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The use of agricultural resources for global food supply

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2015

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Ibarrola Rivas, M. J. (2015). The use of agricultural resources for global food supply: Understanding its dynamics and regional diversity. [Groningen]: University of Groningen.

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Summary

By María José Ibarrola Rivas

The use of resources for human consumption is reaching the limits of the planet, and global food production plays an important part. Food is essential to maintain life and all persons should have a daily supply of food. The production of this food requires large amount of resources. Future global food demand will increase so a sustainable food system is needed: enough food for all people with the lowest environmental impact.

The amount of resources depends on the number of people (population), on their type of food pattern (diets) and on how the food was produced (agricultural production system). The dynamics of these three factors depend on drivers of different disciplines such as socioeconomic development, urbanization, demography, culture, geography, climate, agricultural practices and others.

This thesis takes a food demand perspective to analyse the use of agricultural resources for food production: land, water, nutrients and labour. The aim is to assess the impact of food demand on the use of agricultural resources taking into account the dynamics and regional diversity of population numbers, diets and agricultural systems. A methodology was developed to integrate in one analysis regional differences, interdisciplinary indicators and trade-offs among resources. Chapters 2 to 6 study in detail the main trends of the last decades and/or the relevant regional differences. The main findings of these chapters were used to assess the future sustainability of the global food system (chapter 7).

The availability of land and water for food production is analysed in chapter 2. The study shows that the per capita availability of land and water is unequally distributed between poor and rich countries. Population growth in the poor countries will increase this inequality. By 2050, one third of global population (the richest) will have 3 times more land per capita than the rest. The other two thirds of the population (the poorest) will not have enough land to produce food for an affluent diet. An affluent diet is commonly composed of luxurious products such as animal food products, fruits, vegetables and processed food

items. The people expected to change to affluent diets are the ones with the lowest availability of land and water.

The low availability of land indicates a need for intensification: high amount of food production per area. This is further studied in chapter 3. Intensification is analysed in relation to the nitrogen application rate. A farm scale model integrates: population density, diets and nitrogen fertilizer application rate. The study shows that the nitrogen application highly increases with the reduction of land availability and the type of diet parallels this relation. The food production for an affluent diet in countries with large land availability requires a much lower nitrogen application rate in comparison with a similar diet in countries with low land availability.

The strong trade-off between nitrogen fertilizer and land is studied in detail in chapter 4. Nitrogen fertilizer use per person and its trade-off with land was calculated for five combinations of production systems and diets illustrating the global differences. The global differences in use of resources are enormous: from 3 to 30 kilograms of nitrogen fertilizer per person, and from 1800 to 4500 m2 per person. The methodology used in this chapter allows to identify the impact of production systems and diets individually. Affluent diets in all systems require 4 times more nitrogen fertilizer and land than staple food diets.

In addition to production potentials, the use of agricultural labour in relation to diets and production systems is studied in chapter 5. The hours of farm labour needed for an affluent and a staple diet were calculated using the extreme examples of a mechanized and a non-mechanized production system. Only 5 hours of farm labour are needed to produce an affluent diet in a mechanized system. The increase of labour efficiency with mechanization is enormous: 200 times less farm labour is needed for a person's diet with a mechanized system. The type of diet also plays an important role: affluent diets need two times more farm labour than staple diets. These insights are useful to discuss the trade-off between labour and energy use related with machinery use.

The global differences in diets were studied in detail in chapter 6 due to the strong impact of the dietary patterns on the use of resources. The study shows that regional dietary paths have been stronger than global food pattern trends. So, future changes in diets will follow current regional dietary composition. These regional differences have a strong impact on the use of resources. For an

affluent diet, the type of meat consumed can change the use of resources by a factor of two. Some regions have traditional vegetarian diets with dairy products which do not necessarily use fewer resources than diets with large consumption of meat.

Future demand for resources will be different among regions because of different socioeconomic, geographical and cultural situations. By combining the insights of this thesis, an accumulation of challenges to achieve food supply is identified for a certain group of the global population (chapter 7). By 2050, 70% of global population (the poorest) will live in countries with very low land availability. These people are the ones expected to increase food demand due to population growth and dietary changes. So, strong intensification is required to increase food production per area. Based on our analysis, future needs for nitrogen fertilizer will be higher than the ones projected in other studies. Energy use for agriculture will strongly increase in some of these countries not only because of the increase of nitrogen fertilizer use but also because of the increase in machinery use, which will result in huge increase of farm labour efficiency. Dietary choices could play an important role in the use of resources.

This thesis shows that in order to assess the future of the global food system, it is necessary to have a global perspective and, at the same time, to take into account the relevant regional differences of socioeconomic development, population density, diets, culture and availability of resources. This perspective allows having an integrative understanding of the major factors driving the use of resources and results in new insights for finding sustainable solutions.

Resumen

Por María José Ibarrola Rivas

El uso de recursos naturales para el consumo humano está alcanzando los límites del planeta, y la producción de alimento juega un papel importante en el uso de éstos. Comer diariamente es esencial para la vida y todas las personas del planeta deben tener un suministro diario de alimento. Producir nuestra comida requiere una gran cantidad de recursos. La demanda de alimento aumentará en las siguientes décadas, lo que significa que es esencial que el sistema global de producción de alimento sea sustentable: suficiente para todas las personas y con el menor impacto ambiental posible.

La cantidad de recursos para producir el alimento depende de la cantidad de personas (población), del tipo de alimentación (dietas) y de cómo se produce el alimento (sistemas de producción agrícola). La dinámica de estos tres factores depende de indicadores de diferentes disciplinas como por ejemplo del desarrollo socioeconómico de la población, del grado de urbanización, de la cultura, de la geografía, del clima y de las prácticas agrícolas, entre otros.

Esta tesis toma la perspectiva de la demanda de alimento para estudiar el uso de los recursos agrícolas, en concreto el uso de tierra, agua, nutrientes y trabajo. El objetivo principal es evaluar el impacto de la demanda de alimento en el uso de los recursos agrícolas tomando en cuenta los cambios desde los años 60's y las diferencias regionales en cuanto al tamaño de la población, al tipo de dietas y al tipo de los sistemas agrícolas. Se desarrolló una metodología para integrar en un mismo análisis las diferencias regionales, los indicadores interdisciplinarios y la compensación entre el uso de un recurso agrícola y otro. En los capítulos 2 al 6 se estudian en detalle las principales tendencias de las últimas décadas y las diferencias regionales del uso de los recursos. Las conclusiones de estos capítulos se utilizan en el capítulo 7 para evaluar la sustentabilidad del suministro mundial de alimento para el año 2050.

La disponibilidad de tierra y agua para la producción de alimento se analiza en el capítulo 2. Este estudio demuestra que la disponibilidad per cápita de tierra y agua está distribuida desigualmente entre los países pobres y ricos. Esta desigualdad aumentará por el gran crecimiento demográfico de los países pobres. En el año 2050, una tercera parte de la población mundial (la más rica)

tendrá tres veces más tierra per cápita que el resto de la población. Las otras dos terceras partes (los más pobres) no tendrán suficiente tierra para producir los alimentos para una dieta afluente. Una dieta afluente es considerada como aquella compuesta por alimentos de origen animal, frutas, verduras y alimentos procesados. Las personas que cambiarán a dietas afluentes vivirán en los países con la menor disponibilidad de tierra y agua.

La poca disponibilidad de tierra indica una necesidad de intensificar la producción de alimento: aumentar la producción por unidad de área. Esto es estudiado con más detalle en el capítulo 3. La intensificación se analiza en relación a la aplicación de fertilizante de nitrógeno. Para esto, se utiliza un modelo que integra tres factores que afectan el uso de fertilizantes directa o indirectamente: la densidad de población, el tipo de dieta y la tasa de aplicación de nitrógeno. El estudio demuestra que la aplicación de nitrógeno aumenta exponencialmente con la reducción en la disponibilidad de tierra; adicionalmente el tipo de dieta aumenta esta relación. Los países en los que la población tiene dietas afluentes y poca disponibilidad de tierra aplican mucho más fertilizantes de nitrógeno en comparación a los países con dietas similares y alta disponibilidad de tierra.

La clara relación entre el uso de fertilizantes de nitrógeno y el uso de tierra es estudiada en detalle en el capítulo 4. Para esto se calcula el uso per cápita de tierra agrícola y de fertilizante de nitrógeno para cinco diferentes tipos de dieta y cinco tipos de sistemas agrícolas que ilustran las diferencias globales. Los resultados demuestran diferencias enormes en el uso de fertilizantes y tierra: de 3 a 30 kilogramos de nitrógeno por persona y de 1 800 a 4 500 m^2 de tierra agrícola por persona. La metodología utilizada en este capítulo permite identificar por separado el impacto de los sistemas agrícolas y del tipo de dietas. Por ejemplo, las dietas afluentes requieren cuatro veces más fertilizantes y tierra que las dietas más básicas.

El uso de trabajo agrícola en relación al tipo de dietas y al sistema agrícola es estudiado en el capítulo 5. En este capítulo se calculan las horas de trabajo agrícola necesarias para producir el alimento que una persona consume en un año. Se analizan cuatro escenarios diferentes ilustrando los extremos de tipos de dietas (básica y afluente) y de tipos de producción en relación a la mano de obra (mecanizados y no mecanizados). Los resultados demuestran que sólo se necesitan cinco horas de mano de obra agrícola en un sistema mecanizado para producir el alimento anual que una persona consume con dieta afluente. El

aumento de la eficiencia en la mano de obra con la mecanización es enorme. Se necesitan 200 veces más horas de trabajo con un sistema no mecanizado a diferencia de uno mecanizado. El tipo de dieta también juega un papel importante. Las dietas afluentes requieren dos veces más horas de trabajo a diferencia de una dieta básica. Estos resultados pueden ser utilizados para discutir el uso de energía para la mecanización.

Las diferencias en el tipo de alimentación a nivel mundial son estudiadas en el capítulo 6. Los resultados demuestran que los cambios en las dietas, siguiendo patrones regionales, son más recurrentes que siguiendo patrones globales. Por lo tanto, se puede esperar que en el futuro la población siga las tendencias regionales y no las globales. Estas diferencias regionales tienen un gran impacto en el uso de recursos. Por ejemplo, el consumo de carne difiere entre una región y otra. Para una misma dieta afluente, el uso de recursos agrícolas puede duplicarse por el tipo de carne dependiendo del consumo regional.

El uso de los recursos agrícolas en las siguientes décadas será diferente en cada región del mundo. Estas diferencias dependerán de la situación socioeconómica, geográfica y cultural de cada región. Con los resultados de esta tesis es posible identificar una acumulación de retos para el suministro de alimento para un grupo específico de la población mundial (capítulo 7). En el año 2050, el 70% de la población mundial (los más pobres) vivirán en países con muy baja disponibilidad de tierra. Son estos países en los que se espera que aumente la demanda de alimento debido al crecimiento poblacional y a los cambios en los patrones alimenticios. Por lo tanto, en estos países se necesita intensificar los sistemas de producción agrícola: más alimento producido por unidad de área. Con los resultados de esta tesis se estima que el uso global de fertilizantes de nitrógeno será superior al proyectado en otros estudios. Así mismo, el uso de energía para la agricultura aumentará enormemente en algunos países no sólo por el aumento indirecto en relación al uso de fertilizantes sino también por el aumento en mecanización. Este último aumentará enormemente la eficiencia en la mano de obra agrícola.

En conclusión, esta tesis demuestra que para evaluar el futuro del suministro mundial de alimento es necesario tener una perspectiva global y al mismo tiempo tomar en cuenta las diferencias regionales relevantes en cuanto al desarrollo socioeconómico, la densidad de población, los patrones alimenticios, la cultura y la disponibilidad de recursos agrícolas. Este enfoque permite obtener un entendimiento integral de los principales factores que afectan al uso

de los recursos agrícolas obteniendo nuevos resultados que proponen nuevas ideas para la sustentabilidad del suministro mundial de alimento.

Samenvatting

By Sanderine Nonhebel

In de komende jaren zal de wereldbevolking toenemen naar 9 miljard mensen. Om deze mensen te voeden zal er meer voedsel geproduceerd moeten worden. De hoeveelheid voor landbouw geschikte grond in de wereld is beperkt en er zijn grote regionale verschillen. Hetzelfde geldt voor de beschikbaarheid van zoet water. Hoeveel voedsel je kunt produceren op een stukje grond hangt af van het gekozen productiesysteem. Je kunt in principe een gewas verbouwen zonder externe inputs, door gebruik te maken van de natuurlijke bodemvruchtbaarheid en handelingen op de akker met de hand uit te voeren (extensieve productie). In dat geval is de opbrengst laag en is er veel arbeid in het veld nodig. Door kunstmest te gebruiken kan de productie per oppervlakte worden verhoogd en door het gebruik van machines kan de arbeidsinzet worden verlaagd. Voor de productie van kunstmest is veel energie nodig en voor het gebruik van machines ook. Het gebruik van kunstmest heeft daarnaast grote gevolgen voor de wereldwijde nutriënten kringloop.

Hoeveel voedsel we nodig hebben hangt niet alleen af van het aantal mensen, maar ook wat deze mensen eten. Een dieet met veel dierlijke producten vraagt meer grondstoffen dan een vegetarisch dieet. In China is de laatste 20 jaar de vleesconsumptie verdubbeld en naar verwachting zullen meer landen dit voorbeeld volgen. In de komende decennia verwachten we dus meer mensen, die meer vlees gaan eten, die allemaal van een beperkt landbouwareaal gevoed moeten gaan worden. De productie per hectare van dit areaal kan verhoogd worden door het gebruik van kunstmest, alleen heeft dat gevolgen voor het milieu.

De te verwachten veranderingen in bevolkingsaantallen, consumptiepatronen etc. verschillen sterk voor de verschillende gebieden op aarde; de verwachte bevolkingsgroei bijvoorbeeld vindt vooral plaats in de arme landen. Daarom wordt in dit proefschrift onderscheid gemaakt tussen de verschillende regio's op aarde. Voor al deze regio's wordt onderzocht hoe de veranderende vraag naar voedsel invloed heeft op het gebruik van de beschikbare hoeveelheid landbouwgrond en water en hoeveel energie (met name kunstmest) en nodig is om voldoende te kunnen produceren.

Eerst wordt er nagegaan hoeveel land en water er in de verschillende regio's beschikbaar is voor de productie van voedsel en hoe dit in de komende decennia zal veranderen door de te verwachten bevolkingsgroei (hoofdstuk 2). Op het moment zijn er grote verschillen: in sommige gebieden is er meer dan 5000 m2 landbouwgrond per persoon beschikbaar, maar in andere minder dan 1000 m2. Aangezien de bevolkingstoename vooral in de arme regio's plaats vindt, zien we dat in die regio's de beschikbaarheid van landbouwgrond per persoon sterk afneemt. In 2050 zal een groot deel van de wereldbevolking (70%) in gebieden wonen met minder dan 1000 m2 landbouwgrond per persoon.

Deze beperkte beschikbaarheid aan landbouwgrond in veel regio's betekent dat er landbouwsystemen met hoge opbrengsten per oppervlakte nodig zijn om genoeg voedsel te produceren voor de bevolking. De relatie tussen landgebruik en kunstmestgebruik en het voedingspatroon onderzocht in hoofdstuk 3. Hier wordt duidelijk dat met name de combinatie van hoge bevolkingsdichtheid en een consumptiepatroon met veel dierlijke producten een grote vraag naar kunstmest met zich meebrengt.

In hoofdstuk 4 wordt dit nader onderzocht: voor verschillende soorten voedingspatronen wordt de kunstmest behoefte uitgerekend. Er wordt gerekend aan een karig dieet, voornamelijk bestaande uit granen, peulvruchten en wortels (het gemiddelde dieet in ontwikkelingslanden) een transitiedieet (met beperkte consumptie van dierlijke producten, kenmerkend voor de opkomende economieën) en een Westers dieet met heel veel luxeproducten als vlees, zuivel, dranken, etc. Er blijkt 4 maal zoveel land en kunstmest nodig te zijn voor de productie van een luxueus Westers dieet dan voor een karig dieet.

We weten inmiddels dat luxueuze diëten meer grondstoffen vragen dan de karige en dat diëten over de hele wereld aan het veranderen zijn. Dan is het interessant om na te gaan op wat voor manier de diëten aan het veranderen zijn, verschuiven alle diëten richting de Westerse hamburger of zijn er regionale verschillen. Dit wordt onderzocht in hoofdstuk 6. Voor 13 regio's in de wereld worden de veranderingen in diëten over de laatste 50 jaar geanalyseerd. We zien algemene patronen (toename van de dierlijke producten), maar ook grote regionale verschillen. De regionale verschillen zitten vooral in het soort dierlijk product. In China neemt de varkensvlees consumptie toe, in India de melkconsumptie en in Latijns Amerika de rundvlees consumptie, in West Europa en Noord Amerika de consumptie van kip. Aangezien het gebruik

van hulpbronnen als land, water en energie verschilt voor de verschillende dierlijke producten hebben deze regionale voorkeuren voor vlees en zuivel gevolgen voor het gebruik van hulpbronnen voor de verschillende diëten. Regio's met grote voorkeur voor rundvlees hebben grotere hoeveelheden land, water en energie nodig voor de productie van voedsel en produceren meer broeikasgasemissies.

Er is ook energie nodig op de akker voor de mechanisatie (diesel voor de tractor). De hoeveelheid die nodig is hangt af van het gewas (hoeveel bewerkingen zijn er nodig), maar nog veel meer van de mechanisatiegraad. In principe kan alles ook met de hand gedaan worden (alleen duurt het dan wat langer). In hoofdstuk 5 wordt de farm- labour-footprint uitgerekend: hoeveel uur een boer bezig is op zijn land voor de productie van voedsel voor 1 jaar voor een persoon. Ook hier wordt er weer naar de verschillende systemen in de wereld gekeken en naar de verschillende diëten. De verschillen zijn groot. In Nederland is er maar 5 uur landbouwarbeid nodig om voor 1 persoon voedsel te produceren, in Afrika 400 uur. Ook hier heeft het dieet invloed: er is 2 keer zo veel arbeid nodig voor een dieet met vlees als voor een vegetarisch dieet.

In dit proefschrift zijn op verschillende manieren de verbanden tussen het gebruik van land, water en energie voor voedselproductie op wereldschaal geanalyseerd. De bevolkingsgroei in combinatie met veranderende voedingsgewoonten gaan een grote claim leggen op deze hulpbronnen. Deze claim is erg ongelijk verdeeld in de wereld. In Europa en Noord Amerika vindt nauwelijks verandering plaats, er is geen bevolkingsgroei en consumptiepatronen zijn al luxueus, hier zijn geen veranderingen in milieueffecten van voedselproductie te verwachten. In andere delen van de wereld vindt zowel een toename van de bevolking als een verandering van de voedselconsumptie plaats. Dit heeft tot gevolg dat in 2050 70 % van de wereldbevolking in gebieden woont met zeer beperkte beschikbaarheid van landbouwgrond. Alleen intensieve landbouwsystemen (met veel kunstmest) kunnen dan genoeg voedsel produceren om aan de vraag te voldoen. Dit zal grote gevolgen hebben voor het milieu in die regio's.

Acknowledgments

Living in Groningen has been one of the best experiences in my life: living in a foreign country, enjoying and overcoming the struggles of doing a PhD project, starting a life as a couple and growing to a family of four. I'd like to thank the people who inspired me and who helped me make things smoother during these wonderful and challenging years of my PhD.

Sanderine, my daily supervisor, thanks for your support on research and personal issues. I took literally the term "daily supervisor" since I was knocking in your door almost every day during my PhD. You taught me to be strong on my ideas, to defend and to promote my findings. Henk, my promoter, I very much enjoyed our discussions during the last year of my PhD. Ton, thanks for your positive input in my papers. Leandro, my external supervisor, you inspired me to add a social science approach in my research.

My office-mates. Thomas, you have been not only a great colleague but also a great friend. I am very happy that it has been possible to keep on collaborating after you left IVEM. Reino and Ron, talking with you during the difficulties of the last year of my PhD helped me to overcome the problems and to keep on working.

Gideon, my classmate, colleague, friend and paranimf, you are one of the sweetest person I've met. Thanks for the love you have given me and my *gezin*.

People from IVEM and SSG. I enjoyed the coffee and lunch breaks to clear my mind and to get energy to go back to work. It was nice to talk to you or just to sit around with you all.

The international summer schools that I joined in retreated places (Hokkaido, Peyresq and Noordwijk) had the best atmosphere for meeting future colleagues and for gaining inspiration from other PhD students and researchers from other countries. I met wonderful people, especially Francis, Leah and Irene.

In order to achieve a PhD project, persistence, inspiration and motivation is constantly needed. I managed to have it thanks to the great friends that I met in Groningen.

Thanks to my Dutch friends. Mieke, Tsjalling, Eduard and Colien. you have opened your home to us. Gideon, Jorien, Eva and Jeroen you showed us the coolest part of the Netherlands. Jorien, thanks for your advices about motherhood, you made it all easier. Charlotte, we have gone through so much in common these past 7 years; it has been very relaxing to talk with you during all these moments to have someone who understands and is going through the same.

Thanks to my international friends with whom we have overcome the challenges of cultural differences and we have slowly adopted some Dutch habits. Markella, we have grown together these last 7 years. You are an amazing friend. María Jesús, not only because of your strong friendship but also for the love you show to Federico.

Becoming a mother has been the most rewarding and challenging thing during these past years. Sharing this process as a foreigner with Katrina and Virginie has made it all easier, you are wonderful friends.

Thanks to my family who has been closer than ever eventhough an ocean has been separating us. Thanks to my parents and my sisters for their unconditional support and love, for their frequent Skype talks and their visits to Groningen. Thank you Guillermo and Tere for your love.

Finally, and most important, I thank my *gezin* which has started and has grown here in Groningen. The most important thing I've learned in these years has been the value of having a *gezin*. This Dutch word should exist in all languages. Julio, your motivation and example of persistence has given me the strength for finishing this project. Julio, Federico and Emilio, you are the inspiration of my life.

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María José was born in Mexico City on March 7th 1983. She did a bachelor study in Physics Engineering in the Universidad Iberoamericana in Mexico City and she has graduated with honours in May 2007. From September 2008 to August 2010, she completed the master in Energy and Environmental Sciences in the University of Groningen. On September 2010, she started her PhD at the Center for Energy and Environmental Sciences of the University of Groningen, and she has obtained the degree on May 2015.

During her PhD project, she attended several international summer schools for PhD students In 2011, she participated in the GCOE-INeT summer school *Understanding coupled natural and social systems* in Hokkaido University in Japan. In 2012, she participated in the ALTERNET summer school *on Biodiversity and Ecosystem Services* in Peyresq, France. In 2013, she participated in the summer school *Hunger Defeated?* organized by Wageningen University in the Netherlands. In 2014, she did a research visit at the Institute of Social Ecology of Alpen-Adria Universitaet in Vienna collaborating with Dr. Thomas Kastner. She obtained the certificate by the SENSE research partnership of the Netherlands (sense.nl).

Publication during the PhD project

Ibarrola Rivas, M.J., Moll, H.C. & Nonhebel, S (under review, invited paper) Future global use of resources for food: the huge impact of regional diets Global Food Security Journal

Ibarrola Rivas, M.J. & Nonhebel, S (under review) Increasing inequality between poor and rich countries as to availability of land and water by 2050. Agricultural Systems Journal

Ibarrola Rivas, M.J. & Nonhebel, S (under review) Nitrogen fertilizer use per person and its trade-off with land use: An international comparison of agricultural production systems and diets. Industrial Ecology Journal

Ibarrola Rivas, M.J., Kastner, T. & Nonhebel, S (under review) Farm labour footprint of food: an international comparison of the impact of diets and mechanization. Food Policy Journal

Ibarrola Rivas, M.J. & Nonhebel, S (under review) Estimating future global needs for nitrogen based on regional changes of food demands. Environmental Development Journal.

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Presentations at international conferences *(selection)*

Ibarrola Rivas, M.J. & Nonhebel, S (2014) *Increasing inequality on the availability of land and water between poor and rich by 2050* Oral presentation at the ISEE Conference: Wellbeing & Equity within Planetary Boundaries (August 13-15) Reykjavik University, Iceland

Ibarrola Rivas, M.J. & Nonhebel, S (2014) *Integrating the drivers for the global use of synth. Nitrogen fertilizer* Oral presentation at the 2nd GLP Open Science Meeting (March 19-21) Humboldt University, Berlin, Germany

Ibarrola Rivas, M.J. & Nonhebel, S (2013) *Global differences in diets and their relevance for the use of agricultural resources* Oral presentation at the First International Conference on Global Food Security (Sept 29- Oct 2)Noordwijkwehout, Netherlands

Ibarrola Rivas, M.J. & Nonhebel, S (2012) *Ditribution of fertilizers, land and food* Poster presentation at Planet Under Pressure (March 26-29), London, UK

Ibarrola Rivas, M.J. & Nonhebel, S (2010) *Development of land requirements for food: a matter of scale* Oral presentation at the Ester Boserup Conference (Nov 15-17), Institute of Social Ecology (SEC) Alpen-Adria Universitaet, Vienna, Austria

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- European International Relations Summer School 2012: World Society Energy and Transition (2012)

Other PhD and Advanced MSc Courses

- Presentation Skills workshop, University of Groningen, The Netherlands (2010)
- Publishing in English, University of Groningen, The Netherlands (2011)
- Understanding coupled natural and social systems: feedback loops between land-use and ecosystem change, University of Hokkaido, Japan (2011)
- Academic Teaching Skills and Course Design, University of Groningen, The Netherlands (2012)
- Publishing using Word, University of Groningen, The Netherlands (2013)
- Hunger Defeated? Long-term dynamics of global food security, Wageningen University, The Netherlands (2013)

External training at a foreign research institute

- Research visit for collaboration with Dr Thomas Kastner, Institute of Social Ecology, Alpen-Adria Univeristy, Austria (2014)

Selection of Oral Presentations

- *Development of Land Requirements for food: a matter of scale.* Ester Boserup Conference, 15-17 November 2010, Vienna, Austria
- *Global differences in diets and their relevance for the use of agricultural resources.* 1st International Conference on Global Food Security, 29 September-2 October 2013, Noordwijkerhout, The Netherlands
- *Integrating the drivers for the global use of synthetic Nitrogen fertilizer.* 2nd Global Land Project (GLP) Open Science Meeting, 19-21 March 2014, Berlin, Germany
- *Increasing inequality on the availability of land and water between poor and rich by 2050.* The International Society for Ecological Economics (ISEE) conference 2014: Well-being an equity within planetary boundaries, 13-15 August 2014, Reykjavik, Iceland

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