transporters and assimilatory proteins are commonly controlled by the genes involved in NO_3^- and NH_4^+ uptake (Garnett et al., 2009). Moreover, switchgrass root N concentration increases with added N in soils (Garten, Jr. et al., 2011; Heggenstaller et al., 2009). Switchgrass under lower N rate (140 kg N ha^{-1}) favored allocation of nutrients to roots over shoots, and high N rate (220 kg N ha^{-1}) shifted the allocation of nutrients to shoots over roots (Heggenstaller et al., 2009). In this study, because of different cultivars and NUEs at the three sites (NUE in VA was substantially higher than that for OK and SD, as mentioned previously), resulting in higher N in OK and SD than VA, likely leading to allocation of N to shoots over roots at the OK and SD under the high N rate. Whereas, the low N rate favors the allocation of nutrients to roots over shoots (Heggenstaller et al., 2009). Therefore, the RTN at the OK and SD sites under the high N rate could be significantly higher than for the low N rate (Tables 2 and 3).

Impacts of Landscape Position on Soil Properties

The findings from this experiment showed that the landscape position did not impact soil properties in OK (Supplemental Table S1), but in SD, the position significantly impacted SOC, BD, pH, EC, and TN for most five depths (Fig. 1 and Supplemental Table S2) (no position treatment available for the VA site). The different results from the OK and SD sites are likely because the land slope at the OK site (0–3%) was lower than that for the SD site (2–20%). At the SD site, the SOC and TN contents and EC at the footslope position were significantly higher than the backslope and shoulder positions for most soil depths, and BD and pH at the footslope position were significantly lower than the backslope and shoulder positions at most soil depths (Fig. 1 and Supplemental Table S2). These findings in this experiment are in accord with previous experiments (Guzman and Al-Kaisi, 2011; Ofori et al., 2013). This could be attributed to the specific effects of long-term erosion and soil development in the lands with constant slopes (Mbonimpa et al., 2015). Specifically, the shoulder and backslope positions in land are eroded, and the footslope position is deposited, that is, the soil nutrients are usually accumulated at the lower positions (McCarty and Ritchie, 2002). Therefore, the SOC, TN, and salts are usually higher at the footslope position than the upper positions (the increasing salts indicate the higher EC at the footslope position [NRCS, 2016]). This can result in an increase in root biomass and soil aggregates at the lower positions and soil degradation at the upper positions (Lai et al., 2018b). The increases in SOC, soil aggregates, and root biomass at the footslope position can result in decreased BD (Guzman and Al-Kaisi, 2011). The pH at the footslope was significantly lower than the backslope and shoulder (backslope ≤ shoulder) for all depths in SD (Supplemental Tables S2). This observation differs from the previous results that showed that the higher pH value at the footslope position was due to the accumulation of soluble cations (e.g., Na^+ and Ca^{2+}) at the lower positions (Khan et al., 2013). The observation in this experiment is likely because the accumulation of N at the footslope position through water erosion increased the acidifying effect (Barak et al., 1997).

Impacts of Landscape Position on Switchgrass Root Growth Parameters

The landscape position, generally, did not significantly impact the root parameters at the OK and SD sites for the total profile and each depth, but the effects of interaction between landscape position and N rate for the total profile on these parameters were significant (Tables 2, 3, Supplemental Tables S4–S6, and S7–S9) (no position treatment available for the VA site). The non-significant impacts are strongly related to the switchgrass capacity to "compete" with added N (Parrish and Fike, 2005) as mentioned previously. Another reason may be greater switchgrass biomass and C belowground compared to aboveground mature stand biomass, most of the aboveground production is removed annually, and belowground root production and turnover are essential to the maintenance of SOM (Garten, Jr. et al., 2011). Therefore, the position might not significantly impact the root RW, TLD, and TSA. This indicates that the impacts of switchgrass roots on soils are similar at various positions. In other words, when the landscape slope is high, such as 2 to 20% at the SD site, the growing switchgrass can still maintain similar changes in root parameters at various positions over time.

The significant impacts of interaction between landscape position and N rate on the root parameters for the total profile are mostly because of soil changes by the interaction. At the shoulder and backslope positions at the OK site, the mean TLD, TSA, LD01, SA01, LD12, and SA12 under the low N rate were significantly higher than that for the high N rate (Supplemental Table S4). This is because water erosion at the shoulder and backslope positions can mix the topsoil and subsoil or soils in plots with different N rates, redistributing SOC in the eroded soils (e.g., Lai et al., 2018b; Martinez-Mena et al., 2012). This could level switchgrass can still maintain similar changes in root parameters at various positions over time.

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On the other hand, under the low N rate at the OK site, the mean RW, TLD, TSA, LD01, SA01, LD12, and SA12 at the shoulder and backslope positions were significantly higher than that for the footslope position for the total profile (Supplemental Table S4). This can be attributed to the facts that include: (i) under the low N rate (no N fertilization), the water erosion at the shoulder and backslope positions could not move N inputs into the footslope. (ii) There could be more N leaching at the footslope (Lai et al., 2018c). (iii) Photosynthesis of switchgrass is limited by the amount of light available (Pierson et al., 1990) at the footslope because plant leaf area is shaded each other. (iv) More water at the footslope position likely resulted in flood, restricting the root growth through filling pores of soil due to high precipitation at the OK site (1137 mm per year) (Table 1) and then water erosion. However at the SD site, these interaction effects were not significant (Supplemental Table S7). This is mostly because the rainfall amount at the SD (619 mm per year) was much lower than that for the OK site (1137 mm per year), resulting in less water flood at footslope position for the SD site.

The mean RTC at the shoulder was significantly higher than the footslope for the total profile at the SD site (Table 2). Roots completely depend on the C supply provided by plant shoots (Lambers et al., 1998). The total amount of C is fixed during photosynthesis (Huang et al., 2012). Total photosynthesis is limited by the amount of light available (Pierson et al., 1990), which depends on the amount of plant leaf area that can capture light, and a major limitation of photosynthesis of a plant is shaded by other plants (Wikipedia, 2018). Therefore, at the footslope position, more plant leaf area is shaded by other plants due to denser switchgrass, compared with the shoulder, limiting photosynthesis and resulting in the higher mean RTC at the shoulder than the footslope position. However, at the OK site, the position effect was not significant (Table 2). This is because the OK field slope was lower than for the SD site, resulting in less difference of photosynthesis between the shoulder and footslope positions. On the other hand, the mean RTN at the both OK and SD sites had significantly higher content at the footslope than the shoulder position (Tables 2 and 3). This is primarily because the N level at the footslope is higher than that for the shoulder through deposit by water erosion, and the switchgrass root N concentration increases with added N in soils (Garten, Jr. et al., 2011; Heggenstaller et al., 2009).

Switchgrass Roots with Depth

Switchgrass has deeper dense roots. For example, in the 60- to 100-cm depth, the RW was still 0.031, 0.10, 0.22 g 100 cm^{-2} in OK, SD, and VA, respectively; the TLD 74.02, 161.5, 124.7 cm 100 cm^{-2} in OK, SD, and VA, respectively; the TSA 11.68, 20.26, and 22.96 cm^2 100 cm^{-2} in OK, SD, and VA, respectively (Supplemental Tables S5, S8, and S10). Switchgrass roots can even extend to a soil depth of 3 m (Weaver, 1968) and 3.3 m (Ma et al., 2000). However, these prolific roots have similar C and N contents for all five depths (Fig. 2 and 3) and can provide the C and N into the deeper soils (Liebig et al., 2005). Switchgrass root systems can increase C sequestration, particularly, a single harvest per year (e.g., at these experimental sites) could result in more C sequestration in the roots and belowground (Parrish and Fike, 2005). It is estimated that after months or years of cultivation, 40% of the estimated RTC input was retrieved as soil C (Rasse et al., 2005). This is mostly because he deeper dense roots, along with a relatively small dead root biomass due to the production of long-lived rhizomes of switchgrass (Tufekcioglu et al., 2003), can maintain whole rhizome interconnections among roots for more than 10 yr, functioning as sites of C storage (Hartnett, 1989) and allowing greater uptake of nutrients (Lai et al., 2017). This indicates that switchgrass could reduce atmospheric CO_2 from this system because more C could be sequestrated (Ma et al., 2001). Further, switchgrass root systems can reduce the risk of N loss associated with non-point pollution (Cavagnaro et al., 2015; Ma et al., 2000). This is mostly because the deep root system of perennial switchgrass can provide for annual dieback and regrowth to form an extensive fibrous root system to contribute organic matter to soils (Kibet et al., 2016; Thomas et al., 1996). The increasing SOM due to the deep rooting system could be more protected from decomposition (Garten, Jr. et al., 2011). The natural processes of mineralization of SOM could increase TN content in soils (Randall and Mulla, 2001). Also, the switchgrass deep rooting system can develop an abundant and dense network with arbuscular mycorrhizal (AM) fungi (Hooker et al., 1992; Wang et al., 2011), enhancing N mineralization, significantly increasing the availability of N to the plants, particularly in soils with low nutrient status (Jackson et al., 2008). The deep rooting depth can also result in the higher ability of switchgrass to intercept N, particularly NO_3^-, reducing the NO_3^- leaching in the soils (Gastal and Lemaire, 2002). Moreover, the deep roots of switchgrass can improve water infiltration rate (Katsvairo et al., 2007) and reduce soil compaction over time (Clark et al., 1998) because soils under switchgrass have more continuous macropores created by the elongated and prolonged root channels (Blanco-Canqui, 2010). The high biomass and deep roots can also reduce the soil's susceptibility to compaction due to increased SOM (Thomas et al., 1996). The root size in the soil surface (generally in the top 30-cm depth) was much higher than those for the 30- to 100-cm depth. The mean RW, TLD, and TSA in OK, SD, and VA in the 0- to 30-cm depth were approximately 300, 150, and 180%; 68.8, 34.3, and 33.0%; and 180, 36.9, and 81.9% higher, respectively, compared with the parameters within the 30- to 100-cm depth (Supplemental Tables S5, S8, and S10). This finding is in accord with a previous study (McLaughlin and Kszos, 2005). The distribution of deep root systems of switchgrass in the soils can increase more SOC concentration at the top 30 cm soil (Garten, Jr. et al., 2011; Thomas et al., 1996). These findings in this study can provide policymakers with references to support switchgrass as an alternative bioenergy feedstock, while these findings can provide the information about the impacts of N fertilizer and its interactions with different positions on soils and root growth for producers to improve their farm management and economic benefits.

VA in the 0- to 30-cm depth were approximately [illegible] and 180, 36.9, and 81.9% higher, respectively, compared with the parameters within the 30- to 100-cm depth (Supplemental Tables S5, S8, and S10). This finding is in accord with a previous study (McLaughlin and Kszos, 2005). The distribution of deep root systems of switchgrass in the soils can increase more SOC concentration at the top 30 cm soil (Garten, Jr. et al., 2011; Thomas et al., 1996). These findings in this study can provide policymakers with references to support switchgrass as an alternative bioenergy feedstock, while these findings can provide the information about the impacts of N fertilizer and its interactions with different positions on soils and root growth for producers to improve their farm management and economic benefits.

CONCLUSIONS

The present experiment was conducted at locations in OK, SD, and VA, to evaluate the impacts of N rate and landscape position on selected soil properties and root parameters. Data showed that the N rate did not significantly impact SOC, BD, pH, EC, and TN for each depth in switchgrass fields at the three sites. However, the TLD, TSA, LD01, SA01, LD12, and SA12 were significantly increased by the N rate in the total profile at the OK site only. The RTC was not impacted by the N rate at the three sites, but the N rate significantly increased RTN at the OK and SD sites only. The landscape position did not impact the soil properties at the OK site, but in SD, the position significantly impacted them for most five depths (mean SOC, TN, and EC at footslope > backslope > shoulder; mean BD and pH at footslope < backslope < shoulder) (no position treatment available for the VA site). The landscape position, generally, did not significantly impact RW, LD, and RSA at the OK and SD sites for the total profile, but the effects of interaction between landscape position and N rate on these parameters for the total profile were significant. The RTC was significantly impacted by the position (shoulder > footslope) at the SD site only; however, the position significantly impacted RTN at both OK and SD sites (footslope > shoulder). As soil depth increased, the root parameters and SOC, TN, and EC reduced, while soil BD and pH increased. Our findings indicate that the N rate did not impact soils but influenced root parameters depending on local site conditions. The landscape position impacted soil properties and RTC and RTN depending on site slopes, but did not impact RW, LD, and SA. Particularly, the interaction between landscape position and N rate significantly impacted these root parameters. The deeper dense root system of switchgrass could improve soils and increase C accumulation and reduce the risk of N loss to benefit the environment.

SUPPLEMENTAL MATERIAL

Table S1. Mean soil bulk density (BD), pH, electrical conductivity (EC), and total nitrogen (TN) in switchgrass field for the 0- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 100-cm depths in 2014 under the high and low nitrogen fertilization rates at the shoulder, backslope, and footslope positions at the Oklahoma (OK) site.

Table S2. Mean soil bulk density (BD), pH, electrical conductivity (EC), and total nitrogen (TN) in switchgrass field for the 0- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 100-cm depths in 2014 under the high and low Nfertilization rates at the shoulder, backslope, and footslope positions at the South Dakota (SD) site.

Table S3. Mean soil bulk density (BD), pH, electrical conductivity (EC), and total nitrogen (TN) in switchgrass field for the 0- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 100-cm depths in 2014 under the high and low nitrogen fertilization rates at the Virginia (VA) site.

Table S4. Mean root weight (g 100 cm^{-3}), root length density (cm 100 cm^{-3}), and surface area (cm^2 100 cm^{-3}) of switchgrass for the 0- to 100-cm depth in 2014 for each N rate and position at the Oklahoma (OK) site.

Table S5. Mean root dry weight, length density, and surface area of switchgrass for the 0- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 100-cm depths in 2014 under the high and low N fertilization rates at the shoulder, backslope, and footslope positions at the Oklahona (OK) site.

Table S6. Mean root length density (cm 100 cm^{-3}) and surface area (cm^2 100 cm^{-3}) of switchgrass for the 0- to 15-cm depth in 2014 for each N rate and position at the Oklahona (OK) site.

Table S7. Mean root dry weight (RW, g 100 cm^{-3}), root length density (cm 100 cm^{-3}) and surface area (cm^2 100 cm^{-3}) of switchgrass for the 0- to 100-cm depth in 2014 for each N rate and position at the South Dakota (SD) site.

Table S8. Mean root dry weight, length density, surface area, and root C and N of switchgrass for the 0- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 100-cm depths in 2014 under the high and low nitrogen fertilization rates at the shoulder, backslope, and footslope positions at the South Dakota (SD) site.

Table S9. Mean root length density (cm 100 cm^{-3}) and surface area (cm^2 100 cm^{-3}) of switchgrass for the 45- to 60-cm depth in 2014 for each N rate and position at the South Dakota (SD) site.

Table S10. Mean root dry weight, root length density and surface area, and root C and N of switchgrass for the 0- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 100-cm depths in 2014 under the high and low N fertilization rates at the Virginia (VA) site.

Acknowledgments

This experiment was supported by the North Central Regional Sun Grant Center at South Dakota State University (SDSU) through a grant provided by the U.S. Department of Energy Bioenergy Technologies Office under Award no. DE-FC36-05GO85041. We thank Mr. Jerry Roitsch for providing the land for the study.

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Agronomy Journal Abstract - NITROGEN MANAGEMENT

Performance of an Optimized Nutrient Management System for Double-Cropped Wheat-Maize Rotations in North-Central China

This article in AJ

Vol. 101 No. 6, p. 1489-1499

Received: Mar 9, 2009
Published: Nov, 2009

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doi:10.2134/agronj2009.0099

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+ Author Affiliations

Abstract

Overapplication of N and P and insufficient supply of K are considered primary reasons for restriction of yield improvement in the North China Plain. Optimized nutrient management practices based on soil testing and yield targets have been developed. Other large scale field experiments have indicated that additional improvement for yield and nutrient use benefits is needed. The objective of this study was to evaluate the effects of the optimized nutrient management system on yield, nutrient uptake, nutrient utilization, and profit in the North China provinces of Shanxi, Hebei, Shandong, and Henan. Treatments consisted of a check without fertilizer use (CK); a balanced, optimum nutrient application (OPT); the farmers' practice (FP); and a series of nutrient omission treatments (minus N, P, and K, respectively). The results indicated that the OPT optimized grain yield, nutrient use efficiency, and profitability. Maize (*Zea mays* L.) yield increased by 12.2% at Shanxi and 18.5% at Hebei, respectively. Inputs of N and P across the wheat (*Triticum aestivum* L.) and maize system at the four sites was reduced by 13% (266 kg N ha^{-1}) and 45% (430 kg P_2O_5 ha^{-1}), while K input was increased by 43% (265 kg K_2O ha^{-1}). The OPT improved both measurements of nitrogen use efficiency (NUE); agronomic nitrogen efficiency (AE_N) and nitrogen recovery efficiency (RE_N) in the majority of cases. Although the OPT tested in this study increased yields and nutrient uptake, there remains considerable potential to improve AE_N and RE_N further for this intensive winter wheat–summer maize rotation system.

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EXHIBIT 2

ESTTA Tracking number:	**ESTTA960088**
Filing date:	**03/13/2019**

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
BEFORE THE TRADEMARK TRIAL AND APPEAL BOARD

Proceeding	91246167
Party	Defendant Verdesian Life Sciences U.S., LLC
Correspondence Address	Kirsten S. Carlos Verdesian Life Sciences LLC 1001 Winstead Drive, Suite 480 Cary, NC 27513 trademarks@vlsci.com, CSimoes@SneedLegal.com, trademarks@sneedlegal.com no phone number provided
Submission	Answer and Counterclaim
Filer's Name	Sarah Hsia
Filer's email	trademarks@sneedlegal.com, sarah@sneedlegal.com, jsneed@sneedlegal.com
Signature	/sch/
Date	03/13/2019
Attachments	2019-03-13 Answer and Counterclaim - Opp. No. 91246167.pdf(110687 bytes)

Registration Subject to the filing

Registration No.	4795520	Registration date	08/18/2015
Registrant	HORIZON AG-PRODUCTS, L.P. 1450 Infinite Drive Louisville, CO 80027 UNITED STATES		

Goods/Services Subject to the filing

Class 001. First Use: 2015/02/25 First Use In Commerce: 2015/02/25 All goods and services in the class are requested, namely: Soil applied fertilizer for agricultural use, and excluding chemicals for use in industry and science

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
BEFORE THE TRADEMARK TRIAL AND APPEAL BOARD

Horizon AG-Products, L.P.,	
Opposer,	
v.	Opposition No. 91246167
Verdesian Life Sciences U.S., LLC,	
Applicant.	

ANSWER AND COUNTERCLAIMS

Respondent, Verdesian Life Sciences U.S., LLC ("Verdesian" or "Applicant"), respectfully submits this Answer to the Notice of Opposition filed by Opposer, Horizon AG-Products, L.P. ("Horizon" or "Opposer").

1. Verdesian is without knowledge or information sufficient to form a belief as to the truth of the allegations contained in Paragraph 1 of the Notice of Opposition, and therefore denies the same.

2. Verdesian is without knowledge or information sufficient to form a belief as to the truth of the allegations contained in Paragraph 2 of the Notice of Opposition, and therefore denies the same.

3. Verdesian is without knowledge or information sufficient to form a belief as to the truth of the allegations contained in Paragraph 3 of the Notice of Opposition, and therefore denies the same.

4. Verdesian is without knowledge or information sufficient to form a belief as to the truth of the allegations contained in Paragraph 4 of the Notice of Opposition, and therefore denies the same.

5. Verdesian is without knowledge or information sufficient to form a belief as to the truth of the allegations contained in Paragraph 5 of the Notice of Opposition, and therefore denies the same.

6. Verdesian admits that it filed an application for the mark NUE on January 31, 2018 for fertilizers; chemicals for use in agriculture for crop protection, except fungicides, herbicides, insecticides and parasiticides; plant growth nutrients for crops in Class 1 and for fungicides, herbicides, insecticides and parasiticides in Class 5. Verdesian specifically denies that it has not used the NUE mark in commerce in the United States, and denies each and every other allegation in Paragraph 6 of the Notice of Opposition.

7. Verdesian denies each and every allegation contained in Paragraph 7 of the Notice of Opposition.

8. Verdesian admits that a US Trademark Registration for the mark NUE would give it at least a prima facie exclusive right to use that mark. Verdesian denies each and every other allegation in Paragraph 8 of the Notice of Opposition.

DEFENSES AND AFFIRMATIVE DEFENSES

1. Opposer has failed to state a claim on which relief can be granted.

2. Opposer's Notice of Opposition is barred by the equitable doctrines of waiver, estoppel, unclean hands and/or acquiescence.

3. Opposer's cited mark is unenforceable by virtue of being descriptive, and lacking in secondary meaning and/or generic.

4. Verdesian reserves all rights, including, but not limited to, the right to add additional affirmative defenses as discovery develops.

COUNTERCLAIM FOR CANCELLATION

1. Applicant Verdesian Life Sciences U.S., LLC, is a limited liability company organized and existing under the laws of the State of Delaware, with its principal place of business at 1001 Winstead Drive, Suite 480, Cary, NC 27513.

2. Applicant is a leading manufacturer and seller of agrochemicals, including, *inter alia*, fertilizers, fertilizer additives, biostimulants, seed treatment products, innoculants, micronutrients, fungicides and pesticides ("Applicant's Goods and Services").

3. To market and promote Applicant's Goods and Services, and to build goodwill among relevant consumers of Applicant's Goods and Services, Applicant uses the NUE Mark for "fertilizers; chemicals for use in agriculture for crop protection, except fungicides, herbicides, insecticides and parasiticides; plant growth nutrients for crops" in Class 1 and for "fungicides, herbicides, insecticides and parasiticides" in Class 5.

4. To strengthen its rights in the NUE mark, Applicant applied for trademark registration with the United States Patent and Trademark Office ("USPTO") on January 31, 2018 for "fertilizers; chemicals for use in agriculture for crop protection, except fungicides, herbicides, insecticides and parasiticides; plant growth nutrients for crops" in Class 1 and for "fungicides, herbicides, insecticides and parasiticides" in Class 5. The application was examined by the USPTO, and was approved for publication and published on January 8, 2019. The Examining Attorney did not cite any existing trademark application or registration against Applicant's trademark application as likely to cause confusion under Section 2(d) of the Lanham Act, 15 U.S.C. § 1052(d). Although the application was filed pursuant to Section 1(b) of the Lanham Act, 15 U.S.C. § 1051(b), the NUE mark has been in use in commerce in the United States in connection with the claimed goods by Applicant since at least as early as January 10, 2018.

5. Upon information and belief, Opposer-Counterclaim Respondent, Horizon AG-Products, L.P., is a limited partnership organized and existing under the laws of the State of Texas, with its principal place of business at 1450 Infinite Drive, Louisville, CO 80027.

6. Upon information and belief, Opposer-Counterclaim Respondent is the owner of U.S. Registration No. 4,795,520 for NUE-plex for "soil applied fertilizer for agricultural use, and excluding chemicals for use in industry and science" in International Class 001. However, the term "NUE" is an acronym for the wording Nutrient Use Efficiency, and this wording is merely descriptive of Opposer-Counterclaim Respondent's goods, because Opposer-Counterclaim Respondent advertises its subject goods as intended to increase the nutrient use efficiency in crop production.

7. Accordingly, Opposer-Counterclaim Respondent's U.S. Reg. No. 4,795,520 should be cancelled on the basis that it consists of or comprises, according to 15 U.S.C. §1052(e)(1) "a mark which…describes a feature, characteristic, purpose and/or use of [Opposer-Counterclaim Respondent's] goods."

8. Additionally, upon information and belief, Opposer-Counterclaim Respondent does not presently use the NUE-plex designation in commerce and does not intend to resume use of the mark. Accordingly, the '520 Registration should be cancelled on the basis that the registered mark has been abandoned in accordance with 15 U.S.C. § 1064 (3).

9. On January 31, 2019, Opposer-Counterclaim Respondent filed the instant Opposition Proceeding with the United States Trademark Trial and Appeal Board, claiming that Applicant's NUE Mark was likely to cause confusion with Opposer-Counterclaim Respondent's Registration for NUE-plex.

10. Applicant is likely to be damaged by the continuance of Opposer-Counterclaim Respondent's Registration No. 4,795,520 for NUE-plex.

11. Accordingly, Respondent prays that Registration No. 4,795,520 (NUE-plex) be cancelled pursuant to 15 U.S.C. §1064(3).

WHEREFORE, Applicant requests judgment:

1. dismissing the Notice of Opposition and this proceeding in its entirety, with prejudice;
2. holding that Applicant's Application Serial No. 87/778,016 be allowed; and
3. cancelling Registration No. 4,795,520.

Respectfully submitted,

Dated: March 13, 2019

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Certificate of Filing and Service

The undersigned counsel of record certifies that a copy of the foregoing **APPLICANT'S ANSWER AND COUNTERCLAIM** has been filed through the Electronic System for Trademark and Trial Appeals, and served upon Applicant via email, this the 13th day of March 2019, to the following counsel of record:

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/s/ Jason M. Sneed
An Attorney for Applicant

EXHIBIT 3

Invest in the Future of Farming with a Nutrient Use Efficiency (NUE™) Plan

Share

The business of agriculture is rapidly changing. And with tight margins, high input costs and unpredictable weather patterns, efficiency optimization is absolutely critical. Technological developments in precision agriculture are a critical component, but not effective in isolation.

Producers today must pay close attention to enhancing soil fertilizer efficiency, and focusing on plant uptake and utilization using enhanced efficiency fertilizer (EEF) technologies that limit nutrient loss and improve crop yields and quality.

Nutrients can be lost in a number of ways. Soluble nutrients like nitrates and potassium can be lost in runoff, drainage water and through leaching while less soluble nutrients like phosphorus are more likely to be lost with sediment movement in eroding soils.

Research has found that soluble polymer technology, whether used for phosphorus or nitrogen fertilizers, can reduce soil fixation of nutrients and keep more of them available for plants – reducing nutrient losses and optimizing your return on investment.

Using that research as a foundation, one of the best ways to ensure your operation is running as effectively as possible is by creating a nutrient use efficiency (NUE™) plan.

What is Nutrient Use Efficiency?

Nutrient use efficiency (NUE) is simply a measure of how well plants use the available mineral nutrients. It can also be defined as yield per unit input (e.g., fertilizer, nutrient content, etc.)

NUE is rooted in research-based, best management practices. However, there is no one-size-fits-all approach to implementing a successful NUE strategy on a farm. It's dependent on the type of crop, soil conditions, weather, irrigation and level of precision agriculture adopted on any given operation.

As is the case with most farming operations, decisions should be based upon data driven insights. In the case of optimizing crop nutrient use on-farm, that means looking at data insights from soil sampling, weather data, historical yield and input maps, and other information that helps provide a complete picture of an operation.

Using proven metrics for greater NUE

Verdesian is adopting a new set of metrics that specifically calculates the efficiency of nutrients used in your operation. Using these metrics, you'll be able to benchmark your nutrient use efficiency, highlight any inefficiencies, make changes to your maps, and other information that helps provide a complete picture of an operation.

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NUE Term	Calculation	Reported Example
PFP Partial Factor Productivity	**Yield (Y) / Applied Nutrient (F)**	Unit of yield per unit of nutrient
AE Agronomic Efficiency of applied nutrient	$(Y - Y_0) / F$	Unit of incremental yield per unit of nutrient
PNB Partial Nutrient Balance (Removal-to-use ratio)	Uptake $(U_H) / F$	Ratio of 0 to greater than 1 depends on narrative soil fertility and maintenance objectives
RE Apparent Crop Recovery Efficiency of applied nutrient	$(U - U_0) / F$	Scale from 0.1 - 0.9 dependent on nutrient

Here is an example of these metrics calculated with a nitrogen treatment:

Treatment	Yield	Total N Uptake (U)	Grain Uptake (UH)	N Applied (F)	PFP	AE	PNB	RE
No N	209.33	272.97	188.4	0	-	-	-	-
165lbs N	230.09	300.03	207.08	165	78.1	7.04	1.26	0.113
165lbs N + Stabilizer	237.2	309.31	213.48	165	80.5	9.46	1.29	0.152

Why is NUE important?

There is a massive business opportunity rapidly developing for North American producers – the exploding middle class in countries like India and China.

The World Bank estimates that the **global middle class** will **grow** from under 2 billion consumers today to nearly 5 billion within two decades. This means millions of people will have more money to spend on food.

The importance of NUE is a critical factor to the sustainability of this growth. To keep our soil healthy and productive to meet this demand for generations to come, we need to manage the nutrients inside it.

According to **Food and Agriculture Organization's (FAO)'s 2006 guide for integrated nutrient management**, nutrients added through fertilizers, manures and composts can have negative as well as positive effects on the environment depending on the operation's integrated nutrient management plan. When done right, the guide concludes NUE achieves the following:

• Nutrients removed from the soil through harvesting and export of produce can be largely replenished through various types of recycling in order to maintain and enhance the production potential of the soil.

• Eases the problem of erosion control on the cropped area because of the protection provided by a dense crop cover.

• Adds more organic matter through greater leaf residues, and root and stubble biomass.

• Greater nitrogen uptake by crops and less nitrate is leached down the profile for the pollution of groundwaters or further loss through denitrification.

• Promotes the correct management of all plant nutrient sources on the farm and helps reduce the losses of plant nutrients to the environment.

All of those soil and environmental benefits of NUE management systems ultimately lead to increased yields, which help

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All of these soil and environmental benefits of NUE management systems ultimately lead to increased yields, which help growers create and maintain a sustainably profitable operation when commodity prices are low or unpredictable.

Implemented correctly, NUE promotes **the protection of valuable resources like water and soil**, which in turn satisfies the growing consumer demand for food that is produced in an environmentally responsible way.

NUE will also play an instrumental role as competition for land between food and energy sources increase in the years ahead.

Labor shortages in agriculture have already led to increased demand for "smart inputs" (e.g., nutrients, bio-stimulants and repellents in a single application) and increased mechanization.

The building blocks of NUE: The 4Rs of nutrient stewardship

The Fertilizer Institute along with their industry partners have developed a set of best practice guidelines that provide a scientifically-based framework to achieve cropping system goals, such as increased production, increased farmer profitability, enhanced environmental protection and improved sustainability.

The **4Rs of Nutrient Stewardship** calls for the **right fertilizer source** applied at the **right rate**, at the **right time** and in the **right place.**

The 4Rs apply to growers around the world, but how they are used locally varies depending on field and site-specific characteristics such as soil, cropping system, management techniques and climate.

Right source
For more information about determining the right source, check out these Verdesian Groundwork blogs:

- https://www.vlsci.com/blog/with-nutritional-phosphites-quality-matters-for-stabilization
- https://www.vlsci.com/blog/fall-applied-phosphorus-cost-effective-and-convenient
- https://www.vlsci.com/blog/seed-treatments-expand-management-options

Right rate
For more information about determining the right rate, check out these Verdesian Groundwork blogs:

- https://www.vlsci.com/blog/the-goldilocks-dilemma
- https://www.vlsci.com/blog/investing-in-soil-health-pays
- https://www.vlsci.com/blog/too-much-of-a-good-thing

Right time
For more information about determining the right time, check out these Verdesian Groundwork blogs:

- https://www.vlsci.com/blog/crop-leftovers-can-eat-yield
- https://www.vlsci.com/blog/faster-emergence-for-early-season-planters
- https://www.vlsci.com/blog/making-the-most-of-your-soybean-inoculants

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- https://www.vlsci.com/blog/making-the-most-of-your-soybean-inoculants

Right place
For more reading about determining the right place, check out these Verdesian Groundwork blogs:

- https://www.vlsci.com/blog/striking-a-balance-utilizing-subsurface-tile-drainage
- https://www.vlsci.com/blog/to-till-or-not-to-till
- https://www.vlsci.com/blog/cover-up-to-lock-nutrients-down

Putting nutrient use efficiency into practice

The 4Rs of nutrient stewardship simply provide a framework to assess whether a given crop has access to the necessary nutrients. Asking the right question helps identify opportunities to improve fertilizer efficiency.

To put the 4Rs into practice requires patience, hard work and a strong belief in doing what's right for the future of your farm – and future generations.

Utilizing trusted agronomists and retailers, nutrient use efficiency (NUE) experts, and farm advisors is strongly recommended when developing a nutrient use efficiency (NUE) strategy for your operation.

Overcoming 4 main challenges to implementing nutrient use efficiency

1. INVESTMENT OF TIME AND MONEY
   Think big picture. While it does take more planning and investment up front, a solid nutrient use efficiency strategy for your farm will save you big input bucks in the future, make your yields larger and protect your land and water source.

2. RELUCTANCE TO ADOPTING NEW TECHNOLOGY
   Just because it wasn't done in the past, doesn't mean it shouldn't be done now. It's always possible to outdo what's always been done. Recent technological advancements have revolutionized agriculture and made it possible to optimize the growing cycle right down to the individual plant.

3. CUTTING THROUGH THE CLUTTER OF NEW FARMING SOLUTIONS
   New agricultural products and technologies have exploded over the past decade, which can make it difficult for producers to decide what makes financial sense for their operation. By **partnering with a nutrient use efficiency (NUE) expert**, you'll ensure you're getting the right advice and developing the right plan for your individual operation.

4. IMPLEMENTING IT ALL AT ONCE
   Start small and expand slowly. You don't need to introduce a comprehensive NUE strategy for your entire operation all at the same time. Experiment with a particular crop or field and go from there. A smart NUE plan is constantly changing and evolving as conditions change and new data becomes available.

Applying NUE to specific crops

While developing the correct NUE strategy takes some work, the NUE products and solutions developed by Verdesian Life Sciences are designed to be easy to use and seamless to apply to your operation.

Recognizing that every NUE strategy needs to be developed on a field-by-field basis, here's a snapshot of some of the nutrient management basics for some specific crops.

Corn
To maximize yield and crop quality, corn needs nutrients — especially nitrogen. But when it comes to fertilizer, the rule of thumb is quality, not quantity. Too much applied potassium and nitrogen can get lost in the soil. For optimal results in those critical growth stages (especially V6), nitrogen and potassium need efficiency increases to improve plant metabolism or reduce fixation – and that's where Verdesian's products can help.

Read more about **Verdesian's NUE solutions for corn**

Cereals
Nitrogen, potassium and phosphorus are the three most important nutrients for successful growth in cereal crops. However, it isn't enough to apply fertilizer and hope for the best — cereals can only take up so many nutrients, and any excess will simply be lost through fixation or leaching. By improving plant metabolism or reducing fixation, nutrient use efficiency products can help increase nutrient uptake and maximize the effectiveness of your inputs.

Read more about **Verdesian's NUE solutions for cereals**.

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Read more about **Verdesian's NUE solutions for cereals**.

Pulses and soybeans
Pulses and soybeans produce most of their own nitrogen through rhizobium — a main reason why they're commonly grown to help improve soil health. Inoculants can provide an added rhizobium boost for optimal growth, while nutrient use efficiency products can help ensure pulses and soybeans are getting adequate levels of other key nutrients.

Read more about Verdesian's **NUE solutions for pulses** and **soybeans**.

Vegetables
To maximize yield and quality, vegetable crops require intensive management, and growers must ensure soil is well-drained, and that plants are receiving water with low salinity and the right balance of nutrients.

Read more about Verdesian's **NUE solutions for vegetables**.

Tree nuts
As the world's largest producer of almonds and pistachios, the U.S. is a massive player in the global tree nut market. Nitrogen and potassium are key at different rates during all growth stages while phosphorus should be applied at flowering and post-harvest for strong root development and maintenance.

Read more about Verdesian's **NUE solutions for tree nuts**.

Potatoes
Because potatoes strive for a healthy number of packable tubers, nutrient management and agronomy are key. In fact, nitrogen deficiency is typically the number one cause of limited growth. In the first two growing stages, potassium helps enhance quality and size while phosphorus is also crucial when roots are close to the surface.

Read more about Verdesian's **NUE solutions for potatoes**.

Citrus
Citrus crops are both extremely sensitive to pests and disease and also very receptive to pest and disease management. A solid fertility plan that includes nutrient use efficiency products can give citrus crops the boost needed for healthy growth.

Read more about Verdesian's **NUE solutions for citrus**.

How Verdesian can assist in your NUE plan

Sharing and seeking out knowledge is crucial as you develop your NUE management plan. At Verdesian, we're committed to helping farmers improve crop performance, plant nutrition, water quality and soil health as they strive for the 4Rs of nutrient stewardship.

Verdesian has launched a number of new nutrient use efficiency technologies over the past year for both row crop and specialty crop growers along with a number of planned launches in 2018 and 2019. Consider adding any of these technologies to your NUE plan:

1. **Row crops**

AVAIL T5
A VERDESIAN NUE™ SOLUTION

1. Row crops

AVAIL T5

A VERDESIAN NUE™ SOLUTION

AVAIL T5™ uses an all-new patented polymer technology to reduce the fixation of applied phosphorus, keeping more available for plant uptake, speeding early growth, and improving crop health and yield potential.

NUE CHARGE G

A VERDESIAN NUE™ SOLUTION

NUE Charge G™ allows plants to more efficiently assimilate carbon and utilize nitrogen and other nutrients. The end result is enhanced nutrient use efficiency, leading to more bushels per acre per amount of nutrients applied.

TAKE OFF LS

A VERDESIAN NUE™ SOLUTION

Take Off LS™ is a nitrogen utilization and carbon assimilation technology that optimizes efficient plant nutrient acquisition, allowing for more efficient plant development, and better crop quality and yield potential.

2. Specialty crops

AVAIL HV

A VERDESIAN NUE™ SOLUTION

AVAIL HV™ is a phosphorus efficiency technology for high-volume fertilizer applications designed to provide better nutrient access during early plant development, early season plant performance and crop quality potential.

primacyALPHA

A VERDESIAN NUE™ SOLUTION

Primacy ALPHA
works inside the plant to stimulate the efficient assimilation and utilization of nutrients and also functions as a reproductive growth catalyst that collectively stimulates, intensifies and optimizes plant metabolism.

NUTRI-PHITE PLUS

A VERDESIAN NUE™ SOLUTION

Nutri-Phite® enhances nutrient uptake to improve plant health and vigor by slowing the oxidation of phosphorus, leading to increased yield potential.

3. Row and specialty crops

microSync

A VERDESIAN NUE™ SOLUTION

MicroSync™ is a micronutrient and sulfur technology designed to improve micronutrient efficiency and soil fertility programs in row crops and vegetables.

You can learn more about all of our products, including what solutions will work best for your operation, at: https://www.vlsci.com/products.

Latest blog posts

Meet The NUE People: Jim Pullins

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acquisition, allowing for more efficient plant development, and better crop quality and yield potential.

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"I spent a large part of my career keeping it clean between the rows, then productive in the rows and, now, I'm focused on what happens under the rows to improve results."

May 02, 2019

Lab + Field

Introduction to Seed+ and Crop+ Technology

In this short, seven minute audio introduction to Seed+Dry and Crop+ technologies, Molly McGrath, Ph.D. and Technical Development Manager at Verdesian Life Sciences, joins Reuel Heyden, Corporate Communications for Verdesian Life Sciences, to provide an introduction to and the fundamentals for these technologies' chemistries.

Apr 03, 2019

Groundswell

Poor Seed Quality? Get The Most From The Seed ...

Chronic wet weather can significantly impact soybean seed quality. A seed treatment can make all the difference.

Mar 20, 2019

Lab + Field

See all blog posts

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Get more grain from every unit of N with NUE Charge™ G.

The new proprietary polymer from Verdesian Life Sciences means premium Nutrient Use Efficiency (NUE™) when it comes to nitrogen (N).

More available nitrogen = better use of your investment.

NUE Charge G provides long-lasting protection of treated granular nitrogen fertilizers like urea and ammonium sulfate from volatilization, leaching and denitrification. This keeps more nitrogen in the root zone until the plant needs it. The innovative granular formulation of NUE Charge G keeps more nitrogen in the root zone longer, allowing the plant to access the nutrients when they are needed most.

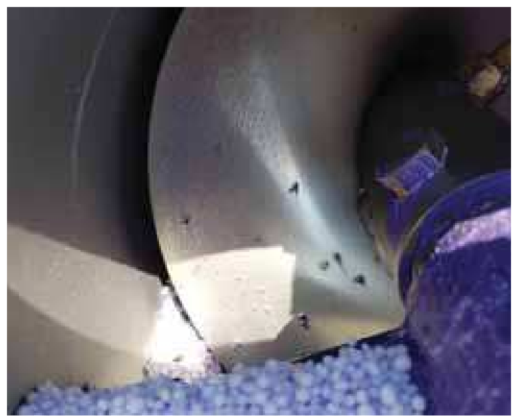
Months of protection, instead of days.

NUE Charge G with urea results in months of protection, not just days. In addition, NUE Charge G can be pretreated on urea and stored for an indefinite period of time without loss of protection when applied to a field. This gives you not only a long-lasting and hard-working product, but peace of mind.

Excellent handling, minimal buildup and consistent delivery.

NUE Charge G offers simple handling and spreading on urea and other dry nitrogen fertilizers. NUE Charge G means significantly less buildup on steel equipment vs. other nitrogen products, meaning less wear and tear on equipment. In addition, NUE Charge G offers more uniform after blending on dry nitrogen fertilizers, which directly correlates to more evenly distributed N across the field.

The distinctive violet color of NUE Charge G not only differentiates from the competitors, but clearly shows consistent coverage.



NUE Charge G offers minimal buildup on equipment, down time, frustration and expense.

PROTECTS AGAINST THREE FORMS OF N LOSS

PROTECTS SOIL HEALTH AND WATER QUALITY

CAN BE STORED FOR AN INDEFINITE PERIOD

50-90%

50-90% LESS BUILDUP ON EQUIPMENT

WORKS WELL IN ALL WEATHER CONDITIONS

9.0 BU/ACRE * ADVANTAGE OVER UNTREATED CHECK

Verdesian Life Sciences makes farming more efficient, more sustainable, and more profitable. Verdesian Life Sciences develops nutrient use efficiency and management technologies to enhance crop uptake, reduce nutrient losses to the environment, and improve yields. As a 4R Nutrient Stewardship Partner, Verdesian is committed to researching and developing environmentally sustainable products.

VERDESIAN
THE NUTRIENT USE EFFICIENCY PEOPLE™

NUE CHARGE G
A VERDESIAN NUE™ SOLUTION

4R nutrient stewardship

For more information: vlsci.com | 800.868.6446

Based on historic performance of similar chemistries and mode of action. Important: Always read and follow label use directions. NUE Charge is a trademark and NUE is a trademark of Verdesian Life Sciences.

EXHIBIT 4

NUE⚡CHARGE™G

A **VERDESIAN** NUE™ SOLUTION

NUE Charge™ G

Nitrogen Use Efficiency Technology

Nitrogen Use Efficiency. Lasting protection. Consistent coverage.

NUE Charge™ G provides long-lasting protection of treated granular nitrogen fertilizers from volatilization, leaching and denitrification. Its innovative granular formulation keeps more nitrogen in the root zone longer, allowing plants to access essential nutrients when they are needed most.

When compared to other nitrogen products, NUE Charge G creates significantly less buildup on steel equipment, meaning less wear and tear, down-time and expense. It also offers consistent, uniform coverage when blended with dry nitrogen fertilizers, which directly correlates to a more even distribution of N across the field.

When pretreated on urea, ammonium sulfate, or a blend of these fertilizers, NUE Charge G results in months of protection, rather than days, and can be stored indefinitely without loss in quality. In addition, it offers simple handling and spreading on urea and other dry nitrogen fertilizers, making NUE Charge G a long-lasting, hard-working technology that delivers strong results and peace of mind.

NUE Charge G is a critical part of your nutrient plan and best management practices when incorporating 4R Nutrient Stewardship, protecting your nitrogen from loss to the environment by providing better uptake availability to the plant, growing a stronger, healthier plant capable of yielding a better crop.

The details

- Next Generation T5 Polymer
- Protects against three forms of N loss
- Protects soil health and water quality
- 50-90% less buildup on equipment
- Can be stored indefinitely with no loss in quality
- Works well in all weather conditions
- Part of Nitrogen Use Efficiency and 4R Nutrient Stewardship

Application Guidelines

Always read and follow label instructions and restrictions before use.

TRIAL DATA

9.0 bu. / acre advantage over untreated control*

**based on historic performance of similar chemistries and mode of action.*

Managing for Profit: Preventing Nitrogen Loss in Crops

https://soundcloud.com/user-22...

Managing For Profit: Consistently Performing and Yielding Results

https://soundcloud.com/user-22...

Videos

About NUE Charge G

About NUE Charge G

Related Products

CHOOSE ANOTHER PRODUCT

Application Guidelines

- Broadcast
- Fertigation
- Foliar
- In-Furrow
- Post-harvest

Formulations

NUE-Charge™ G

Downloads & Printables

NUE-Charge-Sell-Sheet-3.27.2019

Packaging

2.5 Gal. | 250 Gal. Tote

Managing For Profit: Consistently Performing and Yielding Results

https://soundcloud.com/user-22...

Videos

About NUE Charge G

About NUE Charge G

Related Products

Application Guidelines Legend

Ask a Specialist | Broadcast | Fertigation | Foliar | In-Furrow | Post-harvest | Seed Treatments & Inoculants

more than manure
A VERDESIAN NUE™ SOLUTION

More Than Manure® Nutrient Manager reduces farm odors while protecting your manure's phosphorus and nitrogen for improved plant uptake.

LEARN MORE

TAKE OFF®
A VERDESIAN NUE™ SOLUTION

Take Off® is a revolutionary nitrogen-management technology that accelerates nutrient acquisition and assimilation as well as nitrogen use efficiency.

LEARN MORE

TAKE OFF® LS
A VERDESIAN NUE™ SOLUTION

Take Off® LS is a revolutionary nitrogen-management technology that accelerates nutrient acquisition and assimilation as well as nitrogen use efficiency.

LEARN MORE

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Verdesian-ASA Provide Crop Advisers Nitrogen Use Efficiency Webinar

Verdesian Life Sciences and the American Society of Agronomy Host December Webinar on Corn Nitrogen Use Efficiency

Oct 10, 2018

CARY, NC: The American Society of Agronomy (ASA) will provide a corn nitrogen (N) use efficiency webinar sponsored by Verdesian Life Sciences on **Tuesday, December 4, 2018** from 11 am – 12 pm Central, 12 pm – 1 pm Eastern.

This live webinar will focus on N use efficiency best practices for corn and will provide participants with:

- **An understanding of the N uptake patterns of modern corn hybrids,**
- **A research-based review of fertilization technologies that provide N at the right time and in the right place (e.g., Y-drop technology, side-dressing tools, nitrification inhibitors),**
- **An examination of the impacts of different N fertilizer sources on corn N use and productivity.**

This educational webinar will be presented by Dr. Fred Below, a professor of Crop Physiology at the University of Illinois Urbana-Champaign, and Brad Bernhard, a research specialist and Ph.D. student under the advisement of Dr. Below. Dr. Below's Crop Physiology Laboratory creates strategies to teach farmers and agricultural professionals the value of crop management decisions and develops systems to sustainably produce high-yielding corn and soybeans. Below's research evaluates environmental, genetic, and management factors that impact the productivity of corn and soybeans. Bernhard's work focuses on in-season fertility using different fertilizer sources and application methods.

Certified Crop Advisers (CCA) and Certified Professional Agronomists (CPAg) will receive one continuing education unit (CEU) in nutrient management for participating. Sponsored by Verdesian Life Sciences, the webinar is free to all those who register online.

Registration for this webinar can be completed using ASA's Online Learning Platform. Participants will receive a recording of the on-demand webinar upon completion of the event. For details or to register, please visit https://www.agronomy.org/education/classroom/classes/606.

ASA is dedicated to providing continuing education on the latest findings in the field of agronomy using a robust portfolio of online learning opportunities specifically designed for agricultural professionals. Verdesian Life Sciences is committed to education and adoption of nutrient use efficiency (NUE) technologies that, when implemented, enable sustainable agricultural farming practices.

About ASA
The American Society of Agronomy (ASA) is a progressive international scientific and professional society that empowers scientists, educators, and practitioners in developing, disseminating, and applying agronomic solutions to feed and sustain the world. Based in Madison, WI, ASA is the professional home for 8,000+ members and 13,000+ certified professionals dedicated to advancing the field of agronomy. For more information, visit agronomy.org.

About Verdesian
Verdesian Life Sciences enables a sustainable future for farmers through nutrient use efficiency (NUE™). Grown from the ground up in 2012, Verdesian Life Sciences offers farmers and growers biological, nutritional, seed treatment, and inoculant technologies that maximize performance on high-value row crops and specialty crops as well as turf and ornamental plants. As a 4R Nutrient Stewardship Partner, Verdesian is committed to researching and developing environmentally- and financially-sustainable products. Further information about Verdesian is available at www.vlsci.com.

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EXHIBIT 5

To:	Verdesian Life Sciences U.S., LLC (michele.glessner@alston.com)
Subject:	U.S. TRADEMARK APPLICATION NO. 88123749 - A VERDESIAN NUE SOLUTION - 65666/520670
Sent:	12/28/2018 1:37:57 PM
Sent As:	ECOM107@USPTO.GOV
Attachments:	Attachment - 1 Attachment - 2 Attachment - 3 Attachment - 4 Attachment - 5 Attachment - 6 Attachment - 7 Attachment - 8 Attachment - 9

UNITED STATES PATENT AND TRADEMARK OFFICE (USPTO)
OFFICE ACTION (OFFICIAL LETTER) ABOUT APPLICANT'S TRADEMARK APPLICATION

U.S. APPLICATION SERIAL NO. 88123749

MARK: A VERDESIAN NUE SOLUTION

88123749

CORRESPONDENT ADDRESS:
MICHELE M. GLESSNER
ALSTON & BIRD LLP
101 SOUTH TRYON STREET, SUITE 4000
CHARLOTTE, NC 28280-4000

CLICK HERE TO RESPOND TO THIS LETTER:
http://www.uspto.gov/trademarks/teas/response_forms.jsp

VIEW YOUR APPLICATION FILE

APPLICANT: Verdesian Life Sciences U.S., LLC

CORRESPONDENT'S REFERENCE/DOCKET NO:
65666/520670

CORRESPONDENT E-MAIL ADDRESS:

michele.glessner@alston.com

OFFICE ACTION

STRICT DEADLINE TO RESPOND TO THIS LETTER

TO AVOID ABANDONMENT OF APPLICANT'S TRADEMARK APPLICATION, THE USPTO MUST RECEIVE APPLICANT'S COMPLETE RESPONSE TO THIS LETTER **WITHIN 6 MONTHS** OF THE ISSUE/MAILING DATE BELOW. A RESPONSE TRANSMITTED THROUGH THE TRADEMARK ELECTRONIC APPLICATION SYSTEM (TEAS) MUST BE RECEIVED BEFORE MIDNIGHT **EASTERN TIME** OF THE LAST DAY OF THE RESPONSE PERIOD.

ISSUE/MAILING DATE: 12/28/2018

TEAS PLUS OR TEAS REDUCED FEE (TEAS RF) APPLICANTS – TO MAINTAIN LOWER FEE, ADDITIONAL REQUIREMENTS MUST BE MET, INCLUDING SUBMITTING DOCUMENTS ONLINE: Applicants who filed their application online using the lower-fee TEAS Plus or TEAS RF application form must (1) file certain documents online using TEAS, including responses to Office actions (see TMEP §§819.02(b), 820.02(b) for a complete list of these documents); (2) maintain a valid e-mail correspondence address; and (3) agree to receive correspondence from the USPTO by e-mail throughout the prosecution of the application. *See* 37 C.F.R. §§2.22(b), 2.23(b); TMEP §§819, 820. TEAS Plus or TEAS RF applicants who do not meet these requirements must submit an additional processing fee of $125 per class of goods and/or services. 37 C.F.R. §§2.6(a)(1)(v), 2.22(c), 2.23(c); TMEP §§819.04, 820.04. However, in certain situations, TEAS Plus or TEAS RF applicants may respond to an Office action by authorizing an examiner's amendment by telephone or e-mail without incurring this additional fee.

The referenced application has been reviewed by the assigned trademark examining attorney. Applicant must respond timely and completely to the issue below. 15 U.S.C. §1062(b); 37 C.F.R. §§2.62(a), 2.65(a); TMEP §§711, 718.03.

SUMMARY OF ISSUE:
- DISCLAIMER REQUIRED

SEARCH RESULTS
The trademark examining attorney has searched the Office's database of registered and pending marks and has found no conflicting marks that would bar registration under Trademark Act Section 2(d). TMEP §704.02; *see* 15 U.S.C. §1052(d).

DISCLAIMER REQUIRED
Applicant must provide a disclaimer of the unregistrable part of the applied-for mark even though the mark as a whole appears to be registrable. *See* 15 U.S.C. §1056(a); TMEP §§1213, 1213.03(a). A disclaimer of an unregistrable part of a mark will not affect the mark's appearance. *See Schwarzkopf v. John H. Breck, Inc.*, 340 F.2d 978, 979-80, 144 USPQ 433, 433 (C.C.P.A. 1965).

In this case, applicant must disclaim the wording "NUE" in the mark because it is not inherently distinctive. This unregistrable term at best is merely descriptive of an ingredient, quality, characteristic, function, feature, purpose, or use of applicant's goods. *See* 15 U.S.C. §1052(e)(1); *DuoProSS Meditech Corp. v. Inviro Med. Devices, Ltd.*, 695 F.3d 1247, 1251, 103 USPQ2d 1753, 1755 (Fed. Cir. 2012); TMEP §§1213, 1213.03(a).

The attached evidence from https://www.acronymfinder.com/Nitrogen-Use-Efficiency-(NUE).html and https://www.midwesternbioag.com/systems-approach-to-nutrient-use-efficiency/ indicates that "NUE" is an acronym for "Nitrogen Use Efficiency" or "Nutrient Use Efficiency." The attached evidence from https://eco-web.com/edi/061218.html further indicates that plant additives and growth regulators have been used to improve NUE. Applicant's website indicates that applicant provides products that improve NUE (see attachment from https://www.vlsci.com/products/nue-charge-g). Thus, "NUE" in the mark merely describes an ingredient, quality, characteristic, function, feature, purpose, or use of applicant's goods because they are metabolic plant fertilizers and growth regulators for agricultural use that could be used to improve NUE.

Applicant may respond to this issue by submitting a disclaimer in the following format:

No claim is made to the exclusive right to use "NUE" apart from the mark as shown.

For an overview of disclaimers and instructions on how to satisfy this issue using the Trademark Electronic Application System (TEAS), see the Disclaimer webpage.

Please call or email the assigned trademark examining attorney with questions about this Office action. Although the trademark examining attorney cannot provide legal advice or statements about applicant's rights, the trademark examining attorney can provide applicant with additional explanation about the requirement in this Office action. *See* TMEP §§705.02, 709.06. Although the USPTO does not accept emails as responses to Office actions, emails can be used for informal communications and will be included in the application record. *See* 37 C.F.R. §§2.62(c), 2.191; TMEP §§304.01-.02, 709.04-.05.

/Kathy de Jonge/

Trademark Examining Attorney
Law Office 107
(571) 272-9152
kathleen.dejonge@USPTO.gov (informal use only)

TO RESPOND TO THIS LETTER: Go to http://www.uspto.gov/trademarks/teas/response_forms.jsp. Please wait 48-72 hours from the issue/mailing date before using the Trademark Electronic Application System (TEAS), to allow for necessary system updates of the application. For *technical* assistance with online forms, e-mail TEAS@uspto.gov. For questions about the Office action itself, please contact the assigned trademark examining attorney. **E-mail communications will not be accepted as responses to Office actions; therefore, do not respond to this Office action by e-mail.**

All informal e-mail communications relevant to this application will be placed in the official application record.

WHO MUST SIGN THE RESPONSE: It must be personally signed by an individual applicant or someone with legal authority to bind an applicant (i.e., a corporate officer, a general partner, all joint applicants). If an applicant is represented by an attorney, the attorney must sign the response.

PERIODICALLY CHECK THE STATUS OF THE APPLICATION: To ensure that applicant does not miss crucial deadlines or official notices, check the status of the application every three to four months using the Trademark Status and Document Retrieval (TSDR) system at http://tsdr.uspto.gov/. Please keep a copy of the TSDR status screen. If the status shows no change for more than six months, contact the Trademark Assistance Center by e-mail at TrademarkAssistanceCenter@uspto.gov or call 1-800-786-9199. For more information on checking status, see http://www.uspto.gov/trademarks/process/status/.

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Acronym Finder

Abbreviation to define NUE Find abbreviation word in meaning location

Examples: NFL, NASA, PSP, HIPAA, random Word(s) in meaning: chat "global warming" Postal codes: USA: 81657, Canada: T5A 0A7

What does NUE stand for?

NUE stands for Nitrogen Use Efficiency

Suggest new definition

This definition appears frequently and is found in the following Acronym Finder categories:

- Science, medicine, engineering, etc.

See other **definitions of NUE**

Other Resources:
We have 10 other **meanings of NUE** in our Acronym Attic

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FEATURED VIDEOS

the lap of luxury
the lap of luxury A luxurious and comfortable lifestyle due to one's abundant money and resources. After winning the lottery, they moved to Paris so they could live in the lap...

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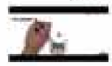
take (one's) picture
take (one's) picture To take a photograph of one. Don't take my picture—I'm only in my dressing gown! Hi...



(as) stiff as a board
(as) stiff as a board Very straight, rigid, or inflexible. Used to describe someone's physical posture or...

spring a leak
spring a leak To suddenly begin leaking liquid or gas into or out of a vessel. The tire is already flat, even...

Systems Approach to Nutrient Use Efficiency

"nutrient use efficiency" (NUE). Midwestern BioAg has been practicing soil health and nutrient use efficiency for over 30 years and is truly the leader within the Ag Industry. So why are "soil health" or "NUE" just now becoming buzz words? Industry experts and growers are starting to understand that there is no silver bullet, no one product or practice to get to soil health or improved NUE. Only Midwestern BioAg can help you un-lock NUE in your fields.

Impacts of Nutrient Use Efficiency

Let's look at your crop and soil performance in a socioeconomic manner. As world population grows, 9 billion people projected by the year 2050, growers need to produce more food to keep up with demand. The US Corn Yield trend-line has been increasing for the last 20 years (figure 1):

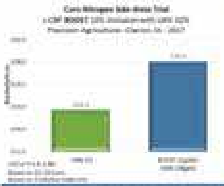
As yields increase, more nutrients are needed to be added to replace the nutrients removed in the

price volatility. Improving the return on fertilizer purchased is a must, it and starts with a healthy soil. Keeping fertilizer where it is applied is also critical. No one wants to see their nitrogen, let alone fertilizer dollars, flow down the Mississippi River or infiltrate Lake Erie or any other sensitive environmental watershed. Another aspect of NUE is social. Consumers are demanding healthier foods. Healthier food starts with healthier soils and protecting the environment in a sustainable way is essential to this process.

Soil health and NUE are all in the "Carbon" SYSTEM.

The system approach to farming, one that Midwestern BioAg has perfected, is the only way to optimize NUE and soil health. A simple start to building your farming system this spring is for you to take advantage of carbon delivery. Carbon is important as a food source for native soil biology. Carbon in the products in the subheadings below stimulates soil biology and improves NUE once they are applied.

balanced nutrients in a carbon-delivery system. TerraNu Nutrient Technology is a granulated fertilizer that is homogenized with essential nutrients for plant growth. Midwestern BioAg can customize your fertilizer blend to optimize TerraNu inclusion for your field. Ask us today!



Incorporate L-CBF products into your fertility system as a starter fertilizer or a blend companion.

L-CBF products are another great way to deliver essential nutrients to your crop in a carbon delivery system. Growers utilizing liquid starter fertilizer can take advantage of the benefits L-CBF 7-21-3 either in-furrow or in 2×2. Growers can also add L-CBF Boost into their side-dress or foliar applications. L-CBF Boost has shown consistently promising crop response (figure 2, left). Ask your Midwestern BioAg consultant for more information today!

‹ NUTRIENT USE EFFICIENCY ON ORGANIC FARMS

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Better Farming Through Better Soil. CONTACT A SALES CONSULTANT

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Promoting Healthy Environment through Enhanced Nitrogen Use Efficiency and Improved Crop Yields by using Calcium Carbide

By Ahmad Zeshan[1], Zia-ul-Hassan Shah[1] and Dr. Muhammad Arshad[2]
December 2006

1. Agriculture Chemist (Soils), presently Higher Education Commission Pakistan PhD Scholars
2. Professor and Director; PhD from University of California, Riverside, USA

The Authors conduct research at the Institute of Soil and Environmental Sciences at the University of Agriculture in Faisalabad, Pakistan.

Pakistan is basically an agricultural country and its economy is mainly agrarian. Agriculture is the biggest sector of the economy and contributes approximately 25% of GDP of the country (FAO, 2004). Pakistan, like many developing countries of the world, has been facing the problem of low agricultural productivity. One of the main reasons of low yields is the low fertilizer use efficiency, especially low nitrogen use efficiency (NUE) which is in no case more than 60% (Ahmad and Rashid, 2003). It means that about 40% of the applied nitrogen is lost. Consequently, it not only plays havoc with the sustainable crop production but also badly affects the environmental health. By estimating Pakistan's monetary loss due to low NUE during 2004-05, we come to this terrifying conclusion that out of a total consumption of about 2.8 million tonnes of nitrogenous fertilizers (MINFAL, 2006), 1.2 million tones is lost to the environments, causing a loss in national wealth of about 186 million US dollars. Another aspect is the large crop yield gaps, brought about by this low NUE, which further elevates the national economic losses. Hence, the gravity of the situation is direly demanding sound strategies to come up with workable solutions to improve the NUE, not only for improving agricultural productivity but also for cleaning the environments.

A wide range of products are being used to improve the growth and yield of crops. The use of plant growth regulators for this purpose has consistent success stories. The application of exogenous hormones has been found useful in increasing crop production (Fathima and Balasubramanian, 2006). Calcium carbide (CaC_2) is a rich source of the nitrification inhibitor acetylene and the plant hormone ethylene. It releases acetylene gas upon its reaction with water (Yaseen et al., 2006) and increases the concentration of the plant hormone ethylene in soil air as a result of microbial reduction of acetylene (Bibik et al., 1995; Arshad and Frankenberger, 2002; Khalid et al., 2006a). Acetylene inhibits the activity of ammonia-oxidizing enzyme involved in the nitrification process. (Porter, 1992; Chen et al., 1994). This inhibits nitrification and denitrification processes and increases NUE (Sahrawat, 1989; Keerthisinghe et al., 1996; Thompson, 1996; Aulakh et al., 2001). Ethylene formed from biotic reduction of acetylene may accumulate in soil at physiologically active concentrations. Ethylene is a potent plant growth regulator involved in almost all the phases of plant growth and development, ranging from germination of seed to senescence of various organs (Muromstev et al., 1995; Arshad and Frankenberger, 2002).

The use of ethylene for the improvement of agricultural production has been limited because of its gaseous nature and therefore difficulty in its direct application to soil in the field. In the late 1960s, application of ethylene in liquid form under the trade name 'Ethephone' was a great breakthrough (Cooke and Randall, 1968; Sterry, 1969). At present, various ethylene releasing sources are available in market such as methionine, ethrel, CaC_2, etc. (Bibik et al., 1995; Akhtar et al., 2005; Khalid et al., 2006a and Khalid et al., 2006b). The use of CaC_2 has a dual benefit since it can act as a source of acetylene as well as ethylene gases, thereby improving growth and yield of crops.

CaC_2 improves plant growth due to its double action, i.e. reducing N losses by acting as a nitrification inhibitor and by releasing a physiologically active concentration of ethylene to the soil. Moreover, partial inhibition of the nitrification process may release both nitrate and ammonium forms of nitrogen in the soil and this co-provision could have a synergistic effect on total nitrogen fluxes compared with the supply of either nitrate or ammonium forms alone (Lin et al., 2005).

Major crops such as wheat, rice, cotton and sugarcane occupy a central position in agricultural policies. So there is need to increase the production of these crops substantially by using non-conventional technologies. The use of CaC_2 based formulation is an innovative approach to improve the growth and yield of crops.

The effectiveness of CaC_2 in improving the growth, yield and NUE of different crops is demonstrated in the results of various studies conducted globally. Table 1 presents some results of improved NUE as a [illegible] result of the application of encapsulated CaC_2. According to one study, about 50% of the applied N was lost when urea was broadcasted into flooded water. Total N losses were significantly reduced when urea was either incorporated or deep placed in the presence of encapsulated CaC_2 These losses were further reduced and the lowest loss (34%) was noted when urea was deep placed with encapsulated CaC_2 (Keerthisinghe et al., 1996).

Table 1 · Nitrogen Use Efficiency (NUE)

Crop	Nature of Study	NUE (%)	Reference
Wheat	Pot	> 60	Yaseen et al., 2006
Cotton	Pot	> 60	Yaseen et al., 2006
Rice	Field	66	Keerthisinghe et al., 1996

In some other field and pot experiments, conducted to investigate the effect of CaC_2 on growth and yield of rice, wheat and cotton crops, the encapsulated CaC_2 released large amount of acetylene that was slowly reduced to ethylene. It was observed that CaC_2 slowed down the release of nitrate from the applied urea, which might help in improving N use efficiency (Yaseen et al., 2004)

Research on the subject explained that the addition of wax coated CaC_2 effectively inhibited the process of nitrification. The effectiveness of a urease inhibitor could not be judged solely from ammonical N concentrations in flooded water of a single treatment with the inhibitor. However, treatment with N-butylthiophosphoric triamide (NBPT) reduced ammonia losses and increased grain yield of rice up to 31% (Chaiwanakupt et al., 1996, Table 2.)

Table 2 · Benefits of using CaC_2 in Improving Crop Growth and Yield

Crop	Nature of Study	Increase in	Reference
Wheat	Pot	number of tillers by 46%	Yaseen et al., 2006
		root weight by 15%	
		straw yield by 33%	
		grain yield by 37%	
Rice	Field	grain yield by 31%	Chaiwanakupt et al., 1996
		grain yield by 20%	Yaseen et al., 2005
Cotton	Pot	number of bolls by 39%	Yaseen et al., 2006
		seed cotton yield by 31%	
		shoot weight by 28%	

Some researchers showed that ethylene might play a role in rice grain quality. They sprayed AVG (aminoethoxyvinylglycine, an inhibitor of ethylene biosynthesis) or Ethephon from anthesis to grain ripeness. They found that ethylene production increased during flag leaf senescence and panicle ripening and starch concentration increased significantly in grains (Carbone and Vidal, 1997).

It was studied that ethylene increases the adventitious root formation in rice in early developmental stages which increases the nutrient uptake and growth of rice when applied in the form of Ethephon or 1-aminocyclopropane-1-carboxylic acid that is the direct natural precursor of acetylene and is converted to ethylene by endogenous 1-aminocyclopropane-1-carboxylic acid oxidase activity at optimal concentration without side effects (Lorbiecke and Sauter, 1999).

The research conducted at the Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, revealed the usefulness of CaC_2 application to wheat and cotton crops. In a pot experiment, the effect of time of application of encapsulated CaC_2 was studied with and without NPK fertilizers on growth and yield of wheat. The study showed that plants responded positively to CaC_2 application (60 kg ha^{-1}). CaC_2 treatment after one weak of germination was most effective in increasing number of tillers, length of spikes, number of spikelets, total biological yield, straw and grain yield of wheat (Mahmood et al., 2002). In two other pot trials conducted on wheat and cotton, it was found that encapsulated CaC_2 applied at 30 mg kg^{-1} soil significantly increased the number of tillers (45.5%), root weight (14.9%), straw (32.8%) and grain yield (37.3%) of wheat over the fertilizer application alone (Table 2). In case of cotton, the number of bolls, root weight and seed cotton weight were also increased by 38.5%, 24.5% and 31.0%, respectively (Table 2), in response to the application of encapsulated CaC_2 at 60 mg kg^{-1}. However, increase in shoot weight was 28.1% due to encapsulated CaC_2 applied at 30 mg kg^{-1}. Moreover, application of encapsulated CaC_2 resulted in greater NUE of >60% (Table 1) by both wheat and cotton crops than that observed at the same rates of N fertilizer alone (Yaseen et al., 2006).

In a field experiment involving rice crop, it was observed that the encapsulated CaC_2 applied alone or along with chemical fertilizer significantly increased early emergence of panicle, number of tillers and paddy

NUE CHARGE G

A **VERDESIAN** NUE™ SOLUTION

NUE-Charge® G

Nitrogen Use Efficiency Technology

Nitrogen Use Efficiency. Lasting protection. Consistent coverage.

NUE-Charge® G provides long-lasting protection of treated granular nitrogen fertilizers from volatilization, leaching and denitrification. Its innovative granular formulation keeps more nitrogen in the root zone longer, allowing plants to access essential nutrients when they are needed most.

When compared to other nitrogen products, NUE-Charge G creates significantly less buildup on steel equipment, meaning less wear and tear, down-time and expense. It also offers consistent, uniform coverage when blended with dry nitrogen fertilizers, which directly correlates to a more even distribution of N across the field.

When pretreated on urea, ammonium sulfate, or a blend of these fertilizers, NUE-Charge G results in months of protection, rather than days, and can be stored indefinitely without loss in quality. In addition, it offers simple handling and spreading on urea and other dry nitrogen fertilizers, making NUE-Charge G a long-lasting, hard-working technology that delivers strong results and peace of mind.

NUE-Charge G is a critical part of your nutrient plan and best management practices when incorporating 4R Nutrient Stewardship, protecting your nitrogen from loss to the environment by providing better uptake availability to the plant, growing a stronger, healthier plant capable of yielding a better crop.

The details

- Next Generation T5 Polymer
- Protects against three forms of N loss
- Protects soil health and water quality
- 50-90% less buildup on equipment
- Can be stored indefinitely with no loss in quality
- Works well in all weather conditions
- Part of Nitrogen Use Efficiency and 4R Nutrient Stewardship

CHOOSE ANOTHER PRODUCT

Application Guidelines

- Broadcast
- Fertigation
- Foliar
- In-Furrow
- Post-harvest

Formulations

NUE-Charge® G

Downloads & Printables

Nue Charge Sell Sheet 9.7.2018

Packaging

2.5 Gal. | 250 Gal. Tote

Application Guidelines

Always read and follow label instructions and restrictions before use.

TRIAL DATA

9.0 bu. / acre advantage over untreated control*

*based on historic performance of similar chemistries and mode of action.

Videos

About NUE-Charge G

About NUE-Charge G

Related Products

Application Guidelines Legend

Ask a Specialist · Broadcast · Fertigation · Foliar · In Furrow · Post-harvest · Seed Treatments & Inoculants

more than manure — A VERDESIAN NUE™ SOLUTION

More Than Manure® Nutrient Manager reduces farm odors while protecting your manure's phosphorus and nitrogen for improved plant uptake.

TAKE OFF — A VERDESIAN NUE™ SOLUTION

Take Off® is a revolutionary nitrogen-management technology that accelerates nutrient acquisition and assimilation as well as nitrogen use efficiency.

TAKE OFF LS — A VERDESIAN NUE™ SOLUTION

Take Off® LS is a revolutionary nitrogen-management technology that accelerates nutrient acquisition and assimilation as well as nitrogen use efficiency.

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Subject:	U.S. TRADEMARK APPLICATION NO. 88123749 - A VERDESIAN NUE SOLUTION - 65666/520670
Sent:	12/28/2018 1:38:02 PM
Sent As:	ECOM107@USPTO.GOV
Attachments:	

UNITED STATES PATENT AND TRADEMARK OFFICE (USPTO)

IMPORTANT NOTICE REGARDING YOUR U.S. TRADEMARK APPLICATION

USPTO OFFICE ACTION (OFFICIAL LETTER) HAS ISSUED
ON **12/28/2018** FOR U.S. APPLICATION SERIAL NO. 88123749

Please follow the instructions below:

(1) TO READ THE LETTER: Click on this link or go to http://tsdr.uspto.gov, enter the U.S. application serial number, and click on "Documents."

The Office action may not be immediately viewable, to allow for necessary system updates of the application, but will be available within 24 hours of this e-mail notification.

(2) TIMELY RESPONSE IS REQUIRED: Please carefully review the Office action to determine (1) how to respond, and (2) the applicable response time period. Your response deadline will be calculated from **12/28/2018** (*or sooner if specified in the Office action*). A response transmitted through the Trademark Electronic Application System (TEAS) must be received before midnight **Eastern Time** of the last day of the response period. For information regarding response time periods, see http://www.uspto.gov/trademarks/process/status/responsetime.jsp.

Do NOT hit "Reply" to this e-mail notification, or otherwise e-mail your response because the USPTO does NOT accept e-mails as responses to Office actions. Instead, the USPTO recommends that you respond online using the TEAS response form located at http://www.uspto.gov/trademarks/teas/response_forms.jsp.

(3) QUESTIONS: For questions about the contents of the Office action itself, please contact the assigned trademark examining attorney. For *technical* assistance in accessing or viewing the Office action in the Trademark Status and Document Retrieval (TSDR) system, please e-mail TSDR@uspto.gov.

WARNING

Failure to file the required response by the applicable response deadline will result in the ABANDONMENT of your application. For more information regarding abandonment, see http://www.uspto.gov/trademarks/basics/abandon.jsp.

PRIVATE COMPANY SOLICITATIONS REGARDING YOUR APPLICATION: Private companies **not** associated with the USPTO are using information provided in trademark applications to mail or e-mail trademark-related solicitations. These companies often use names that closely resemble the USPTO and their solicitations may look like an official government document. Many solicitations require that you pay "fees."

Please carefully review all correspondence you receive regarding this application to make sure that you are responding to an official document from the USPTO rather than a private company solicitation. All official USPTO correspondence will be mailed only from the "United States Patent and Trademark Office" in Alexandria, VA; or sent by e-mail from the domain "@uspto.gov." For more information on how to handle private company solicitations, see http://www.uspto.gov/trademarks/solicitation_warnings.jsp.

EXHIBIT 6

Response to Office Action

The table below presents the data as entered.

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LAW OFFICE ASSIGNED	LAW OFFICE 107
MARK SECTION	
MARK	https://tmng-al.uspto.gov/resting2/api/img/88123749/large
LITERAL ELEMENT	A VERDESIAN NUE SOLUTION
STANDARD CHARACTERS	YES
USPTO-GENERATED IMAGE	YES
MARK STATEMENT	The mark consists of standard characters, without claim to any particular font style, size or color.
ADDITIONAL STATEMENTS SECTION	
DISCLAIMER	No claim is made to the exclusive right to use NUE apart from the mark as shown.
SIGNATURE SECTION	
RESPONSE SIGNATURE	/sch/
SIGNATORY'S NAME	Sarah C. Hsia
SIGNATORY'S POSITION	Attorney of Record, NY bar member
SIGNATORY'S PHONE NUMBER	8447633347
DATE SIGNED	06/18/2019
AUTHORIZED SIGNATORY	YES
FILING INFORMATION SECTION	
SUBMIT DATE	Tue Jun 18 17:19:21 EDT 2019
TEAS STAMP	USPTO/ROA-XXX.XXX.XXX.XXX -20190618171921442871-881 23749-620baeb8c4ba5b3805a 94a457ef78c31cc77540ef978 f513fc8522e5b72e522a65b-N /A-N/A-201906181718083852 28

Response to Office Action

To the Commissioner for Trademarks:

Application serial no. **88123749** A VERDESIAN NUE SOLUTION(Standard Characters, see https://tmng-al.uspto.gov/resting2/api/img/88123749/large) has been amended as follows:

ADDITIONAL STATEMENTS
Disclaimer
No claim is made to the exclusive right to use NUE apart from the mark as shown.

SIGNATURE(S)
Response Signature
Signature: /sch/   Date: 06/18/2019
Signatory's Name: Sarah C. Hsia
Signatory's Position: Attorney of Record, NY bar member

Signatory's Phone Number: 8447633347

The signatory has confirmed that he/she is an attorney who is a member in good standing of the bar of the highest court of a U.S. state, which includes the District of Columbia, Puerto Rico, and other federal territories and possessions; and he/she is currently the owner's/holder's attorney or an associate thereof; and to the best of his/her knowledge, if prior to his/her appointment another U.S. attorney or a Canadian attorney/agent not currently associated with his/her company/firm previously represented the owner/holder in this matter: (1) the owner/holder has filed or is concurrently filing a signed revocation of or substitute power of attorney with the USPTO; (2) the USPTO has granted the request of the prior representative to withdraw; (3) the owner/holder has filed a power of attorney appointing him/her in this matter; or (4) the owner's/holder's appointed U.S. attorney or Canadian attorney/agent has filed a power of attorney appointing him/her as an associate attorney in this matter.

Serial Number: 88123749
Internet Transmission Date: Tue Jun 18 17:19:21 EDT 2019
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