Estimating Nitrogen Content of Dryland Wheat Fields Using Landsat Imagery

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Authorization to Submit Thesis

This thesis of Samuel Finch, submitted for the degree of Master of Science with a Major in Environmental Science and titled "Estimating Nitrogen Content of Dryland Wheat Fields Using Landsat Imagery," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Inefficient use of synthetic nitrogen (N) fertilizers on wheat fields increases costs of production and can cause numerous undesirable environmental consequences. Specifically, increasing the efficiency of plant nitrogen uptake may decrease agricultural sources of nitrous oxide, nitrate leaching, and soil acidification, while maintaining crop yield and quality. A main cause of inefficient nitrogen fertilizer application in agricultural systems is a dearth of information about in-field nitrogen variability in crops. Though mapping the in-field variability of crop N based on red-edge (700-730 nm) providing satellite data has shown great promise, the data are not freely available, hampering widespread use. The objective of this study was to determine whether non red-edge providing, but free, publicly available Landsat imagery could be a viable alternative to red-edge providing satellite data for estimating N content in wheat. We derived field-scale N content maps by extrapolating plot-level destructive samples using commercially available red-edge providing satellite data over five farms located in the Palouse of eastern Washington and northern Idaho, USA, in 2012 and 2013. We then used these results to compare with Landsat-derived Normalized Difference Vegetation Index (NDVI) to estimate N content across all five farms. We found statistically significant ($p<0.001$) relationships between predicted N content and NDVI, with R^2 values ranging between 0.20 to 0.82, depending on the field site. Landsat-derived versus observed field-scale N content maps showed that Landsat-derived NDVI can estimate N content of wheat crops to within 13 to 28 kg ha^{-1} of the N content map created with red-edge providing satellite data. Our results suggest that freely available Landsat data could be a viable, cost-effective alternative to red-edge providing satellite data that is currently not freely available.

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Dedication

Most importantly, I could not have made it through this adventure in education without the love and support from my fiancé, Molli Lee-Painter, and our families. My friends in Moscow helped me lead a balanced life and forced me to enjoy the parts of the world I am trying to better understand and protect for the future. This dissertation is dedicated to all of you that make this world so great.

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CHAPTER 1

Introduction

Nitrogen (N) fertilizer applications to wheat (*Triticum spp.)* fields constitute a significant economic cost of production to farmers. The environmental effects of over-applying N fertilizer in industrial agriculture systems include the production of the greenhouse gas (GHG) nitrous oxide (N_2O), pollution of groundwater, eutrophication of surface water, and increased soil acidity (Erisman, Sutton, Galloway, Klimont, & Winiwarter, 2008; Vitousek, Mooney, Lubchenco, & Melillo, 1997). Developing methods to estimate the amount and spatial variation of N content in crops at the field scale is paramount for improving N fertilizer application efficiency, and has the potential to result in desirable environmental outcomes while also decreasing production cost (Erisman et al., 2008).

Environmental and ecophysiological limitations cause plants to utilize only a fraction of soil N. Globally, harvested crops utilize about 33% of N fertilizer applied to a field (Raun & Johnson, 1999). In the Palouse region of Washington and Idaho, nitrogen use efficiency for wheat ranges between 25% and 85% of available soil N (Huggins, Pan, & Smith, 2010). The fate of fertilizer-derived N not taken up by plants is diverse, with various fractions remaining in the soil, leaching into groundwater and surface water, or volatilizing to the atmosphere in various oxidized nitrogenous species (e.g. NO, N_2O) (Erisman et al., 2008). Nitrous oxide (N_2O) emissions mainly derive from agriculture through the use of synthetic nitrogen fertilizers (Forster et al., 2007) (Robertson & Vitousek, 2009). Due to N fertilizer use in agriculture, N_2O emissions have increased about 0.26% per year for the past few decades (Forster et al., 2007). The N_2O emissions from agriculture makes it the fourth most powerful GHG in terms of its global radiative forcing effect (Forster et al., 2007) and accounts for 75% of all human created N_2O emission (U.S. Environmental Protection Agency, 2015). The inefficient application of N fertilizers is the primary culprit of N_2O emissions. But, understanding spatially variable fertilizer needs for a farm field requires information that estimates and quantifies those specific needs contiguously across space (Robertson & Vitousek, 2009). Thus, accurately estimating N content in crops at the field scale using satellite imagery would allow improved management decisions to reduce the economic cost of N fertilizer application and the amount of N being lost to the environment.

Destructive sampling, low spatial resolution, and highly labor-intensive practices limit traditional techniques used for mapper crop N. Destructive sampling of wheat crops provides accurate measures of plant N content, but it also destroys the crop in the process, is time consuming, and expensive (Feng, Xiao, Zhang, Yang, & Ding, 2014; Wang et al., 2004). Hand-held chlorophyll meters have been shown to accurately predict N content in wheat crops, but since only individual leaves can be measured field-wide measurements are impracticable (Reeves et al., 1993). Tractor mounted sensors allow growers to survey crops in-season over the entire extent of their land but are costly and often their utility depends on proper sensor use and calibration (Samborski, Tremblay, & Fallon, 2009). Ideally, information about field-scale crop N content would be spatially extensive (i.e. covering entire farm fields), cheap, and easily obtained.

Early research into the ability of using remote sensing techniques to estimate N content suggested that ground-based instruments could detect N content in wheat crops using the normalized difference vegetation index (NDVI) (Sembiring et al., 1998). However, subsequent research into the usefulness of NDVI to estimate crop characteristics discovered that NDVI was generally limited in its ability to detect

Remotely sensed data acquired from satellite is an important tool for evaluating field-scale crop characteristics (REFS) because it can collect data over entire fields or regions, allowing continuous mapping of crop characteristics like N content. Early remote sensing research established links between canopy reflectance, chlorophyll concentrations, and nitrogen content

Freely available and geographically extensive remote sensing datasets have significantly improved the ability for growers to access global surface reflectance data. The Landsat project, supported and funded by the United States Geological Survey (USGS) and National Aeronautics and Space Administration (NASA), is the longest running continuously acquired satellite-based remote sensing dataset in the world (United States Geological Survey, 2015). Accordingly, it is paramount to understand the utility of this dataset with respect to real-world environmental and agricultural problems like high costs of agricultural production and environmental degradation. The ability of farm managers to obtain high quality, preprocessed satellite data free of charge could ease the burden of obtaining accurate information about the N content of wheat fields and lead to more efficient N fertilizer application. The main objective of this study was to determine whether Landsat’s High Level Science normalized difference vegetation index (NDVI) product could accurately estimate nitrogen (N) content in wheat crops. Whether Landsat NDVI data can accurately predict N content in wheat could be the difference between farm managers using public data versus commercial data. Landsat data products are also substantially easier to work with than raw, commercial remote sensing products. Thus, understanding the utility of Landsat data products could considerably improve N fertilizer management in wheat fields.

Methods

Study area

Field data was collected at four farms (Colfax, Cook, Genesee, and Troy) in the Palouse region of eastern Washington and Northern Idaho (**Figure 1: Study area 16**). Each farm contained 12 sampling sites with varying aspects within a particular field to ensure a representative sampling of the entire field. Average annual precipitation ranges from 260mm to 610mm, with the west side of the Palouse generally being dryer than the east side of the Palouse. Elevation for the field sites ranged from 683m to 828m. The average annual air temperature is 8-10 ºC across the region. All study areas are dryland farm fields that are entirely rain fed; no irrigation was used at any of the field sites.

Data

Destructive N and biomass measurements were taken just before harvest, in August and September of 2012 and 2013. *In situ* measurements of *crop* height, relative chlorophyll content (SPAD), and leaf area index (LAI), were collected at each of the 12 sampling sites once a week from Feeke's Stage 2 until harvest for 2012 and 2013. Relative chlorophyll measurements were taken with a SPAD 502 Plus Chlorophyll Meter (Konica Minolta Sensing, Inc.) by sampling 10 leafs at each sample site and averaging the results. Destructive N-concentration was sampled at each field site two to three times throughout the growing season to determine actual above ground protein and N contents. Protein and N concentrations were also calculated at harvest using a modified Kjeldhal procedure and dry combustion (Bremner and Mulvaney, 1982; Huggins et al., 2010). Using the protein concentration collected at harvest has shown to be a good estimate of total N by multiplying grain concentrations by 5.7 and assuming a 1% N concentration in dry biomass (Huggins et al, 2010). It is important to note that still ~30% of the N measured at harvest can be assimilated into the crop after peak biomass (when Landsat images were acquired) (D. Huggins, personal communication).

An N content model was built using *in situ* measurements of grain and foliar N, as outlined by Magney et al. (*in prep*) and Huggins et al. (2010). Grain N concentrations at each field site were determined using dry combustion to calculate grain protein concentrations, dividing grain protein concentrations by 5.7, and multiplying percent N in the grain by yield (kg/ha) (Huggins et al., 2010). Foliar N was calculated by multiplying grain N concentrations by 0.01, or 1%, and then multiplying by above ground biomass. Total above ground N content was then calculated by adding grain N content to foliar N content. Regression analyses between above ground N content and seventeen vegetation indices determined the best predictor of N content to be the normalized difference red-edge index (Magney et. al., *in prep*).

Rapid Eye satellite images were acquired at the closest date possible to peak biomass at each of the field sites, which were based on vegetation index analysis by Magney et. al., 2015 (*in prep*) (Figure 2). Rapid Eye 3A level images were processed in Environment for Visualizing Images (ENVI) image analysis software (Exelis Visual Information Solutions) to create normalized difference red-edge index (NDRE) maps. The N content model from Magney et al. (in prep.), was applied to the Rapid Eye NDRE maps to create Rapid Eye N content maps. The RapidEye-derived NDRE explained 72% of the variance in N content for all available field samples (Magney et al., in prep.). These data allowed continuous maps of

N content to be produced for all farms at the 5m x 5m scale. The N content maps were then resampled to 30x30m using nearest neighbor resampling to match the spatial resolution of Landsat. Each pixel in the resulting image had a value of N content in kg ha^{-1}. Pre-processed Landsat NDVI images were obtained from USGS Bulk Data Download web interface (Landsat High Level Science Data Products courtesy of the USGS). Rapid Eye Images were georeferenced to Landsat images and resampled to an RMSE of <0.5 pixel. Spatial subsets of both the Rapid Eye and Landsat images were taken to encompass each of the five field sites. For each farm and each image platform, corresponding NDVI pixels from Landsat and N-content pixels from Rapid Eye were extracted for statistical analysis in the open source software package R 3.1.3(R Core Team).

NDVI (Tucker, 1979) is one the most well-known and widely used vegetation indices. The Landsat project currently provides preprocessed NDVI images through its High Level Science Data Products and the Earth Explorer web interface. Landsat NDVI products are calculated as:

$$\mathrm{NDVI} = \frac{\mathrm{P}_{\mathrm{nir}} - \mathrm{P}_{\mathrm{red}}}{\mathrm{P}_{\mathrm{nir}} + \mathrm{P}_{\mathrm{red}}} \qquad [1]$$

Where $\mathrm{P}_{\mathrm{nir}}$ is the reflectance of the near-infrared band (760 to 900nm) and $\mathrm{P}_{\mathrm{red}}$ is the reflectance of the red band (630 to 690nm). Chlorophyll strongly absorbs red light to use it for photosynthesis, but do not absorb near-infrared light (Gates et al., 1965; Knipling, 1970; Sinclair, 1971; Wooley, 1971; Jensen 2011). Near-infrared light is strongly reflected by the spongy mesophyll cells within mature plant leaves (Jensen 2011). Thus, green leaves strongly absorb red light, while strongly reflecting near-infrared light. However, the absorption of red light is a function on plant greenness and not photosynthesis, which results in NDVI having a difficult time detecting small changes in rates of photosynthesis (Carter,

1993) (Jan U H Eitel et al., 2011). NDVI is good at measuring seasonal changes in vegetation growth, but it can be unresponsive to changes in chlorophyll concentrations when LAI is also high due to saturation of the red signal (Jenson, 2011). Nevertheless, NDVI has been shown to be related to N in cereals like wheat, as long as N covaries with LAI (Curran & Milton, 1983; Sembiring et al., 1998; Hansen & Schjoerring, 2003; Moges et al., 2005; J. U H Eitel, Long, Gessler, & Hunt, 2008). Hansen et al. (2003) also demonstrated that increased nitrogen supply causes increased absorption of red light due to higher density of pigments in plant leaves and increased reflectance of near-infrared light due to greater canopy and internal leaf scattering. With respect to N content, NDVI is a measure of both biomass and chlorophyll content, but not necessarily indicative of which one (Hansen & Schjoerring, 2003). Thus, it is important to note that NDVI values are function of both biomass and chlorophyll concentration.

Understanding how efficiently crops use applied N is often explained as nitrogen use efficiency (NUE). NUE calculates how much N is utilized by the crop compared with how much is biologically available. The equation for NUE is:

$$NUE = N_p / (N_a + N_r) \qquad [2]$$

where N_p is the amount of above ground N in the plant or grain, N_a is the amount of N applied as fertilizer, and N_r is the amount of residual N in the soil. However, this simple concept is extremely difficult to quantify in practice because N_r is difficult to determine. The most common way to accurately measure NUE takes a more methodical approach:

$$NUE_a = (Y_f - Y_0)/N_{rate} \qquad [3]$$

Where NUE_a is applied NUE, Y_f is yield in fertilized areas, Y_0 is yield in unfertilized subplots, and N_{rate} is the rate of N fertilizer applied. This method assumes that Y_0 is the amount of residual N in the soil. So, NUE_a has shown to be a better measure of how applied N affects and is utilized by the plant compared to NUE because it controls for N already in the crop system, making residual nitrogen easier to account for.

In the absence of a control plot, an alternative to calculating NUE is the measure of N balance. N Balance is measured using the following equation:

$$\text{N balance} = N_{\text{above}} / N_{\text{applied}} \qquad [4]$$

Where N_{above} is the amount of above ground N in kg/ha, and N_{applied} is the rate of N applied to the field in kg/ha. N balance is a more accurate and accessible calculation of how efficiently applied N is being used by plants because we can often determine with a great level of certainty what the variables actually are at precise sampling points. It is important to note that N balance only tells us how N_{applied} is related to the N_{above}. The N balance does not tell us anything about the role of residual N in the soil or where the N that does not end up in the plant goes. Most importantly for this study, determining N_{above} for an entire farm field is extremely difficult to accomplish due to the limitations in using handheld sensors and destructive sampling as discussed above. This study's goal is to determine the ability of Landsat imagery in estimating above ground N in wheat crops across entire fields.

Analysis

Rapid Eye N content values for each of the fields were plotted against Landsat NDVI values in order to determine the strength of the relationship between RapidEye N content values and NDVI and whether those relationships were statistically significant in R 3.1.3 statistical software (R Core Team). A second order polynomial model was fit to each dataset as well as the aggregated dataset. Coefficients of determination (R^2) values were calculated for each dataset and for the aggregated dataset.

The quality of the regression model was evaluated by using a cross-validation procedure, in which the dataset was randomly split into a training and validation dataset, each consisting of 50% of the total pixels. Cross-validation procedures were run 1000 times for each dataset as well as the aggregated data to ensure robust validation. The analysis calculated root-mean-square-deviation (RMSD) (Zambrano-Bigiarini, 2014), root-mean-square-error (RMSE), and coefficient of determination (R^2). Average RMSD, RMSE, and R^2 values were also calculated. Calculating RMSD was particularly important to quantify the performance of the Landsat N content model because it allowed the error in the Landsat model to be explained in kg ha^{-1} of N, as opposed to less useful R^2 values.

Results

Raw Data Results

Landsat NDVI values and Rapid Eye N content had a statistically significant relationship at all farms ($p<0.05$). When the aggregated data was plotted, the relationship between NDVI and N content demonstrated a leveling off of the NDVI response at high N content values (Figure 3). The subsequent second order polynomial model of Landsat NDVI values and Rapid Eye derived N-content seems to demonstrate a saturation of the NDVI signal consistent with previous research (Daughtry, Walthall, Kim, de Colstoun, & McMurtrey, 2000; Gitelson, Kaufman, & Merzlyak, 1996). Landsat NDVI and RapidEye N content comparisons had varying strengths in the relationship between NDVI and N content. R^2 values ranged from 0.20 to 0.81. The relationship between NDVI and N content for all data was statistically significant, exhibiting an R-squared value of 0.68. These results indicate that NDVI was a strong predictor of N content in a dryland wheat system across the Palouse region of Idaho and Washington.

Cross Validation Results

Cross-validated Landsat model runs produced an average root-mean square deviations (RMSD) that ranged from 13.66 to 28.15 kg/ha of N depending on the field in question. The 1:1 line fell within the 95% confidence interval for all regressions. Cross validation results indicate that the Landsat derived N content model is a good predictor of N content because of its accuracy compared to the RapidEye model.

Discussion

Efficient N fertilizer management is an essential piece of reducing nitrogen pollution and mitigating N_2O emissions (Galloway et al., 2003; Robertson & Vitousek, 2009; Vitousek et al., 1997). NDVI is an easily utilized and widely available vegetation index that could significantly improve on-the-ground N fertilizer management because of its ease of use and availability. While superior vegetation indices for predicting plant N content exist (i.e. NDRE) (J. U H Eitel et al., 2008; Magney et al., *in prep*), the utility, ease of use, and widespread availability make NDVI an adequate tool for improving N management since it seems to estimate N content in wheat crops fairly well when compared to top-of-the-line RapidEye data through model cross-validation (Figure 3). The results from this study show that Landsat NDVI products can accurately estimate N content at the field scale.

Results indicate that Landsat is a good predictor of N content in wheat crops. As was expected, the NDVI signal seems to saturate at higher N content values (J. U H Eitel et al., 2008) (Carter, 1993) .This may explain the strength of the relationship at the Colfax Farm versus some of the other field sites. The Colfax Farm was topographically heterogeneous and contained a wider range of NDVI values than other field sites. Since NDVI is more accurate at lower red reflectance values, it may be that the more prevalent lower NDVI values served to strengthen the relationship between NDVI and N content. Thus, using Landsat NDVI to predict N content at the field scale may be most appropriate for heterogeneous landscapes and farm fields that have a wide range of N content values.

Still, our results indicate that Landsat NDVI fails to perceive changes in N content at high NDVI values. Previous research has come to similar conclusions, but that research has also generally concluded that NDVI is of limited use in predicting N content (Aparicio, Villegas, Casadesus, Araus, & Royo, 1999) (J. U H Eitel et al., 2008). This study supports the general assertion that NDVI saturates at relatively low LAI values due to high red reflectance. However, our results suggest Landsat NDVI can still be useful in determining N content in certain situations. Dryland wheat systems have been shown to have stronger relationships between N and NDVI than irrigated systems (Feng et al., 2014). Our results indicate that Landsat NDVI will perform best in situations where N content varies throughout the field, like in dryland systems.

Future Landsat platforms could improve the ability to predict N content by incorporating a red-edge band. Red-edge vegetation indices have been shown to be much more suitable at detecting early signals of plant stress and changes in canopy reflectance at high LAI values (Jan U H Eitel et al., 2011). The ability of end-users to utilize publicly available red-edge spectral indices would likely be a significant improvement over current Landsat capabilities in assessing field crop N content.

From a management perspective, it seems likely that N management could benefit from the use of Landsat NDVI as an N content prediction tool. N loss to the environment from over applying fertilizers is a serious environmental and economic problem. While Landsat NDVI is not the perfect tool for estimating N content in wheat crops, this study shows that it does provide useable information. Landsat NDVI is a free to use and publicly available dataset that could help reduce the environmental degradation and economic costs associated with inefficient N fertilizer application.

Conclusion

This study evaluated the utility of Landsat NDVI in estimating N content at the field scale. I found that Landsat NDVI at the 30m spatial resolution was significantly correlated to N content from a Rapid Eye derived N content map. While NDVI is not the best vegetation index for estimating N, it is potentially useful. The added benefits of it being publicly available and easy to use make even more useful to farm managers. To improve the future ability of estimating N content in vegetation, Landsat needs to incorporate a red-edge band into its remote sensing platform.

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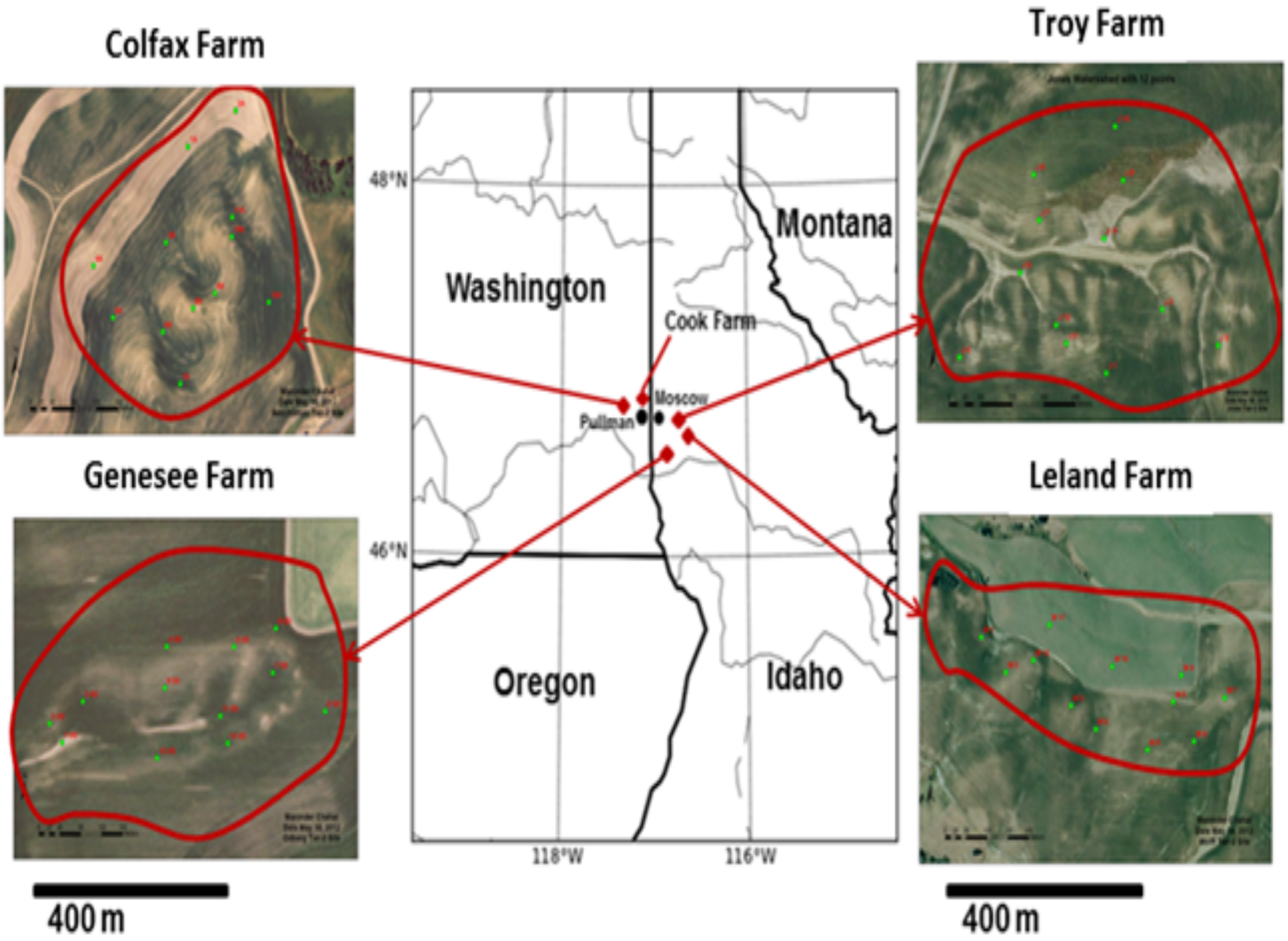

Figure 1: Study area

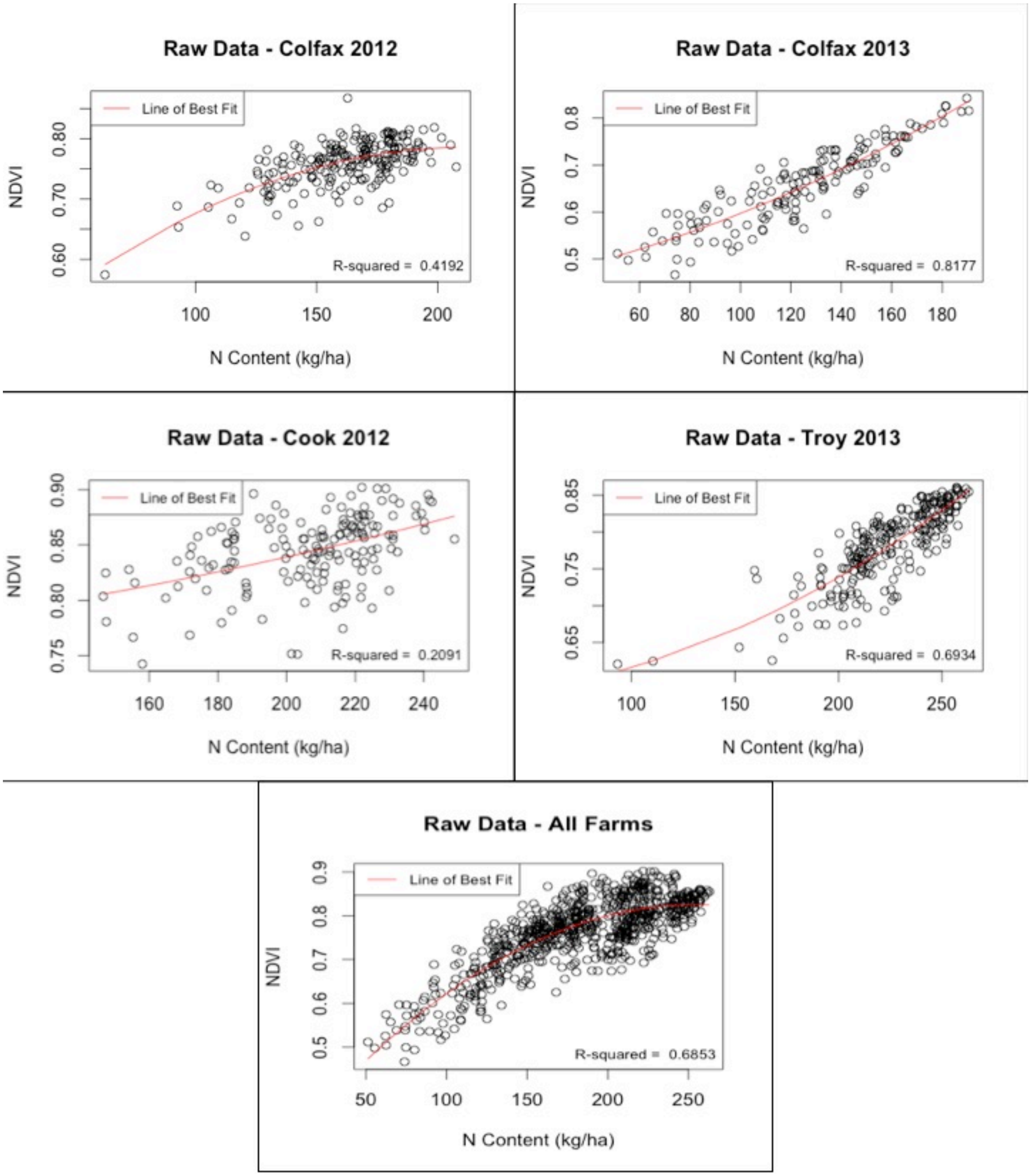

Figure 2: RapidEye Estimated N plotted against Landsat NDVI

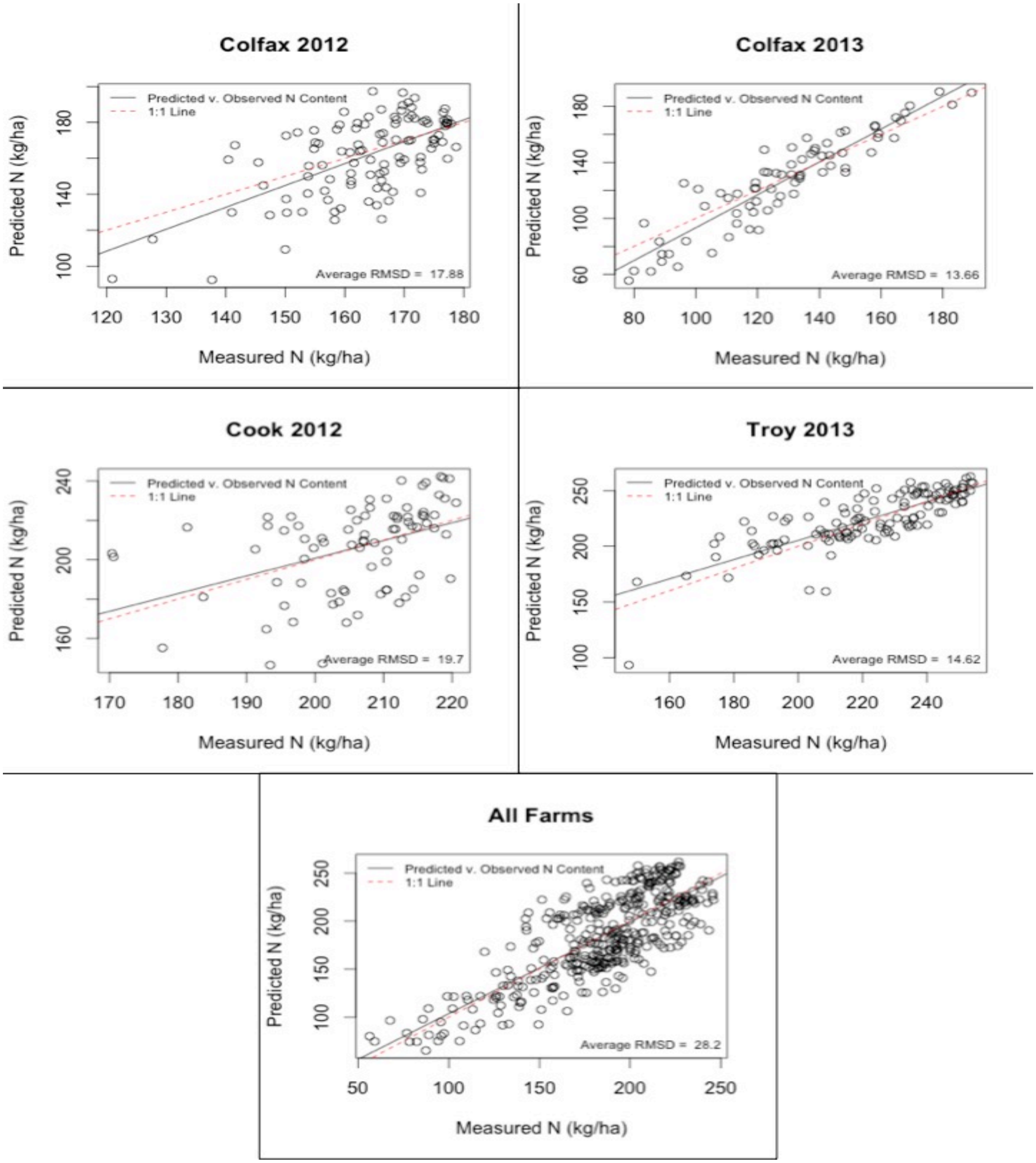

Figure 3: Landsat Estimated N Cross Validation Results

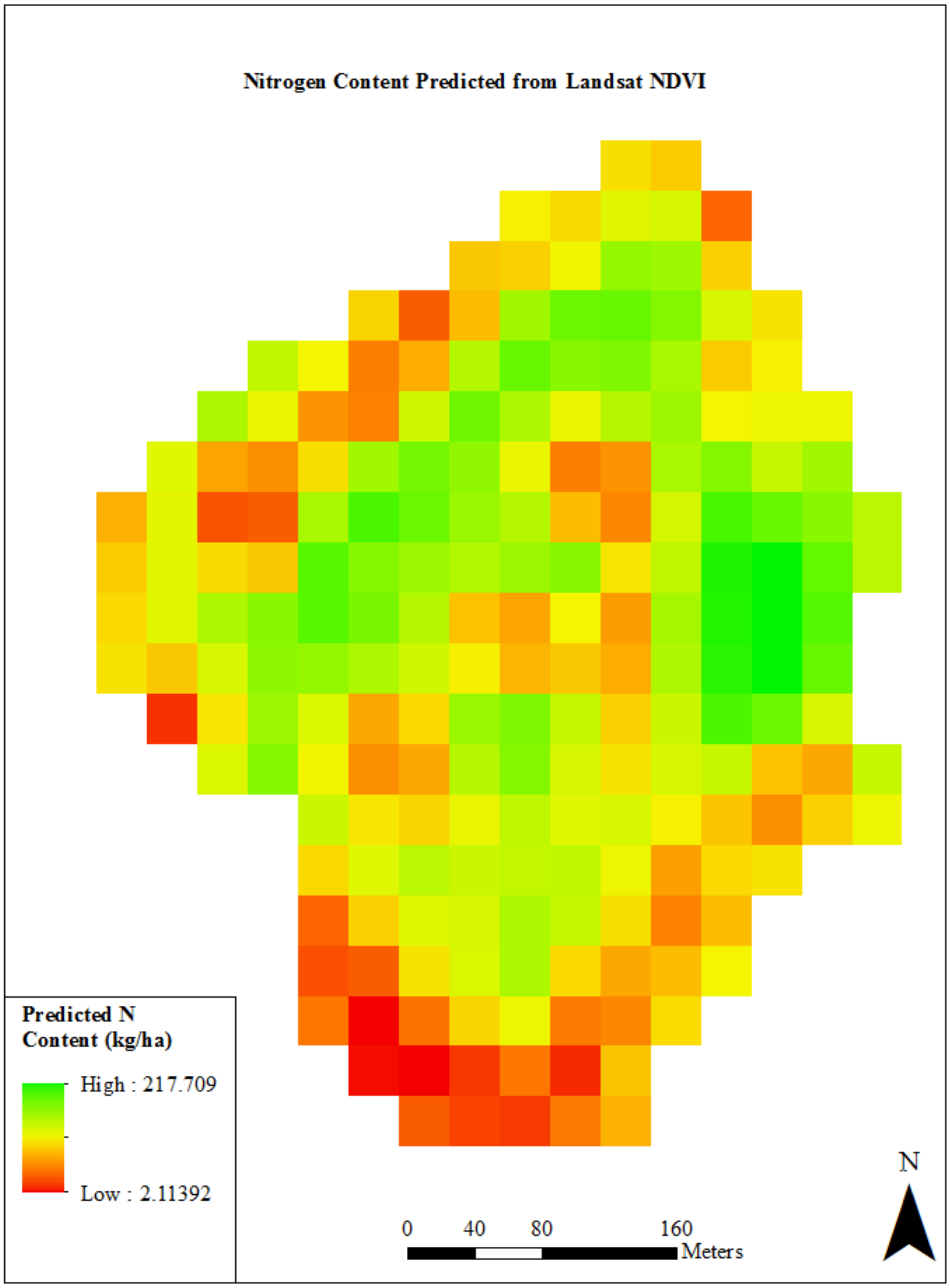

Figure 3: Landsat Estimated N Cross Validation Results

CHAPTER 2

AGRICULTURE'S BRANCHES: EFFICIENCY AND PRODUCTION

> *"There are a thousand hacking at the branches*
> *of evil to one who is striking at the root, and it*
> *may be that he who bestows the largest amount*
> *of time and money on the needy is doing the*
> *most by his mode of life to produce that misery*
> *which he strives in vain to relieve."*
>
> \- Henry David Thoreau
>
> *Walden, 1854*

Abstract

Agricultural research is often justified on environmental, economic, and social grounds. Many agricultural researchers claim that their work will decrease unwanted environmental consequences, increase profit margins, and increase production to help feed a growing population. Given the actual impacts of industrial agriculture, however, the problems addressed by these research projects are not being ameliorated. Instead, the environmental degradation and food security issues agricultural research attempts to address remain global issues that are actually becoming more problematic. The justifications used for many industrial agriculture research projects are actually political and legal problems that will not be improved upon by scientific research. Scientific researchers must change the conversation surrounding agricultural research and recognize that environmental degradation and food security issues are currently not scientific problems.

Introduction

Scientific agricultural research is frequently justified on environmental, economic, and social grounds. Often, such research evaluates the ability of improved agricultural technology to produce the same amount or even more food with fewer fertilizer inputs, thereby decreasing agricultural environmental degradation, like increased greenhouse gas emission, freshwater eutrophication, and reduced biodiversity (Erisman et al., 2008; Muir, Pretty, Robinson, Thomas, & Toulmin, 2010) (Galloway et al., 2008). Increased efficiency through agricultural research has also lead to increases in food production by either agricultural intensification or agricultural extensification by putting land into food production that would not otherwise be profitable. Resulting increases in agricultural production can then contribute to feeding an ever-growing world population. But, is agricultural research actually decreasing environmental degradation or increasing food security? Environmental degradation as a result of agriculture continues to be a major global problem despite 70 years of technical innovation in how we produce food (Vitousek et al., 1997) (Erisman et al., 2008). And, although the percentage of hungry people in the world has decreased since the mid-20th century, the total number of people affected by hunger worldwide has *increased* to almost 1 billion people (Food and Agriculture Organization of the United Nations, 2009).

Generally, researchers make two claims about the impacts of their research. One common claim is that an increased understanding of agricultural systems, like synthetic nitrogen fertilizer management, will increase efficiency and decrease environmental degradation (*See* Ahrens, Lobell, Ortiz-Monasterio, Li, & Matson, 2010; Beever et al., 2007; Galloway et al., 2008; Robertson & Vitousek, 2009). A second claim is the need to increase production in order to meet increasing food demand from a growing population (*See* Beever et al., 2007; Galloway et al., 2008; Tilman, Cassman, Matson, Naylor, & Polasky, 2002). Taken together, the model for justifying agricultural research is to show that environmental degradation and food security can be improved by increasing efficiency within agricultural systems in order to grow more with less. Instead of solving these problems, however, it seems that science is only hacking at the branches without searching for the roots of agricultural issues. If real solutions to these problems are to be found, researchers need to have an uncomfortable conversation about the true impacts of their research, and whether environmental degradation and food security issues really can be solved through increased scientific understandings of the issue.

Environmental Degradation

Environmental degradation arising from industrial agriculture is a global problem. Agriculture has the largest impact of any human activity in the world (Tilman et al., 2002). Industrial agriculture disrupts the long-term processes required to grow food sustainably in the quest for short-term economic growth. Air pollution, biodiversity loss, freshwater acidification, marine eutrophication, habitat degradation, and greenhouse gas emissions resulting from industrial agriculture threaten the very environmental processes all life depends upon (Cowling et al. 1998; Erisman et al., 2008; Howarth et al., 2000; NRC, 2000; Rablais, 2002; Vitousek et al., 1997). Nitrous oxide is the fourth most powerful greenhouse gas in terms of radiative forcing, and agriculture is responsible for 75% of all nitrous oxide emissions (Forster et al., 2007). These problems occur wherever industrial agricultural systems are in place.

The need to reduce the impact agriculture has on the environment is enormous and well accepted within the scientific community. Unfortunately, the actual impact of most agricultural research will not substantially counteract the causes of environmental degradation because the scale of improvements are too small relative to the scale of the problem. Thus, while it may seem intuitive that any reduction in the negative impacts of industrial agriculture is an improvement, small-scale improvements will often have no discernible impact because the scale of the problem being addressed is too large. Solutions to environmental degradation from agriculture will only be solved if the problem is met with an equally powerful solution.

Many of the negative consequences of industrial agriculture are a function of both the intensity of farming (agricultural intensity) and the scale at which it is done (agricultural extent). Agricultural intensification is the process of increasing agricultural production on land that is already agricultural, generally by increasing the use of fertilizers, irrigation, and pesticides. Agricultural extensification is the process of increasing the amount of land being used for agricultural production, usually by adding technology that makes the land arable. Combined, the two cause significant environmental degradation. Although, agricultural practices are not inherently degrading, they are when performed both at an intensity and extent that wreck ecological processes.

Much of the current environmental degradation from industrial agricultural is that current industrial agriculture can be traced to the combination of high agricultural intensity and large agricultural extent. The result is a system that significantly impedes ecological processes and is unsustainable in the long term. Our current industrial agricultural system has only been around for 70 years, and it is affecting almost every ecosystem and ecological process in the world (Galloway et al., 2003; Robertson & Vitousek, 2009; Vitousek et al., 1997). Conversely, human civilization has been farming in some form for over 12,000 years, indicating that agriculture has been sustainable for thousands of years. Considering the environmental degradation resulting from only 70 years of our current industrial agriculture, it is apparent that industrial agriculture practices are inherently unsustainable.

Current solutions to agriculture's environmental problems largely focus on making agriculture less bad through technological innovation, but leave the system of industrial agricultural in place. The rationale for using technological fixes to solve environmental problems is built on the idea that a lack of technology to blame for the adverse environmental consequences. For example, if fertilizer runoff is causing environmental degradation in the form of water pollution, then improved technology would help farmers only apply as much fertilizer as needed, thereby minimizing fertilizer runoff. If technology can be improved to avoid the environmental problem, then the action can continue to provide its benefit and generate profits without the unwanted environmental consequences. Generally, technofixes aim to improve the efficiency of a particular action, thereby requiring fewer inputs while often generating increased outputs. Technological solutions assume that a certain action can occur with acceptable levels of environmental degradation if we can just improve efficiency. Essentially, technofixes let us have our cake and eat it, too.

Past environmental successes are enlightening examples of why technological fixes seldom work. In the Montreal Protocol, chlorofluorocarbons were banned to prevent further ozone depletion. The Montreal Protocol has worked. No technological fix was needed because the solution was behavioral and system-wide; we just stopped doing the thing that was harming the environment, completely. But the problems associated with chlorofluorocarbons were easily solved because the producers of the chemical were identifiable and other alternatives were both easy to implement and cost effective. The problems arising from industrial agriculture lack these characteristics.

The inherent flaw with most technological fixes is that they do not require stopping the damaging action that caused the problem. Instead, they seek to decrease the negative effects, usually by increasing efficiency. Worse, increasing outputs through increased efficiency can increase the scale of the impact and negate benefits from increasing efficiency. For example, if we improve the fuel efficiency of cars by 25%, but total miles driven also increase by 25%, then our technological innovation will have done nothing to reduce the amount of fuel being consumed. Technological fixes are relevant to causing the least amount of damage possible, but, in the case of environmental degradation caused by agriculture, small improvements from technofixes fail to strike at the root of the problems being addressed. When it is all said and done, making something less bad concedes that you are not achieving something good – like a sustainable agricultural system.

Industrial agriculture has already tried to use technology to fix problems. The Green Revolution between the 1940s and 1960s promised huge increases in agricultural production with fewer required inputs. Crops were developed to withstand drought, utilize nutrients more efficiently, and resist the effects of pesticides and herbicides. And while food production has grown exponentially as a result of the Green Revolution, the increased efficiency has actually made environmental degradation more of an issue, not less. Increased efficiency led to both agricultural intensification and extensification because it allowed increased yields on agricultural land already in production, and it allowed new agricultural land to be put into production through the use of irrigation, pesticides, synthetic fertilizers, and new crop varieties. The past is clear: increasing efficiency does not reduce environmental degradation.

The root cause of environmental degradation from industrial agriculture is not a lack of technology, but a failure to recognize limited natural resources, account for externalities, and accept that the human population cannot grow unbounded.

Food Security

The second common justification for conducting agricultural research is to help solve issues of food security. Concerns about world hunger have been at the forefront of agricultural innovation for centuries. It was not until the last century that dramatic changes in how we produce food led people to think we could end world hunger by increasing food production. In the early 1900s, Fritz Haber discovered a process that turned atmospheric nitrogen into ammonia. Carl Bosch refined that process so that it could be used at an industrial scale. Together, they fundamentally changed the way we farm. Between the 1940s and 1960s, the Green Revolution introduced industrial scale farming, new equipment and technology, pesticides, and herbicides. As a result of the Haber-Bosch process and the Green Revolution, food production has increased at a faster rate than human population growth (Robertson & Vitousek, 2009). Without these two changes in the agricultural production system, it would not be possible to feed 7 billion people, especially as more and more people move to cities without access to land for growing food.

Despite the dramatic increase in food production and improvements in agricultural technology, however, food security remains one of the world’s most significant problems. Although, the proportion of hungry people in the world has decreased, the total number of people facing food insecurity has increased to almost 1 billion people (Food and Agriculture

Organization of the United Nations, 2009). After 50 years of unprecedented increase in agricultural production, technological improvements in how we farm, and increased scientific understanding about agricultural systems, food security remains a substantial global issue. The Food and Agricultural Organization of the United Nations states that in order to feed the expected 9.1 billion people in 2050, “food production must increase by 70%” (Food and Agriculture Organization of the United Nations, 2009).

Scientific research has not been unresponsive to food security issues. Crop scientists frequently justify research under the premise that increasing agricultural production will help meet increased demand from a growing world population (Food and Agriculture Organization of the United Nations, 2009; Muir et al., 2010). Through better scientific understanding, farmers will be able to produce more food, more efficiently, and contribute to the increasing agricultural demand (UNEP/WHRC, 2007). Thus, scientific agricultural research that relies largely upon governmental agencies and organizations for funding often support the premise that better scientific research will address food security by increasing agricultural production.

Also of importance is that almost one-third of global food production is wasted, which is about how much food it would take to feed those 1 billion hungry people (United Nations World Food Program, 2014). A large part of the food security issue that industrial agriculture fails to address is that the main cause of world hunger is a lack of access to food, not sufficient production. Although the United States accepts that solving this issue is an important obligation, we have so far failed to fulfill it. Ross Copeland, a lecturer at the University of Kassel, captures the issues: “access to food and other resources is not a matter of availability, but rather of ability to pay.” Peter Rosset of the Institute for Food and Development Policy paints an even more sinister picture of the world hunger crisis:

> *“Research carried out by our Institute reveals that since 1996, governments have presided over a set of policies that have conspired to undercut peasant, small and family farmers, and farm cooperatives in nations both North and South. These policies have included runaway trade liberalization, pitting family farmers in the Third World against the subsidized corporate farms in the North (witness the recent U.S. Farm Bill), forcing Third World countries to eliminate price supports and subsidies for food producers, the privatization of credit, the excessive promotion of exports to the detriment of food crops, the patenting of crop genetic resources by corporations who charge farmers for their use, and a bias in agricultural research toward expensive and questionable technologies like genetic engineering while virtually ignoring pro-poor alternatives like organic farming and agroecology.”*

Given the history of world hunger, addressing food production does not get at the root of issue. Food security remains a global issue despite agricultural production outpacing demand and decades of technological innovation. The origins of hunger are access, poverty, and politics, rather than production. Increasing agricultural production is like sticking a Band-Aid on something that requires stitches: its appearance may make us feel better, but will not heal the wound and may only make it worse. By focusing on producing more food, scientific researchers have erroneously accepted the idea that hunger is a problem of supply that serves to justify increasing production. The history of agriculture suggests that it is possible to sustain human populations for thousands of years. But, it is also clear that industrial agriculture is not a solution to the hungry masses of the world, because hunger is not an issue of food supply.

Conclusion

Scientific agricultural research is often justified under environmental and food security premises. Environmental justifications for agricultural research generally claim that increases in technology and efficiency will decrease unwanted environmental degradation. Similarly, this research also cites food security issues as a basis for increasing agricultural production. Nonetheless, despite decades of technological innovation and increases in food production that outpace demand, both environmental degradation and food security remain enormous world problems. These issues still plague people around the world because they are not issues caused by a lack of scientific understanding. Instead, environmental degradation and food security are really issues of politics, law, and economics. Because of this, science will continue to hack at the branches of industrial agriculture.

At its most fundamental level, the scientific community has a duty to explain how the world works to the public. It seems that the time has come for scientists to change how they talk about environmental degradation caused by agriculture and food security issues. Scientists need acknowledge that their research cannot solve these issues because the root of the problem is not scientific. Improvements in industrial agriculture systems can continued to be justified by needs to increase production and efficiency for economic gain, but doing so under the premise of solving environmental and food security problems continues to perpetuate false solutions to significant global problems.

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