ASSESSING THE SPATIOTEMPORAL DYNAMICS OF CROP YIELDS

ASSESSING THE SPATIOTEMPORAL DYNAMICS OF CROP YIELDS AND EXPLORING THE FACTORS AFFECTING YIELD SYNCHRONY

By

JIMMY H.C. LI, BSc.

A Thesis

Submitted to the School of Graduate

Studies in Partial Fulfillment of the

Requirements for the degree Master of

Science

McMaster University

MASTER OF SCIENCE (2015)
(Biology)

McMaster University
Hamilton, Ontario

TITLE: Assessing the spatiotemporal dynamics of crop yields and exploring the factors affecting yield synchrony

AUTHOR: Jimmy H.C. Li, BSc

SUPERVISOR: Dr. Jurek Kolasa

NUMBER OF PAGES: xiii, 142

LAY ABSTRACT

Fluctuation in crop yields has significant impacts on food supply in many developing nations and on global food prices. I analyzed patterns of variation on global yield of 77 crops recorded in 212 countries over 22 years. I found that if we know how crop yields vary in space, we could predict fluctuation in crop yields over time at various scales. Since crop yields are the most important aspect in raising global food supplies, the ability to accurately forecast how much they will fluctuate would aid governing bodies in dealing with uncertainties and make informed decisions to ensure stability in local and global food supply. I also found that a crop's preferred climatic conditions were strong predictors of its simultaneous drop (or rise) in adjacent countries. This helps to decide which crops are good candidates to use spatial variability in predicting their regional temporal variability in yields.

GENERAL ABSTRACT

Variation in crop yields has significant impacts on food supply in many developing nations and on global food prices. I applied a recently quantified link between spatial and temporal variation to gain general insights on the dynamics of food production, as well as to test whether a prediction that relies on space-for-time substitution applies for crop yields, and at which spatial scale. I analyzed patterns of variation on global yield for 77 crops recorded in 212 countries over 22 years (1990 – 2012). I found that if we know how crop yields vary in space, we could predict variation in crop yields over time at various scales. Specifically, spatial variation can substitute for temporal variation in predicting the variability of yield of certain staple crops when synchrony and persistence (persistence = consistent differences in mean yield values among locations or regions) are taken into account. This space-time substitutability has potential to forecast temporal stability of food production from its spatial data alone, which should allow countries and various agencies to improve agricultural policies and production forecasts to ensure stability in local and global food supply. I also found that a crop's preferred climatic conditions were strong predictors of synchrony between countries at the continental scale. This provided insights on the type of crops that are good candidates for effective use of spatial variability to predict their regional temporal variability in yields. These include crops that have high preferred-germination-soil temperature, low minimum crop water needs, and low minimum growing period. Lastly, as global warming increases crop yield synchrony, the total variability of global food supply increases, which results in lower stability in global food supply and exacerbates food insecurity. Combined with the predicted higher frequencies of climate extremes, the findings in this study reinforce the current view that climate change will have negative consequences on the global food supply.

Key Words: *spatiotemporal, variability, crop yields, synchrony, spatial persistence, food security, climate change, global warming*

ACKNOWLEDGEMENTS

This dissertation would not have been possible without the help of a few individuals who have been very supportive in my work over the past two years. Firstly, I would like to express my sincere gratitude to my supervisor Dr. Jurek Kolasa for his continuous support of my Masters study and research. You are such an inspiring mentor to me in and outside of the lab. Not only did you help develop and guide my ideas, but you also influenced me as an individual in my everyday life. Thank you for always being there to answer my questions. I really appreciate the many opportunities you have provided me, including the times you brought me along to travel outside of Canada for your field course.

Thank you to Dr. Ben Evans for being contributing member during committee meetings and providing me with valuable inputs on how to improve this project. Your guidance throughout this process was much appreciated. Also thank you to Dr. David Rollo for being a part of my final thesis defense.

I would like to acknowledge and thank Dr. John Lott for providing the initial data compilation that made my research possible. Thank you also to FAOstat for making the data accessible.

I thank my fellow lab-mate Dr. Matthew Hammond for answering the many questions I have had over the past two years. From statistical analysis to interpreting results, you have provided insightful comments and encouragements that widened my research from various perspectives.

I would like to thank my mom Hellen Cheung and my fiancée Natasha Kim for their continued love and support. Your faith in my abilities has helped me to strive to be a better person and I would not be who I am today without you.

A final thank you to the McMaster Department of Biology and the Graduate Students Association who have provided funding for the completion of my project.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

List of Tables

List of Figures

Chapter 1

Introduction

BACKGROUND

After many years of hunter-gatherer society where food was obtained from wild plants and animals, agriculture involving domestication of plants began about 12,000 years ago (Klein *et al*., 2011). The advents of agriculture allowed a shift from food gathering to food production, providing a reliable food supply and permanent settlements. Since then, agriculture had gone through significant advances in techniques like irrigation, crop rotation and the development of synthetic fertilizers (Chunjian *et al*., 2003). At the start of the twentieth century, the discovery of the Haber-Bosch process for synthesizing ammonium nitrate allowed crop production to overcome previous fertilization constraints (Erisman *et al*., 2008). The replacement of human labor with synthetic fertilizers, pesticides, selective breeding, and mechanization has also increased productivity and crop yields around the world (Aimin *et al.,* 2000; Meij, 1960).

After years of growth in agricultural outputs in the past decades, global yields of some important crops like millet and sorghum have begun to stagnate. Growth rates in yields of crops like wheat and rice have even slowed since the 1990s (Sinclair *et al*., 2004). While food is readily available in developed countries like Canada, many developing countries continue to experience severe undernourishment from shortage of food due to interacting factors like droughts, poor harvests and rising food prices (Charney, 1975; Reardon *et al*., 1989). Currently, about 795 million people around the world are undernourished, which is 167 million less than the numbers a decade ago. For developing regions, the percentage of undernourished people in the population has declined from 23.3% in 1991 to the current 12.9% (Antle, 2015). However, this progress has been hindered in recent years due to slower economic growth and political instability in some developing regions like Central Africa and Western Asia (Godfray *et al.,* 2010; Friel & Ford, 2015).

As defined in the World Food Summit in 1996, food security exist when “all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life” (Pinstrup-Andersen, 2009). Food security is built upon consistent food availability, sufficient access, and its appropriate usage based on knowledge on nutrition and care. In past decades, efforts have been made to improve food security worldwide. The proportion of people with average calorie intake under 2,200 kcal per day fell from 57% in 1965 to just under 10% in recent years (Lobell *et al*., 2008). However, about one in six people in developing countries are still considered undernourished. Food insecurity and undernourishment is still prevalent in parts of Africa, Asia and South America (Godfray *et al.,* 2010).

Global food security continues to be under threat due to a number of fundamental factors. Market speculations resulting in export restrictions and “panic buys”, along with the increased demand for biofuel are some of the notable economic influences that affect food security (Mitchell, 2008). The rapid rise in food prices has been a burden on the poor in many developing countries, who spend roughly half of their household income on food. Policy failures such as inadequate agri-market regulations and poor waste management, along with the under-investment in worldwide agricultural sectors are also some of the key contributors to the decline in global food security (Mitchell, 2008; Wodon *et al*., 2008). Added with the effects of climate change, increased energy prices, and the ongoing population growth, there are a number of interacting variables that place pressure on international food security (Gilland, 2002; Parry, 2004; Pimentel, 1973).

The current world population projection entails the need for increase in food production at least until 2050 (Tilman *et al*., 2011). In particular, the rapid increase in demand for agricultural products in developing countries has been a major driving force in global food demands. Population growth, rising per capita incomes and growing urbanization have not only increased the total food demand, but also per capita caloric consumption (Subramanian & Deaton, 1996). Consumers in some developing regions are diversifying their food intake and shifting to more meat-intensive diets. Expanding demands for animal feed will further increase for crop products such as coarse grains. In addition, the emergence of biofuel and other industrial uses of agricultural products in developed nations will also raise global demands for crop products such as cereal (Tilman *et al*., 2011). By 2050, food demand is expected to almost double from the levels in 2005 (Tilman *et al*., 2011).

Meeting this demand will require the further expansion of arable agricultural land, increases in cropping intensity (number of times the areas are cropped per year), as well as improvement in yields delivered by new technologies and plant varieties (Tester *et al*., 2010; Tilman *et al*., 2011). Possibilities to expand production are limited by factors such as constrains in the expansion of agricultural land, changes in national policies, and environmental concerns. Throughout the latter half of the 20^{th} century, yield improvements have been the largest source of crop production growth both in developed and developing nations, accounting for roughly three-quarters of the increase from 1960 to 1999. The remaining one-quarter came from the combination of increased cropping intensity and expansion of arable land (Calderini *et al*., 2001).

In most parts of Asia and Pacific, suitable land and natural resources are quite limited and therefore continued yield improvements will be key factor in raising crop production (Mueller *et al*., 2012). In fact, crop production growth in Asia, Europe, and North America, are expected to be driven by yield improvements. South America on the other hand is expected to increase its crop production by expanding additional agricultural areas (Ray *et al*., 2012). Suitable land and natural resources are less constrained in South America, allowing stronger production growth based on both agricultural land expansion and improvements in yield (Brauman *et al*., 2013). In Africa, land remains abundant and agricultural area is expected to expand in the coming years. However, crop yields in most parts of Africa remain below that of global averages. Therefore, low to moderate production growth is expected in Africa unless further investment raises yields and production significantly (Ray *et al*., 2012). Future expansion for agriculture areas will also threaten remaining forests and savanna, so agricultural growth must rely more on productivity gains through increased crop yields.

The expansion of the biofuel sector over the past decade has been the result of various policies including support measures and mandated blending levels. Over periods of high fossil fuel prices, the use of ethanol as octane additive expanded rapidly (Timilsina *et al*., 2012). Even with the recent decline in oil prices, demand for biofuel is tightly related to policies mandating its use. Brazil for example has recently increased its mandatory ethanol blending up to 27% and differential taxes have been established to favor its domestic hydrous ethanol industry (Meyer *et al*., 2014). The increase in demand for biofuel places further pressure on international food supply.

Another pressure on global food supply comes from the projected increase in meat production. As demands and prices for meat recently reached its highest record level, there is high profitability in the livestock sector. This translates into high meat to feed price ratios over the foreseeable future, boosting production growth in meat industries (Hart & Schulz, 2015). Production in the poultry sector is projected to expand by 24% over the coming decade, with most of the additional productions coming from developing countries (Reay *et al*., 2012). As production of meat such as poultry and beef rely heavily on feed grains, the rising use of feed further intensifies demand for crops like coarse grains.

The impacts of climate change also have many consequences on the global food supply and demand. Substantial evidence has shown that the global mean temperature has risen by 0.8°C since the middle of the 19^{th} century, and could be rising another 1 to 3°C by then end of this century (Hansen *et al*., 2010; Richard, 2012). Carbon dioxide levels have increased substantially over the past century and there is a strong link between global warming and the levels of this greenhouse gas in the atmosphere (Canadell *et al*., 2007). Climate change is expected to increase global mean temperature, alter patterns of precipitation, and increase frequency and severity of extreme weather (Cai *et al*., 2014). The warming is anticipated to be greater on land than the oceans, as well as in arid regions and regions towards the poles (Sitch *et al.,* 2007). Sea level rises due to global warming poses risk from flooding of agricultural land in coastal regions. Changes in rainfall patterns is less certain, but is generally predicted that wet areas will become wetter and dry areas will become drier (Dore, 2005). For example, summer Asian monsoon rainfalls are expected to increase, while parts of north and southern Africa are expected to become drier (Hendrix & Salehyan, 2012; Turner & Annamalai, 2012).

Agriculture is intrinsically linked to climate variability and change. Climate change is expected to directly influence crop production and alter the pattern of food trades. These impacts may vary between locations depending on the level of warming and the associated precipitation changes (Kamran & Asif, 2011). Higher concentration of carbon dioxide in the atmosphere is expected to boost productivity of most crops through enhanced photosynthetic rates and increased water efficiency (Rosenzweig & Parry, 1994). However, the effect of temperature increases and changes in rainfall patterns will probably outweigh the benefits of elevated carbon dioxide (Lobell *et al*., 2011). In general, climate change will have a greater negative impact on tropical areas than higher latitudes. Yields are projected to decrease across Africa, South Asia, and South America, coinciding with countries that already have high burdens from hunger (Asseng *et al*., 2013; Mueller *et al*., 2012). Yields of crops like wheat, maize, sorghum, and millet are especially vulnerable to climate change (Knox *et al*., 2012). Thus, the impact of climate change on crop yields will exacerbate food insecurity in areas that already have high prevalence of undernourishment.

Exports of crops are predicted to be concentrated in fewer countries, while import demand will increase and become more dispersed over greater number of countries. The limited number of exporters for most crops is due to the comparative advantages those countries have with respect to natural capacities, climatic conditions, domestic policies (Fader *et al*., 2013). Currently, the United States, Western Europe and Brazil are the top agricultural exporters (Debnath *et al*., 2014). This reliance on relatively fewer countries to supply the global food market increases market risk, as natural disasters or poor yields in key cultivators may have strong repercussions on the international food supply.

These current projections on the outlook of food supply are subjected to a variety of uncertainties, as they are sensitive to temporal variability in yields and macroeconomic factors (Diacono *et al*., 2012). The ability to predict the magnitude of variations in future crop yields would allow policy makers to better prepare for potential shocks to the global food supply. Yield insurance systems could benefit from accurate estimation of temporal yield variability in order to derive reliable risk premiums (Sheerick *et al*., 2004; Goodwin & Ker, 1998). Low temporal yield variability for instance translates into stable food supply and prices. High temporal yield variability on the other hand is a big risk factor that threatens the stability of the food supply and increases food market volatility. Low global food stocks combined with high fluctuation in crop yields can contribute to food price spikes or unstable prices (Bellemare, 2015; Piesse & Thirtle, 2009).

The resulting high and volatile food prices could limit food consumption in economically challenged families.

Variation in climate has a great impact on fluctuations in crop yields. In some regions, climate variability was able to explain more than 60% of temporal yield variability in maize, rice, wheat and soybean (Ray *et al*., 2015). Different aspects of climate variability (i.e., temperature and precipitation) may have different effects on crop growth and its resultant yields (Urban *et al*., 2012). Crops that are not widely irrigated may be more subjected to variability in precipitation, while irrigated crops or crops with sufficient rainfall may be more vulnerable to variability in temperature. For example, almost all rice crops in Japan are irrigated, thus temperature variability was more important than precipitation variability (Nishimura *et al.,* 2004). In contrast, maize and soybean in China are not widely irrigated and so precipitation variability was more important (Zhang *et al*., 2014). Besides temperature and precipitation, variability in a number of other climatic factors can also affect variability in crop yields. For example, amount of cloud covers, wind speed, surface ozone exposure may also contribute to yield fluctuations (Avnery *et al*., 2011).

Differences in yield also exist between countries representing spatial variation in crop yields. Climatic variables such as temperature and precipitation for example are big factors in the spatial differences in yields (Ray *et al*., 2015).

Differences in agronomic challenges such as pest/pathogen infestation and level of irrigation can result in differences in yield between countries. The farming of different adapted crop varieties could also contribute to gap in yields for the same crop grown in different nations. The wider use of genetically modified soybean varieties in North and South America for example, is a big explanation for their greater and more consistent soybean yields than other parts of the world (Shi & Lauer, 2013). Differences in technological investments, as well as differing agricultural management such as crop protection, sowing and fertilizer use can also contribute to the differences in yield between countries (Annicchiarico & Iannucci, 2008; Jensen & Hauggaard-Nielsen, 2010; Flores *et al*., 2012). Developing nations may use less fertilizer due to economic reasons, which could contribute to differences in yields compared to developed countries (Mueller *et al*., 2012).

ANOVA variance partitioning provides a theoretical foundation to tie temporal and spatial variation of a variable. Spatiotemporal variation can be broken down into its spatial and temporal components (Hammond & Kolasa, 2014). Synchrony and persistence are important components of spatiotemporal variability. When the same crop rises or declines in the same year in each of two countries, they are in synchrony. Persistence on the other hand refers to consistent differences in mean yield between two countries or other spatial units.

THESIS OBJECTIVES

The factors contributing to temporal variability and spatial variability of crop yields have been studied previously, but current literature has not touched on their interaction and relatedness. Many of the studies discussed above have focused on predicting the direction (i.e., growth/decline) of future crop yields. Yet, much remains unknown about the magnitude of future yield fluctuations, which may have major implications on food security.

Crop yields exhibit both spatial and temporal variability. Spatiotemporal patterns are found across landscapes and play a major role in the dynamics of agriculture (Turner, 1990). A recent quantitative link between spatial and temporal variability allows prediction of magnitude of temporal variation from patterns of spatial variation. The strong relationship was shown between spatial and regional temporal variation in 136 biotic and abiotic variables from three aquatic ecosystems: microcosms ($R^2 = 0.93$), rock pools ($R^2 = 0.77$) and lakes ($R^2 = 0.73$) (Hammond & Kolasa, 2014). The model allowed distinction between unbiased, stochastic variation and variation dominated by either synchrony among components (a concerted rise and fall of values of a variable) or by persistent spatial differences. As such, it suggested general categories of mechanisms responsible for the observed variation in a collection of variable used to characterize a particular natural system.

I propose to apply the above model at a broader scale, specifically in the context of global crop yields. With the abundance of spatial data on crop yields, it might be possible to extrapolate temporal dynamics from spatial yield data using the model linking these two kinds of variation (Hammond & Kolasa, 2014). In general, my thesis assumes an integrative approach and involves a three-part investigation of spatiotemporal dynamic of global crop yields. This comprehensive investigation allows a better understanding of the relationship between spatial and temporal variation in crop yields and the factors that influence this relationship. The following questions are to be addressed:

I. Space-for-time Substitution – Is it possible to use spatial variability to predict temporal variability in crop yields? If so, under what condition does the substitution work?

II. Effect of scale – Does space-for-time substitution in variation of crop yields work better in some scales than others? What happens to the index of synchrony and persistence (the co-determinants of temporal variability) at different scales?

III. Factors affecting synchrony and persistence – What are the factors affecting synchrony and persistence? Are some factors more important than others?

RESEARCH STRATEGY

To examine the questions outlined above, I compiled global crop production datasets across multiple years to perform a comprehensive investigation of links between spatial and temporal variation in global crop production. I converted data to yield values when needed to equalize the contribution of countries differing in crop harvest areas, which may dominate the landscape spatiotemporal pattern expressed as production. Results therefore emphasize patterns owing to ecological or socioeconomic differences among countries. My data set included the crop yields of 77 crops for 212 countries over 23 years from 1990 – 2012. All yields were measured in hectogram per hectare, and were computed from detailed harvest area and production data expressed in hectares and hectograms, respectively.

To examine the spatiotemporal relationship in crop yields, spatial coefficient of variation between countries was compared with the global temporal coefficient of variation. Then, the correlation was repeated at various scales including continental, sub-regional and general bands of latitude. Using these correlations, I was able to determine the substitutability of spatial variation for regional temporal variation at various scales. Regional temporal variance followed a simple relationship with spatial variation, and the relationship was modified by two spatiotemporal patterns: synchrony (summed inter-patch covariance) and persistence of spatial variation (summed inter-time covariance).

To examine the factors that affected synchrony and spatial persistence, I compared climatic preferences for each crop to their respective indices of synchrony and persistence at various scales. Using these correlations, I was able to identify crops that were good candidates to use spatial variability to predict regional temporal variability.

STUDY SYSTEM

The data compiled for my thesis was mostly from Dr. John Lott and the Food and Agriculture Organization of the United Nations. The 212 countries included in the data set were: Afghanistan, Albania, Algeria, American Samoa, Angola, Antigua and Barbuda, Argentina, Armenia, Australia, Austria, Azerbaijan, Bahamas, Bahrain, Bangladesh, Barbados, Belarus, Belgium-Luxembourg, Belize, Benin, Bermuda, Bhutan, Bolivia (Plurinational State of), Bosnia and Herzegovina, Botswana, Brazil, British Virgin Islands, Brunei Darussalam, Bulgaria, Burkina Faso, Burundi, Cabo Verde, Cambodia, Cameroon, Canada, Cayman Islands, Central African Republic, Chad, Chile, China, China, Hong Kong SAR, China, mainland, China, Taiwan Province of, Colombia, Comoros, Congo, Cook Islands, Costa Rica, Côte d Ivoire, Croatia, Cuba, Cyprus, Czech Republic, Czechoslovakia, Democratic People s Republic of Korea, Democratic Republic of the Congo, Denmark, Djibouti, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Eritrea, Estonia, Ethiopia, Ethiopia PDR, Faroe Islands, Fiji, Finland, France, French Guiana, French

Polynesia, Gabon, Gambia, Georgia, Germany, Ghana, Greece, Grenada, Guadeloupe, Guam, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, Hungary, Iceland, India, Indonesia, Iran (Islamic Republic of), Iraq, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kazakhstan, Kenya, Kiribati, Kuwait, Kyrgyzstan, Lao People s Democratic Republic, Latvia, Lebanon, Lesotho, Liberia, Libya, Lithuania, Madagascar, Malawi, Malaysia, Maldives, Mali, Malta, Marshall Islands, Martinique, Mauritania, Mauritius, Mexico, Mongolia, Montserrat, Morocco, Mozambique, Myanmar, Namibia, Nauru, Nepal, Netherlands, New Caledonia, New Zealand, Nicaragua, Niger, Nigeria, Niue, Norway, Oman, Pacific Islands Trust Territory, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Poland, Portugal, Puerto Rico, Qatar, Republic of Korea, Republic of Moldova, Réunion, Romania, Russian Federation, Rwanda, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Samoa, Sao Tome and Principe, Saudi Arabia, Senegal, Serbia and Montenegro, Seychelles, Sierra Leone, Singapore, Slovakia, Slovenia, Solomon Islands, Somalia, South Africa, Spain, Sri Lanka, Sudan (former), Suriname, Swaziland, Sweden, Switzerland, Syrian Arab Republic, Tajikistan, Thailand, The former Yugoslav Republic of Macedonia, Timor-Leste, Togo, Tokelau, Tonga, Trinidad and Tobago, Tunisia, Turkey, Turkmenistan, Tuvalu, Uganda, Ukraine, United Arab Emirates, United Kingdom, United Republic of Tanzania, United States of America, Uruguay, USSR, Uzbekistan, Vanuatu, Venezuela (Bolivarian Republic of), Viet Nam, Wallis and Futuna Islands, Western Sahara, Yemen, Yugoslav SFR, Zambia, and Zimbabwe.

The 77 crops include in the dataset were almonds, apples, apricots, asparagus, avocados, bananas, barley, green beans, broad beans, horse beans, cabbages, carrots and turnips, cassava, cauliflowers and broccoli, cereals, cherries, chick peas, chillies and peppers, cocoa beans, coconuts, green coffee beans, cucumbers and gherkins, eggplants, figs, citrus fruit, garlic, grapefruit (inc. pomelos), grapes, groundnuts, lemons and limes, lentils, lettuce and chicory, linseed, maize, mangoes, mangosteens, guavas, melons (inc.cantaloupes), millet, oats, palm fruit oil, onions, oranges, papayas, peaches and nectarines, pears, green peas, pineapples, plantains, plums and sloes, potatoes, pulses, pumpkins, squash and gourds, rice paddy, roots and tubers, rye, seed cotton, sesame seed, sorghum, soybeans, strawberries, sugar beet sugar cane, sunflower seed, sweet potatoes, taro (cocoyam), tea, unmanufactured tobacco, tomatoes, watermelons, wheat, and yams.

THESIS OUTLINE

My thesis is comprised of four sections. Chapter 1 includes a detailed introduction providing information regarding factors affecting crop production and its current prospects with respect to food security. Also in this chapter are reviews of the relevant literature and a summary of previous work on spatial and temporal variability. An outline of the exploration into spatiotemporal dynamics of crop yields is also included, along with the research approach used. In chapter 2, I aimed to investigate the possibility to substitute spatial variability for temporal variability in crop yields, the conditions that allow the substitution, as well as scale effects on their relationship. Chapter 3 explores the factors that affect synchrony and persistence, and whether some factors may be more important than others. Finally, chapter 4 contains an overall summary of results as well as concluding thoughts. The strength and limitation of this work are also presented along with its implications and potential future directions.

LITERATURE CITED

Aimin, L., Zhiming, F., & Liming, X. (2000). The modern precision agriculture and technological system. *Journal of China Agricultural University*, *5*(2), 20-25.

Annicchiarico, P. & Iannucci, A. Breeding strategy for faba bean in southern Europe based on cultivar responses across climatically contrasting environments. *Crop Sci.* 48, 983–991 (2008).

Antle, J. M. (2015). Climate Change and Food Security: Improving the Relevance and Credibility of Global and Regional Integrated Assessments. *FACCE MACSUR Reports*, *4*, 4-1.

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., ... & Williams, J. R. (2013). Uncertainty in simulating wheat yields under climate change. *Nature Climate Change*, *3*(9), 827-832.

Avnery, S., Mauzerall, D. L., Liu, J., & Horowitz, L. W. (2011). Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. *Atmospheric Environment*, *45*(13), 2284-2296.

Bellemare, M. F. (2015). Rising food prices, food price volatility, and social unrest. *American Journal of Agricultural Economics*, *97*(1), 1-21.

Brauman, K. A., Siebert, S., & Foley, J. A. (2013). Improvements in crop water productivity increase water sustainability and food security—a global analysis. *Environmental Research Letters*, *8*(2), 24-30.

Cai, W., Borlace, S., Lengaigne, M., Van Rensch, P., Collins, M., Vecchi, G., ... & Jin, F. F. (2014). Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*, *4*(2), 111-116.

Calderini, D. F., & Slafer, G. A. (2001). Changes in yield and yield stability in wheat during the 20th century. *Field Crops Research*, *57*(3), 335-347.

Canadell, J. G., Le Quéré, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., ... & Marland, G. (2007). Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the national academy of sciences*, *104*(47), 18866-18870.

Charney, J. G. (1975). Dynamics of deserts and drought in the Sahel. Quarterly Journal of the Royal Meteorological Society, 101(428), 193-202.

Chunjiang, Z., Xuzhang, X., Xiu, W., Liping, C., Yuchun, P., & Zhijun, M. (2003). Advance and prospects of precision agriculture technology system [J]. *Transactions of the chinese society of agricultural engineering*, *4*, 001.

Debnath, D., Thompson, W., Helmar, M., & Julian, B. (2014). Long term consequences of changing global food consumption patterns on US agricultural commodity export demand. *Agricultural and Applied Economics Association*, 27(14), 170490.

Diacono, M., Castrignanò, A., Troccoli, A., De Benedetto, D., Basso, B., & Rubino, P. (2012). Spatial and temporal variability of wheat grain yield and quality in a Mediterranean environment: A multivariate geostatistical approach. *Field Crops Research*, *131*, 49-62.

Dore, M. H. (2005). Climate change and changes in global precipitation patterns: what do we know?. *Environment international*, *31*(8), 1167-1181.

Erisman, J. W., Sutton, M. A., Galloway, J., Klimont, Z., & Winiwarter, W. (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience*, *1*(10), 636-639.

Fader, M., Gerten, D., Krause, M., Lucht, W., & Cramer, W. (2013). Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. *Environmental Research Letters*, *8*(1), 014046.

Flores, F., Nadal, S., Solis, I., Winkler, J., Sass, O., Stoddard, F. L., ... & Rubiales, D. (2012). Faba bean adaptation to autumn sowing under European climates. *Agronomy for sustainable development*, *32*(3), 727-734.

Friel, S., & Ford, L. (2015). Systems, food security and human health. *Food Security*, *7*(2), 437-451.

Gilland, B. (2002). World population and food supply: Can food production keep pace with population growth in the next half-century?. *Food Policy*, *27*(1), 47-63.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., ... & Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. *science*, *327*(5967), 812-818.

Hammond, M. P., & Kolasa, J. (2014). Spatial variation as a tool for inferring temporal variation and diagnosing types of mechanisms in ecosystems. *PloS one*, *9*(2), e89245.

Hansen, J., Ruedy, R., Sato, M., & Lo, K. (2010). Global surface temperature change. *Reviews of Geophysics*, *48*(4).

Hart, C. E., & Schulz, L. L. (2015). Retail Meat and Crop Demand Continue to Grow. *Agricultural Policy Review*, *2014*(1), 3.

Hendrix, C. S., & Salehyan, I. (2012). Climate change, rainfall, and social conflict in Africa. *Journal of Peace Research*, *49*(1), 35-50.

Jensen, E. S., Peoples, M. B., & Hauggaard-Nielsen, H. (2010). Faba bean in cropping systems. *Field Crops Research*, *115*(3), 203-216.

Kamran, A., & Asif, M. (2011). Climate Change and Crop Production. *Crop Science*, *51*(5), 2299-2300.

Ker, A. P., & Coble, K. (2003). Modeling conditional yield densities. *American Journal of Agricultural Economics*, *85*(2), 291-304.

Klein Goldewijk, K., Beusen, A., Van Drecht, G., & De Vos, M. (2011). The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecology and Biogeography*, *20*(1), 73-86.

Knox, J., Hess, T., Daccache, A., & Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, *7*(3), 034032.

Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., & Naylor, R. L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science*, *319*(5863), 607-610.

Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science*, *333*(6042), 616-620.

McMichael, A. J. (2001). Impact of climatic and other environmental changes on food production and population health in the coming decades. *Proceedings of the nutrition Society*, *60*(02), 195-201.

Meij, J. L. (1960). Mechanization in agriculture. *Mechanization in agriculture,* 1(1), 27-56.

Meyer, D., Mytelka, L., Press, R., Dall'Oglio, E. L., de Sousa Jr, P. T., & Grubler, A. (2014). Brazilian Ethanol: Unpacking a Success Story of Energy Technology Innovation. *Energy Technology Innovation*, *275*.

Mitchell, D. (2008). A note on rising food prices. *World Bank Policy Research Working Paper Series, Vol*.

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature*, *490*(7419), 254-257.

Nishimura, S., Sawamoto, T., Akiyama, H., Sudo, S., & Yagi, K. (2004). Methane and nitrous oxide emissions from a paddy field with Japanese conventional water management and fertilizer application. *Global Biogeochemical Cycles*, *18*(2).

Parry, M. L., Rosenzweig, C., Iglesias, A., Livermore, M., & Fischer, G. (2004). Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change*, *14*(1), 53-67.

Pimentel, D., Hurd, L. E., Bellotti, A. C., Forster, M. J., Oka, I. N., Sholes, O. D., & Whitman, R. J. (1973). Food production and the energy crisis. *Science*,*182*(4111), 443-449.

Pinstrup-Andersen, P. (2009). Food security: definition and measurement. *Food security*, *1*(1), 5-7.

Ray, D. K., Gerber, J. S., MacDonald, G. K., & West, P. C. (2015). Climate variation explains a third of global crop yield variability. *Nature communications*, *6*.

Ray, D. K., Ramankutty, N., Mueller, N. D., West, P. C., & Foley, J. A. (2012). Recent patterns of crop yield growth and stagnation. *Nature communications*, *3*, 1293.

Reardon, T., & Matlon, P. (1989). Seasonal food insecurity and vulnerability in drought-affected regions of Burkina Faso. 118-136.

Reay, D. S., Davidson, E. A., Smith, K. A., Smith, P., Melillo, J. M., Dentener, F., & Crutzen, P. J. (2012). Global agriculture and nitrous oxide emissions. *Nature Climate Change*, *2*(6), 410-416.

Richard, A. (2012). A new estimate of the average earth surface land temperature spanning 1753 to 2011. *Geoinformatics & Geostatistics: An Overview*.

Rosenzweig, C., & Parry, M. L. (1994). Potential impact of climate change on world food supply. *Nature*, *367*(6459), 133-138.

Sherrick, B. J., Zanini, F. C., Schnitkey, G. D., & Irwin, S. H. (2004). Crop insurance valuation under alternative yield distributions. *American Journal of Agricultural Economics*, *86*(2), 406-419.

Shi, G., Chavas, J. P., & Lauer, J. (2013). Commercialized transgenic traits, maize productivity and yield risk. *Nature Biotechnology*, *31*(2), 111-114.

Sinclair, T. R., Purcell, L. C., & Sneller, C. H. (2004). Crop transformation and the challenge to increase yield potential. *Trends in plant science*, *9*(2), 70-75.

Sitch, S., Cox, P. M., Collins, W. J., & Huntingford, C. (2007). Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature*, *448*(7155), 791-794.

Solomon, S., Plattner, G. K., Knutti, R., & Friedlingstein, P. (2009). Irreversible climate change due to carbon dioxide emissions. *Proceedings of the national academy of sciences*, *106*(6), 1704-1709.

Subramanian, S., & Deaton, A. (1996). The demand for food and calories. *Journal of political economy*, 133-162.

Tester, M., & Langridge, P. (2010). Breeding technologies to increase crop production in a changing world. *Science*, *327*(5967), 818-822.

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, *108*(50), 20260-20264.

Tilman, David, et al. "Agricultural sustainability and intensive production practices." *Nature* 418.6898 (2002): 671-677.

Timilsina, G. R., Beghin, J. C., Van der Mensbrugghe, D., & Mevel, S. (2012). The impacts of biofuels targets on land-use change and food supply: A global CGE assessment. *Agricultural Economics*, *43*(3), 315-332.

Turner, A. G., & Annamalai, H. (2012). Climate change and the South Asian summer monsoon. *Nature Climate Change*, *2*(8), 587-595.

Urban, D., Roberts, M. J., Schlenker, W., & Lobell, D. B. (2012). Projected temperature changes indicate significant increase in interannual variability of US maize yields. *Climatic change*, *112*(2), 525-533.

Wodon, Q., & Zaman, H. (2008). Rising food prices in sub-Saharan Africa: Poverty impact and policy responses. *The World Bank Research Observer*, *25*(1), 157-176.

Zhang, S., Sadras, V., Chen, X., & Zhang, F. (2014). Water use efficiency of dryland maize in the Loess Plateau of China in response to crop management. *Field Crops Research*, *163*.

Chapter 2

Examining the relationship between spatial and temporal variability in crop yields

ABSTRACT

Variation in crop yields has significant impacts on food supply (i.e., cost & availability) in many developing nations. I applied a recently quantified link between spatial and temporal variation to gain general insights into the dynamics of food production, as well as to test whether a prediction that relies on space-for-time substitution applies for crop yields, and at which spatial scale. I analyzed patterns of variation on global yield for 77 crops recorded in 212 countries over 22 years (1990 – 2012). I found that if we know how crop yields vary in space, we could predict variation in crop yields over time, at various scales. Specifically, spatial variation can substitute for temporal variation in predicting the variability of yield of certain staple crops when synchrony and persistence (persistence = consistent differences in mean yield values among locations or regions) are taken into account. For example, logged summed spatial variance and logged aggregate temporal variance for all crops at the country scale are correlated with r^2 value of 0.847. I believe that this space-time substitutability has potential to forecast temporal stability of food production from its spatial data alone, which should allow countries and various agencies to improve agricultural policies and production forecasts to ensure stability in local and global food supply.

Key Words: *spatiotemporal, variability, crop yields, crop production, synchrony, spatial persistence, food security*

RATIONALE AND OBJECTIVES

The goal of this chapter is to investigate the link between spatial variance and temporal variance in crop yields. These two kinds of variations allow predicting one from the other in many situations. The objective of this study is to determine whether spatial variance could be an accurate predictor for regional temporal variance of crop yields at various scales. The reason for this is that while data allowing calculation of spatial variation is currently available, projections of temporal variation are of practical importance. Since crop yields are the most important aspect in raising global crop production, the ability to accurately forecast the magnitude of fluctuation in upcoming crop yields would aid governing bodies in dealing with uncertainties and make informed decisions in the context of food management. The ability to predict the level of uncertainty can also benefit agricultural activities from small local farmers to larger corporate growers alike. Through this study, I found:

- Crop yields at the global scale showed significant correlation between their regional temporal variance and mean spatial variance.
- The accuracy of the spatial variance for predicting temporal variance diminishes as spatial gradients across countries or regions persist through time, which shifts crop variables into the persistence region of the model (see later on for details) where spatial variance overestimates temporal variance.

- Most crops generally showed high values of index of persistence across all scales. Crops with higher variability tend to be more spatially persistent.
- By comparison, the values of index of synchrony for most crop yields across all scales were much lower than index of persistence.
- Some crops have similar degrees of synchrony and persistence.

These results suggest that some crops are better candidates than others for using spatial data to forecast their temporal variability in yields. These include crops that have similar values of synchrony and persistence to cancel each other's effects on the crop's spatiotemporal dynamic. The result of this study provides a basis for future study (Chapter 3) that will investigate the factors that influence crop's synchrony and persistence.

INTRODUCTION

Global demand for agricultural products is continuing to rise due to population growth, increased per capita income, rise of biofuels and short-term decline in prices (Mitchell, 2008). The global population is set to reach around 9.3 billion by 2050, which is about a 33% increase from the 7 billion mark at the end of 2011 (Ezeh *et al*., 2012). A predicted 1.4% increase in per capita income is expected to result in greater demand for feed for livestock, especially in developing countries (Alexandratos & Bruinsma, 2012; Keyzer *et al*., 2005). Rising energy prices and shift in policies are expected to raise demands for feedstock to produce biofuels and other industrial materials (Tilman *et al*., 2009). These factors all interplay to elevate global demand for crops.

Increasing crop supply mainly comes in one of two ways: increasing crop area or boosting crop yields. Crop area is a function of arable land area and intensity of cropping (Lambin *et al*., 2000). As increase in arable land area becomes increasing unfeasible in many countries, yield progress will likely remain as the primary focus to boost crop supply in the coming decades (Edgerton, 2009). Crop yield refers to the measure of the production of crop mass per unit area of land under cultivation, and is related to a number of factors (Evans & Fischer, 1999). Aside from obvious climatic variables (e.g., temperature and precipitation) that could affect a country's annual crop yields, many technological variables are also sources of difference in yields between countries (De Ponti *et* al., 2012; Lobell & Field, 2007). Mechanization, crop variety (e.g., genetically modified variety), fertilizers, irrigation, herbicides, pesticides, crop density and the use of greenhouse are some of the factors that could influence crop yields (Challinor & Ramirez-Villegas, 2015; Minten & Barrett, 2008; Shukla & Mallick, 2015).

Crop yields, like most ecological variables, exhibit variation in space as well as in time. Annual yield of a particular crop can vary between countries, representing spatial variability (Mueller *et al.*, 2012). Crop yields within a particular region can also differ from year to year, representing temporal variability (Ray *et al*., 2015). With the strong relationship between crop yield and production quantity, future trajectories of food prices and food security are closely linked to future crop yields in the major agricultural regions of the world (Lobell *et al*., 2009). However, projecting crop yields is fraught with uncertainties (Wang *et al*., 2005). Anticipating future crop yields is clearly important but projected yield trajectories lose their usefulness whenever yields are subject to major year-to-year variation. Assessing this variation may be critical for some if not all crops. The ability to accurately forecast the magnitude of fluctuation in upcoming crop yields would aid governing bodies in dealing with uncertainties and make informed decisions in the context of food management.

Variation is a feature of all natural processes across a range of scales. Spatiotemporal patterns are found across landscapes and play a major role in the ecological dynamics of agriculture (Turner, 1990). It would be quite useful to be able to predict how crop yields vary in time. However, temporal data in crop yields are limited since production dynamics occur over timescales that was well beyond the duration of kept records. Using a new theoretical approach, I attempt to predict magnitude of probable temporal variation of crop yields using its spatial variance.

This type of approach using space-for-time substitution has a long tradition in ecology. The ecological pioneer, Henry Chandler Cowles has demonstrated the feasibility in extrapolating temporal dynamics by comparing multiple sites in a region using chronosequence methods (Johnson *et al*., 2008). This approach is also widely used in biodiversity modeling by using spatial patterns to infer past or future trajectories of ecological systems (Blois *et al*., 2013). In fact, applying a space-time correspondence to infer temporal dynamics follows more than a century of studies involving substitution (Johnson *et al*., 2008). But until recently, this relationship has only been described qualitatively.

A quantitative link between spatial and temporal variability has recently been described by Hammond & Kolasa (2014) using the following equation:

$$\mathrm{Var(Y)} = \frac{\mathrm{n_i}}{\mathrm{n_k}}\sum_{k=1}^{n}\mathrm{var(X_k)} + \frac{2\mathrm{n_i}}{\mathrm{n_i}-1}\sum_{\mathrm{i=1}}^{\mathrm{n}}\sum_{\mathrm{j=1}}^{\mathrm{i-1}}\mathrm{cov(X_i, X_j)} - \frac{2\mathrm{n_i}}{\mathrm{n_k^2}-\mathrm{n_k}}\sum_{\mathrm{k=1}}^{\mathrm{n}}\sum_{\mathrm{l=1}}^{\mathrm{k-1}}\mathrm{cov(X_k, X_l)}$$

where Var(Y) refers to the variance of an aggregated variable, var(X_k) refers to the variance over its components, cov(X_i, X_j) refers to the covariance of the components in time (*i*, *j*), and $cov(X_k, X_l)$ refers to covariance in components in space (*k,l*).

This model links regional temporal variance of a process (Var(Y)) to summed spatial variances at time *k* (Σ $var(X_k)$). This relationship is modified by inter-patch synchrony ($\Sigma cov(X_i,X_j)$) and spatial persistence ($\Sigma cov(X_k,X_l)$). Synchrony can be measured as the ratio of aggregate temporal variance to the component temporal variances, where components refer to the patches within the aggregate (Loreau, 2008). In other words, it refers to the similarity in temporal changes of crop yields between countries in consideration of its absolute magnitude. Spatial persistence is the ratio of temporally aggregated variance to its component spatial variances (Hammond & Kolasa, 2014). It refers to the lack of changes in spatial differences between countries from year to year. Specifically, a high inter-patch synchrony value boosts temporal variance at the regional scale, while a high spatial persistence value lowers temporal variance. Synchrony has an effect on boosting temporal variability and lowering spatial variability by aligning peaks and troughs of fluctuations. Spatial persistence on the other hand, has an effect on lowering temporal variability and boosting spatial variability by stabilizing fluctuation of patches over time (Hammond & Kolasa, 2014).

This model has been tested, and a strong relationship was shown between spatial and regional temporal variation in 136 variables from three aquatic ecosystems of microcosm, rock pools and lakes (Hammond & Kolasa, 2014). Strong relationship was shown between spatial and regional temporal variation, as significant linear regression existed between spatial CV and regional temporal CV for real ecosystem variables (Hammond & Kolasa, 2014). This verified that spatial and temporal CV's are related and substitutable to the degree that synchrony or persistence does not interfere. More importantly, the model allows distinguishing between unbiased, stochastic variation and variation dominated by either synchrony among components or by persistent spatial differences. As such, it suggests general categories of mechanisms responsible for the observed variation in a collection of variables used to characterize a particular natural system (Hammond & Kolasa, 2014).

Using ANOVA variance partitioning as the theoretical foundation to tie temporal and spatial variation of a given variable, Hammond and Kolasa (2014) had come up with the aforementioned equation to break down overall spatiotemporal variation into its spatial and temporal components. This formulation can also be represented by the following corresponding relative relationship that uses unit-less coefficients:

$$CV_Y \cong \frac{1}{\sqrt{n_i}} \overline{CV_k} \qquad + \varphi_T \qquad - \varphi_S$$

where CV_Y is the temporal coefficient of variation of an aggregated variable, CV_k represents its spatial variance, φ_T represents its synchrony, φ_S represents index of spatial persistence. Here, regional temporal variance is represented by regional temporal coefficient of variation; spatial variance is represented by mean spatial CV; while inter-patch co-variances and inter-time co-variances are represented by indices of synchrony and persistence respectively. In this approximation, regional temporal CV is obtained by dividing the standard deviation of the aggregate time series by the mean, while mean spatial CV is obtained by taking the average of spatial CVs measured at time *k*. This simpler equation provides a useful approximation, which scales regional temporal CV to mean spatial CV by a factor of 1 over square root of number of patches (n_i) when synchrony and persistence are negligible.

Plotting spatial variability vs. temporal variability shows three regions in which a variable can fall under: independent dynamics region, synchrony region, and persistence region (Figure 2-1). A variable falls under the independent dynamics region when values are independent between patches and between time points. A variable falls under the synchrony region when inter-patch synchrony boosts temporal variance. Lastly, a variable falls under the persistence region when spatial gradients are retained over time.

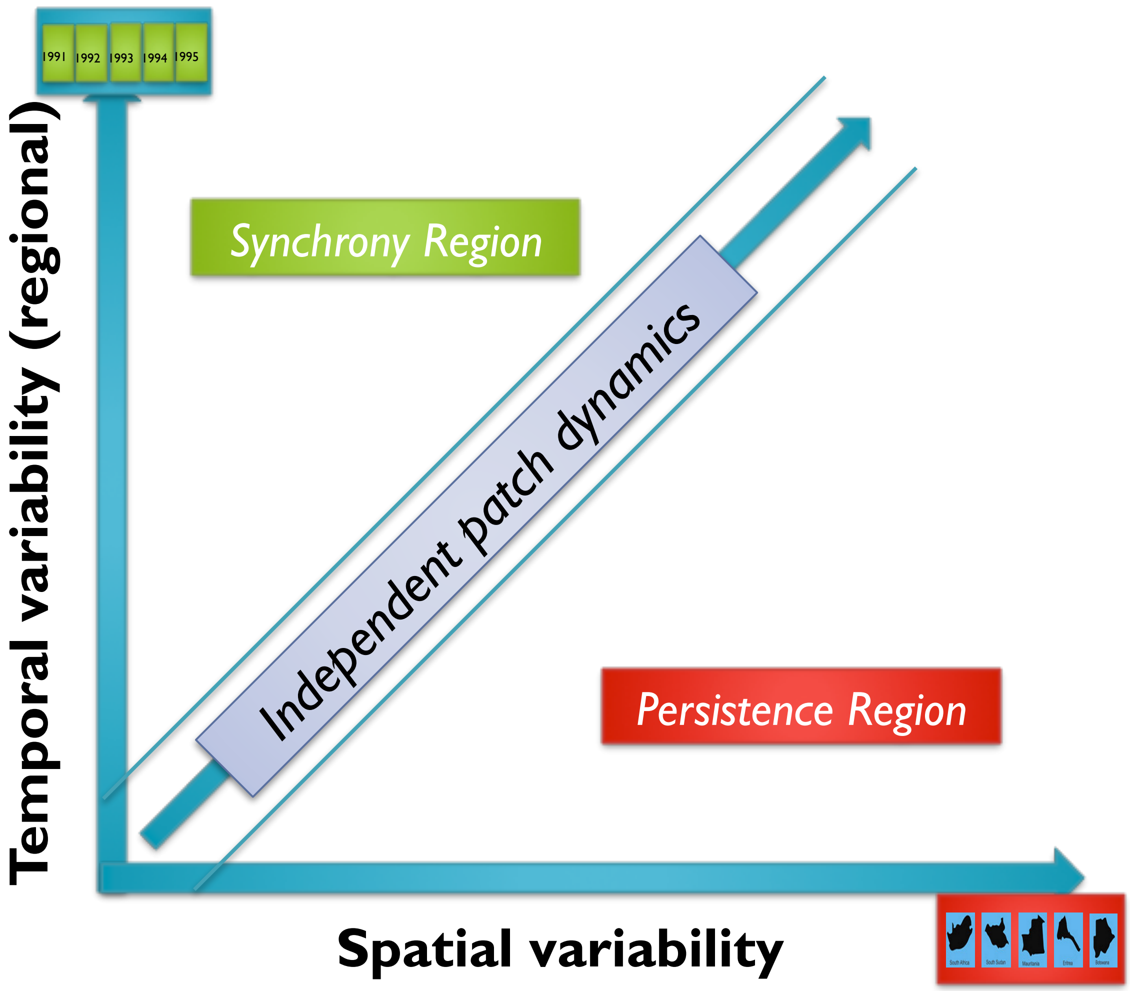

Figure 2-1: Plotting spatial vs. temporal variation against each other yields three interpretable regions a variable can fall into: 1. Independent dynamics region when values are independent between patches and between time points; 2. Synchrony region when inter-patch synchrony boosts temporal CV; 3. Persistence region when spatial gradients are retained over time. Modified after Hammond & Kolasa (2014)

The goal of this research is to apply the model at a broader scale, specifically in the context of global crop yields. If the model is indeed applicable and effective, it should be able to correctly identify the known mechanisms responsible for crop variation, as well as uncovering novel mechanism particularly at the regional and continental scale. Spatial and temporal variations, could have a strong connection that makes it possible to predict one from the other. I therefore hypothesized that spatial crop yield data enable the prediction of temporal variability of that crop.

METHODS

Data organization

The bulk of my data was obtained from the statistical database of the Food and Agriculture Organization of the United Nations. Specifically, the organized data set included the crop yields of 77 crops for 212 countries over 23 years from 1990 – 2012. All yields were measured in hectogram per hectare, and computed from detailed harvest area and production data expressed in hectares and hectograms respectively.

The 77 crops include in the dataset were almonds, apples, apricots, asparagus, avocados, bananas, barley, green beans, broad beans, horse beans, cabbages, carrots and turnips, cassava, cauliflowers and broccoli, cereals, cherries, chick peas, chillies and peppers, cocoa beans, coconuts, green coffee beans, cucumbers and gherkins, eggplants, figs, citrus fruit, garlic, grapefruit (inc. pomelos), grapes, groundnuts, lemons and limes, lentils, lettuce and chicory, linseed, maize, mangoes, mangosteens, guavas, melons (inc.cantaloupes), millet, oats, palm fruit oil, onions, oranges, papayas, peaches and nectarines, pears, green peas, pineapples, plantains, plums and sloes, potatoes, pulses, pumpkins, squash and gourds, rice paddy, roots and tubers, rye, seed cotton, sesame seed, sorghum, soybeans, strawberries, sugar beet sugar cane, sunflower seed, sweet potatoes, taro (cocoyam), tea, unmanufactured tobacco, tomatoes, watermelons, wheat, and yams.

To study the effect of scales, countries were also aggregated into continents, sub-regions and general bands of latitudes. In this study, the six continents relevant in crop productions are Africa, Asia, Europe, North America, Oceania, and South America. The list of countries that fall under each continent can be found in table 2.1, appendix A.

Sub-regions were country aggregates devised by the Statistic Divisions of United Nations in 1999. By convention, the 22 sub-regions relevant in crop productions are Australia and New Zealand, Caribbean, Central Africa, Central America, Central Asia, Eastern Africa, Eastern Asia, Eastern Europe, Melanesia, Micronesia, North America, North Africa, Northern Europe, Polynesia, South

America, South-Eastern Asia, Southern Africa, Southern Asia, Southern Europe, Western Africa, Western Asia, and Western Europe (Figure 2-2). The list of countries that fall under each sub-region can be found in table 2.2, appendix A.

Figure 2-2. The 22 sub-regions relevant in crop productions: Australia and New Zealand, Caribbean, Central Africa, Central America, Central Asia, Eastern Africa, Eastern Asia, Eastern Europe, Melanesia, Micronesia, North America, North Africa, Northern Europe, Polynesia, South America, South-Eastern Asia, Southern Africa, Southern Asia, Southern Europe, Western Africa, Western Asia, and Western Europe.

General latitudes are country aggregates based on country's proximity to the general lines of constant latitude or parallels running east west as circles parallel to the equator. The 7 general latitudes relevant in crop productions are 0°, 15°N, 15°S, 30°N, 30°S, 45°N, 60°N (Figure 2-3). The list of countries that fall under each of the general latitudes can be found in table 2-3, appendix A.

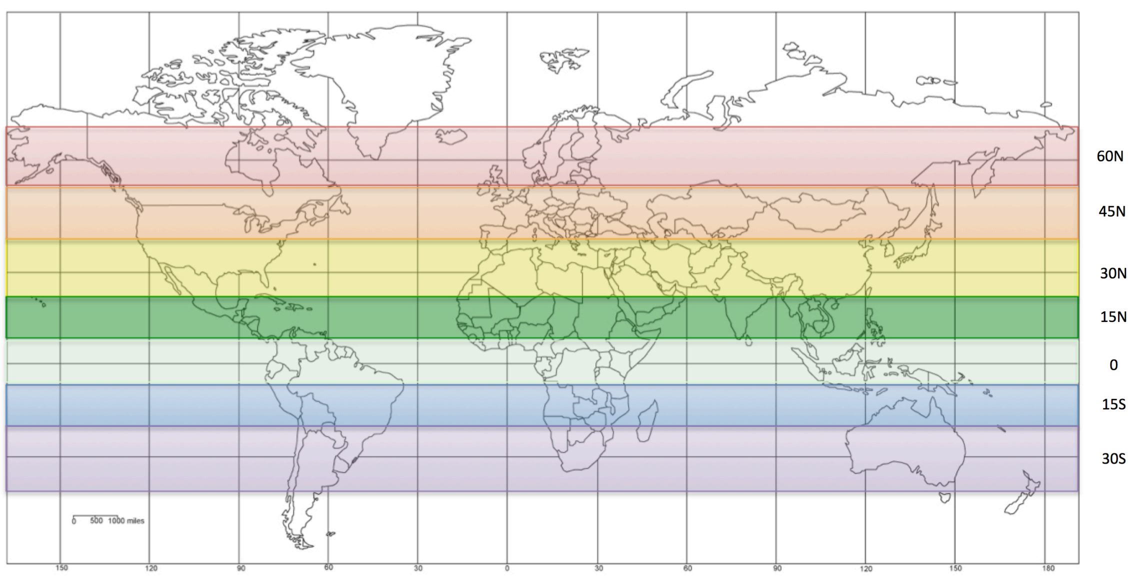

Figure 2-3. The 7 bands of general latitudes relevant in crop productions: 0°, 15°N, 15°S, 30°N, 30°S, 45°N, 60°N.

Statistical Analysis

All data were analyzed using JMP 12 (SAS Institute Inc., Toronto, Ontario, Canada).

Linking spatial variance and temporal variance

Crop yields vary over time (*k…l*) and across patches (*i…j*), which can be represented by mean spatial CV and aggregate temporal CV respectively. Least squares regression lines were calculated to compare the global spatial variation to temporal variation of crop yields by plotting the mean spatial CV against aggregate mean temporal CV. Coefficient of variation is a normalized measure of dispersion of a probability distribution, and it represents a ratio of the standard deviation to the mean. The following demonstrates the steps taken to obtain the mean spatial CV and aggregate mean temporal CV.

Mean spatial CV: At the global scale, the spatial CV for a particular crop yield in a particular year was calculated by taking the standard deviation of crop yields across all countries in a particular year and dividing that by the global yield mean to obtain the spatial CV for each year. The mean spatial CV of a crop was then obtained by taking the average of all 23 spatial CVs available for each of the 23 year.

Aggregate mean temporal CV: At the global scale, the global yield total for each year was added up to obtain the aggregate sums for each of the 23 years. The aggregate temporal CV was then obtained by dividing the standard deviation of the 23 aggregated sums by the mean.

With the above calculations, 77 pairs of mean spatial CV and mean aggregate temporal CV values were computed representing each of the 77 crops. To quantify the relationship between mean spatial CV and mean aggregate temporal CV of global crop yields, I performed a regression analysis with the predictor (independent variable) being the mean spatial CV and the criterion (dependent variable) being the mean aggregate temporal CV. The data were log transformed since the residual distribution suggests that the relationship may be better described by a power function. F-tests were then conducted to determine the goodness of fit of the selected model. Residuals were tested for normal distribution using Komogorov-Smirnov test.

The above mean spatial CV versus mean aggregate temporal CV regression analysis was repeated for continents, general latitudes and sub-regions to explore the effects of spatial aggregation (scale) on the relationship.

Indices of synchrony and persistence

I quantified synchrony using φ_T, first proposed by Loreau & de Mazancourt (2008) for species synchrony. This index varies from 0 to 1, and it works by comparing the aggregate temporal variance of an ecological variable to its theoretical maximum if all components were perfectly synchronous. I calculated this index as in Hammond & Kolasa (2014). In brief, for each crop I summed its yields across land units (e.g., continents, sub-regions, general latitudes) within a region to get an aggregate yield for the region. I then divided the variance of this aggregated series by the theoretical maximum variance, which is the squared sum of the temporal standard deviations of land units.

I quantified persistence using φ_S, first proposed by Hammond & Kolasa (2014). This index also varies from 0 to 1, and it works by comparing the temporally aggregated spatial variance to its theoretical maximum if the differences between all components persisted perfectly. I calculated this index as in Hammond & Kolasa (2014). In brief, for each crop, I summed its yields of each land units (e.g., continents, sub-regions, general latitudes) across all time points (i.e., 1990 – 2012) to get the temporally aggregated yield for the regions. I then divided the variance of this aggregated series by the theoretical maximum variance, which is the squared sum of spatial standard deviations of time points.

I calculated the indices of synchrony and persistence for each of the 77 crops at the continental, general latitude, and sub-regional scales.

RESULTS

Relationship between spatial and temporal variability

At the global scale, spatial and aggregate temporal CV's were positively related (Figure 2-4; slope = 0.754, $F = 26.6$, $p < 0.0001$, $r^2 = 0.262$). The slope deviated from the theoretical slope of 1 when patch dynamics are independent from each other ($t(76) = 8.76$, $p < 0.00001$). The regression y-intercept was also displaced down from the theoretical y-intercept of -0.163 – this occurs when patch dynamics were independent from each other ($t(76) = -25.5$, $p < 0.0001$).

At finer scales (i.e., continental, sub-regional, general latitude), there was a wide range of relationships between mean spatial CV's and mean aggregate temporal CV's (Table 2-1, Appendix A). Some relationships were strong, for example Asia, 30°N, and Western Europe (Figure 2-5). However, most relationships were not as strong as the one found at global scale based on p value and R square values. Overall, the average p and R square values were much lower in finer scales than the global scale (Figure 2-6). The comparison was not done statistically however, as there was only one replicate at the global scale.

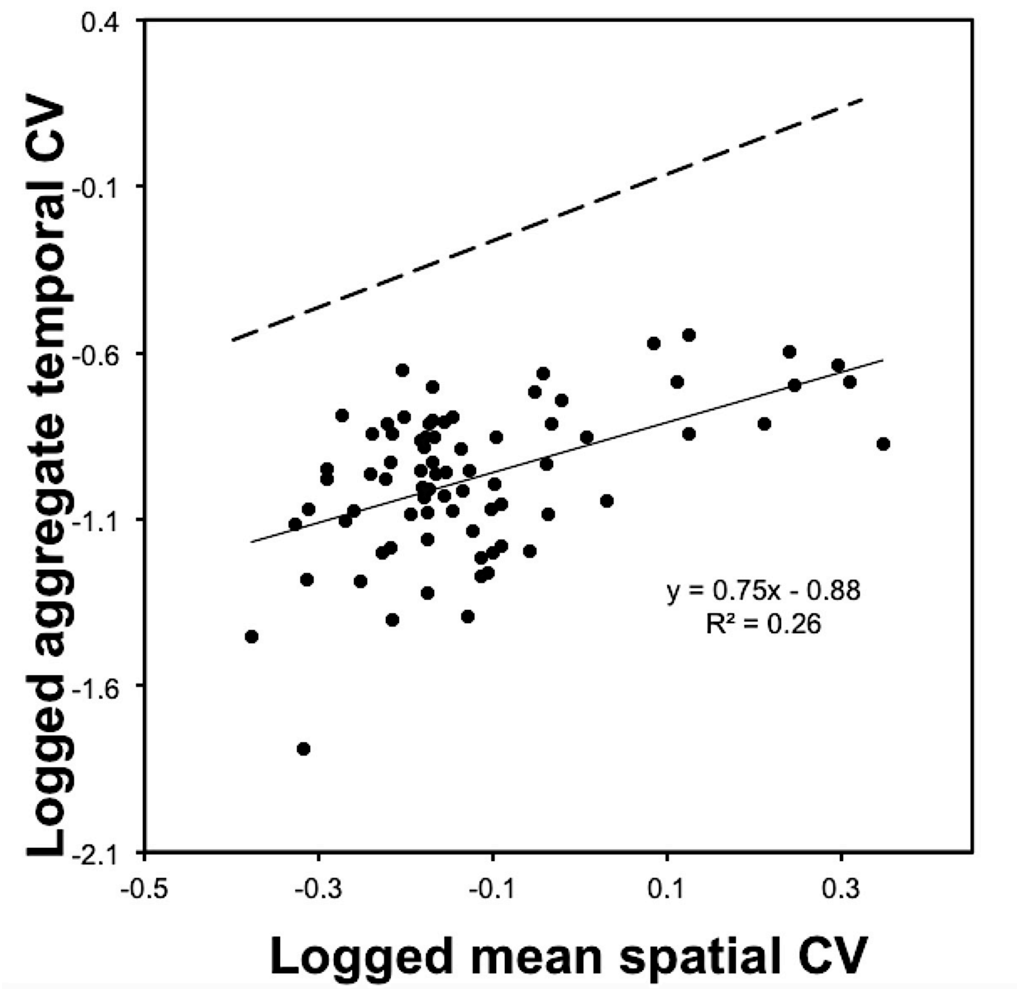

Figure 2-4. Mean aggregate temporal CV increases with the mean spatial CV at the global scale (solid line) at a rate slower than expected if both kinds of variation were independent (broken line). Each point represents a crop.

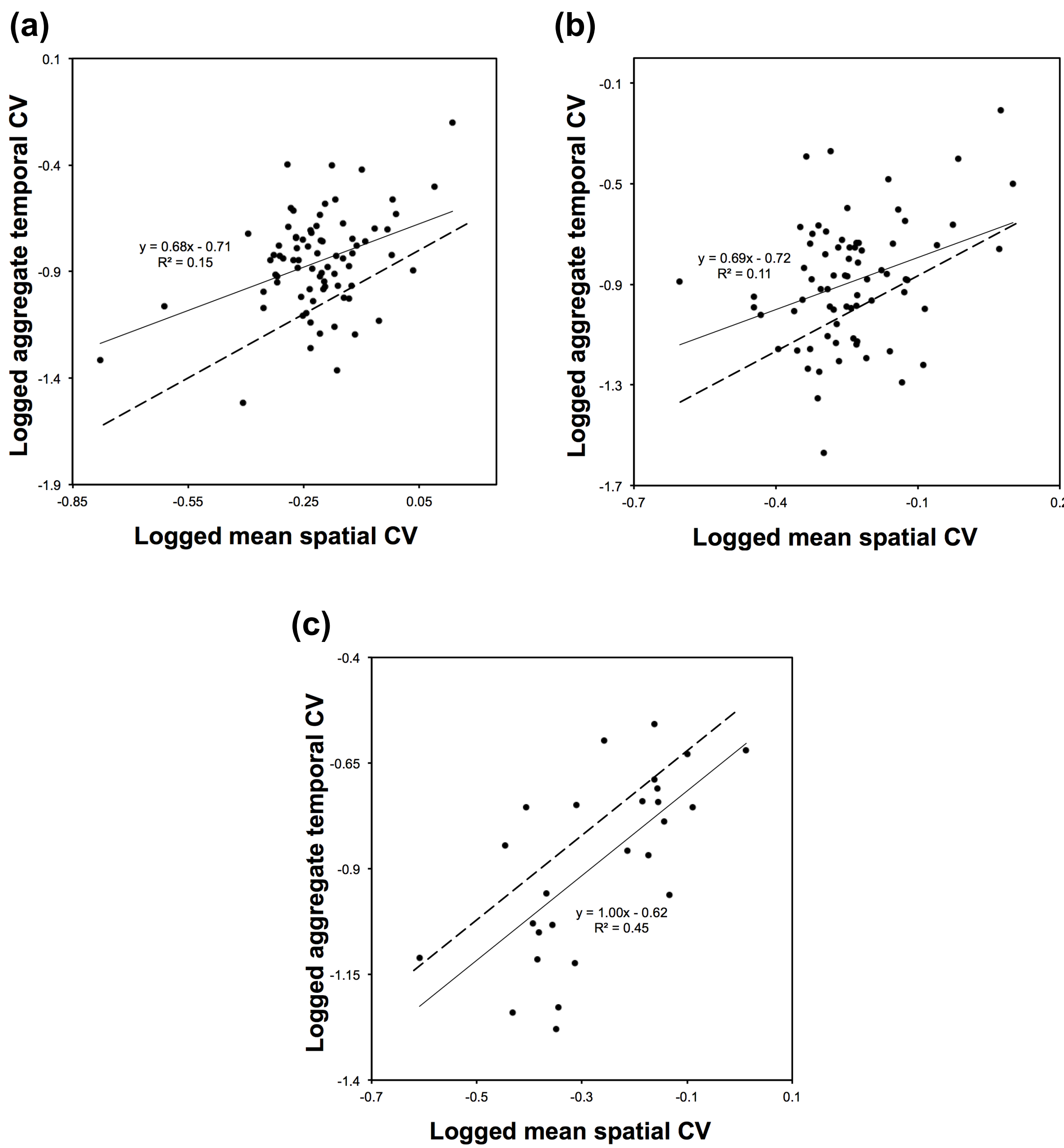

Figure 2-5. Mean aggregate temporal CV increases with the mean spatial CV at **(a)** Asia - continental scale, **(b)** 30°N - general latitude scale, **(c)** and Western Europe – sub-regional scale. Each point represents a crop.

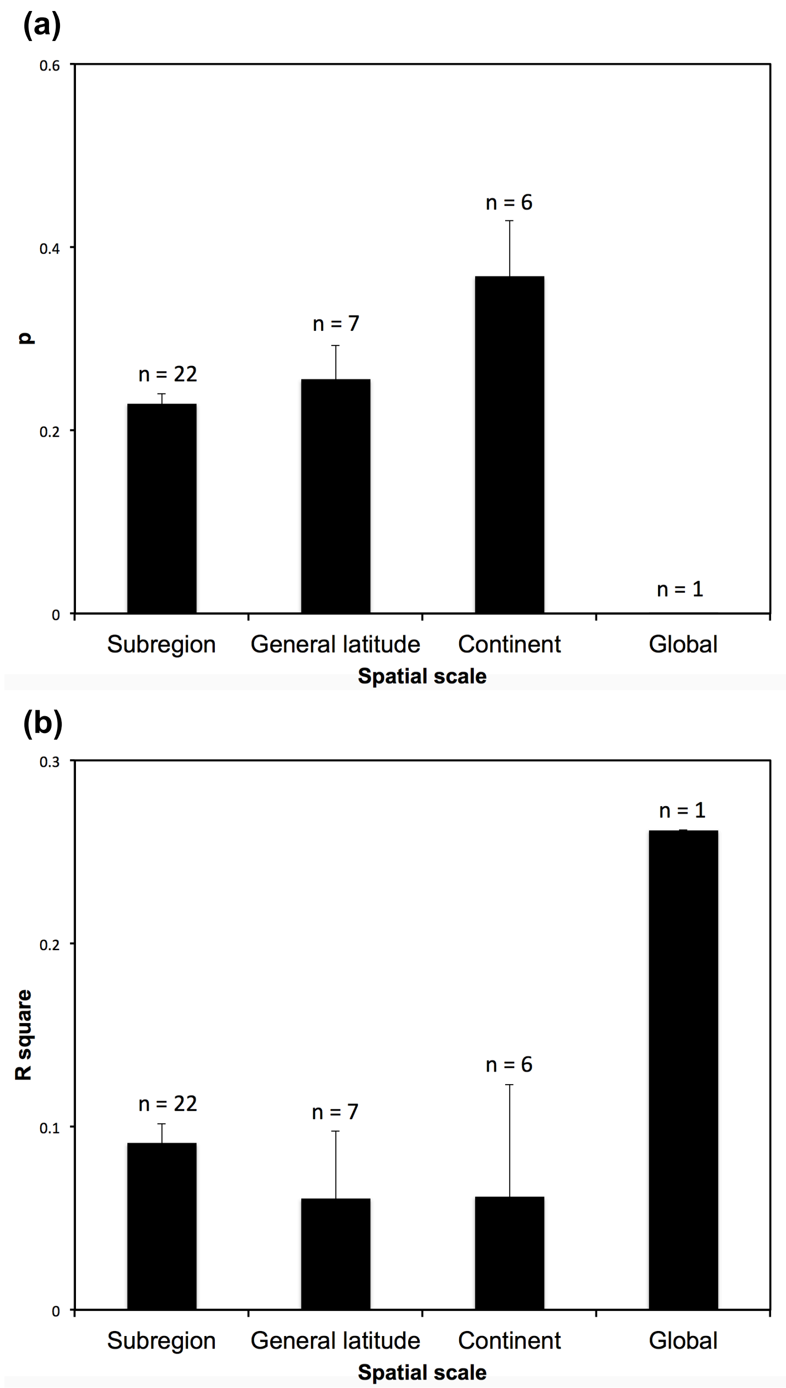

Figure 2-6. Average **(a)** p values and **(b)** R square values for the relationship between mean spatial CV and mean aggregate temporal CV at different scales.

Overall, the relationship was much stronger at the global scale as indicated by the comparatively lower p values and higher R square values than other scales.

Synchrony and persistence

Average index of synchrony was quite high: 0.43 (SD = 0.20) at the sub-regional scale, 0.64 (SD = 0.20) at the general latitude scale, and 0.65 (SD = 0.19) at the continental scale, which implies that yields tend to either rise or fall simultaneously in a particular year at both smaller and larger scales. Average index of persistence was 0.96 (SD = 0.036) at the sub-regional scale, 0.99 (SD = 0.021) at the general latitude scale, and 0.98 (SD = 0.021) at the continental scale, which reflects strong and consistent differences among countries or broader regions (Details and complete results are in Table 2-2, Appendix A).

Persistence was significantly higher than synchrony at all scales (Figure 2-7). At the sub-regional scale, persistence was significantly higher than synchrony ($T(76) = 23.6$, $p < 0.0001$). At the general latitude scale, persistence was significantly higher than synchrony ($T(76) = 16.6$, $p < 0.0001$). At the continental scale, persistence was significantly higher than synchrony ($T(76) = 14.9$, $p < 0.0001$).

Index of synchrony increased with spatial scale (Figure 2-7): smallest at sub-regional scale (M = 0.43, SD = 0.20), intermediate at general latitude (M = 64, SD = 0.20), and largest at continental scale (M = 0.65, SD = 0.19). There was a significant difference in synchrony between the scales, $F(2, 230) = 30.12$, $p < 0.0001$. From the Tukey-Kramer HSD post hoc test, difference in synchrony between continent scale and sub-region scale was significant ($T(76) = -22.87$, $p < 0.0001$), difference in synchrony between general latitude scale and sub-region scale was significant ($T(76) = 23.46$, $p < 0.0001$), while difference in synchrony between continent scale and general latitude scale was insignificant ($T(76) = -1.26$, $p = 0.213$).

Index of persistence increased with spatial scale (Figure 2-7): smallest at sub-regional scale (M = 0.96, SD = 0.036), intermediate at continental scale (M = 0.98, SD = 0.021), and largest at general latitude scale (M = 99, SD = 0.20). There was a significant difference in synchrony between the scales, $F(2, 230) = 20.55$, $p = < 0.0001$. Continent scale and sub-regional scale were differed in synchrony (Tukey-Kramer HSD post hoc test: $T(76) = -7.81$, $p < 0.0001$). Difference in synchrony between general latitude scale and sub-region scale was also significant ($T(76) = 9.39$, $p < 0.0001$), while difference in synchrony between continent scale and general latitude scale was insignificant ($T(76) = 0.76$, $p = 0.451$).

The difference between indices of synchrony and persistence decreased with scale (Figure 2-8, largest at sub-regional scale (M = 0.53, SD = 0.20), intermediate at general latitude scale (M = 0.35, SD = 0.021), and smallest at continental scale (M = 0.34, SD = 0.023).

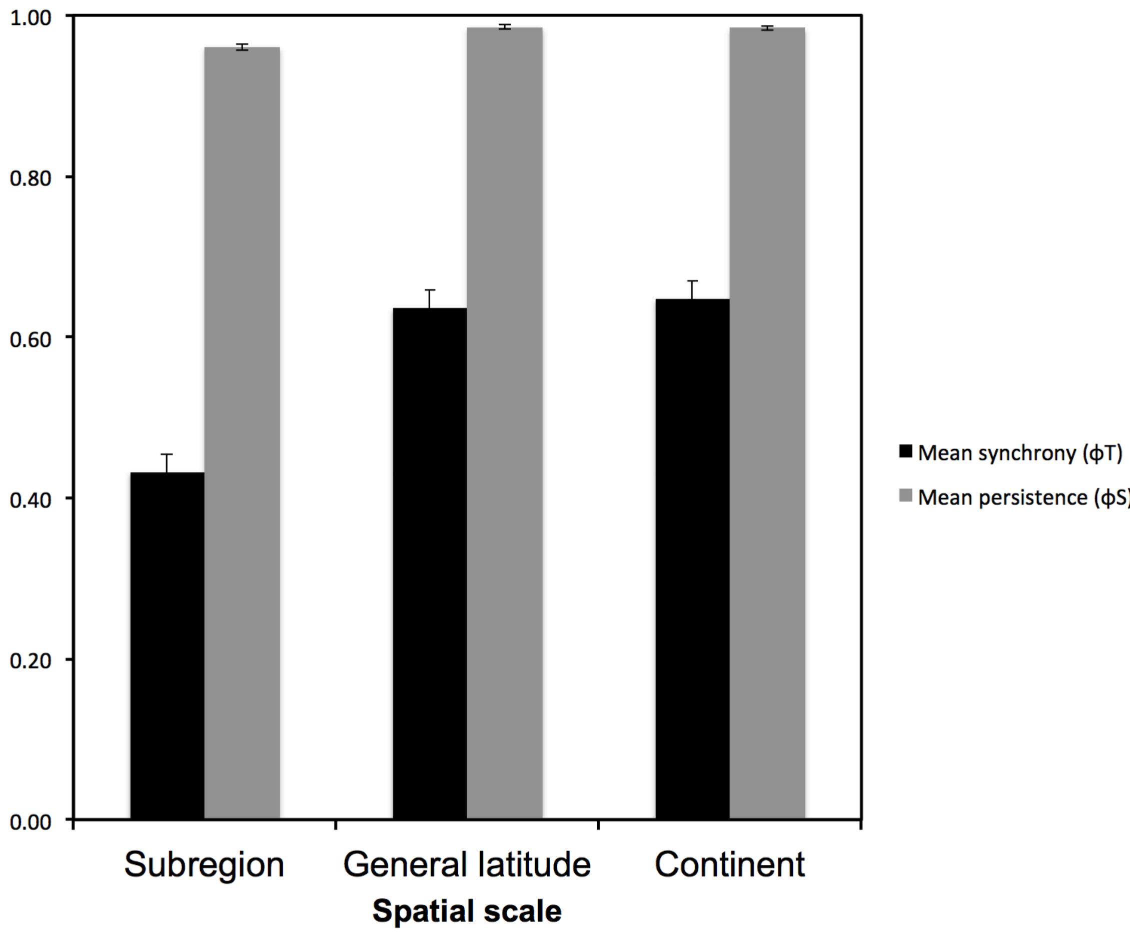

Figure 2-7. Mean index of synchrony (black bars) and mean index of persistence (grey bars) at sub-regional, general latitude, and continental scales. Persistence was significantly higher than synchrony at all spatial scales.

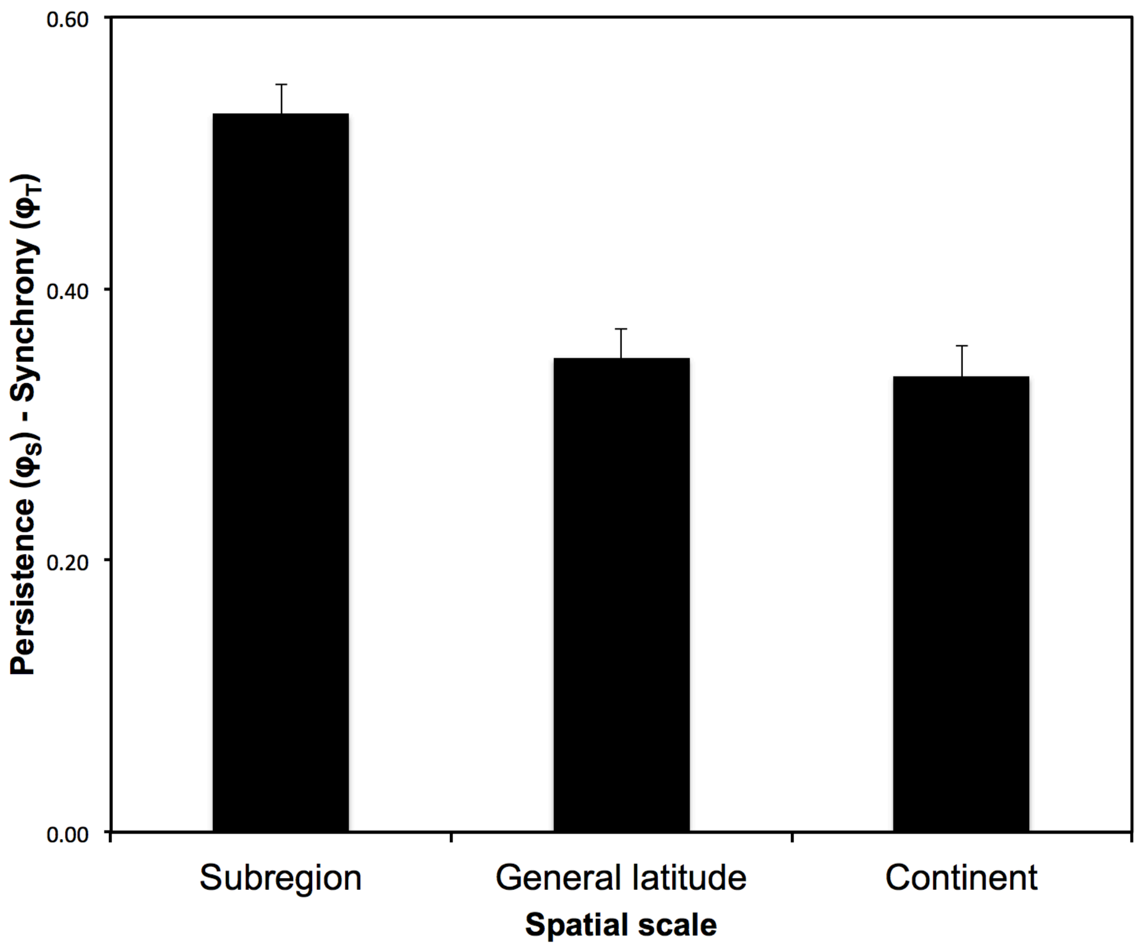

Figure 2-8. Difference between indices of synchrony and persistence at sub-regional, general latitude, and continental scales. There was a significant difference in synchrony between the scales, $F(2, 230) = 23.92$, $p = < 0.0001$. According to the Tukey-Kramer HSD post hoc test, difference in synchrony between continent scale and sub-region scale was significant ($T(76) = -21.06$, $p < 0.0001$), difference in synchrony between general latitude scale and sub-region scale was significant ($T(76) = 20.14$, $p < 0.0001$), while difference in synchrony between continent scale and general latitude scale was insignificant (T(76) = -

1.54, $p = 0.129$). Bars represent mean persistence value ± SE. Raw data are found in Table 2-2, Appendix A.

DISCUSSION

Relationship between spatial and temporal variability

The ability to accurately predict future fluctuations in crop yields is important in order to make decisions to ensure food security (Godfray *et al*., 2010). The results of this illustrate the possibility to use spatial variability to predict regional temporal variability. The significant correlation between crop yield's regional temporal CVs' and mean spatial CVs' at the global scale confirms that it may be possible to use patterns of crop yield data in space to predict future temporal variability of a particular crop. However, the accuracy of the spatial CV for predicting temporal CV diminishes as spatial gradients tend to persist through time and shift crop variables into the persistence region of the graphical model**,** where spatial CV overestimates temporal CV. Spatial persistence of most crop yields can be quite high due to consistent differences in yields between countries. In 1997-99 for example, the top performing 10 percent countries had average wheat yields more than six times higher than those of the worst performing 10 percent (Lobell *et al*., 2009). The high spatial persistence of most crop yields then drags the yield points below the independent patch dynamic region where spatial CV overestimates temporal CV.

There are three conditions when spatial variability of an ecological process can be a precise or accurate predictor for its regional temporal variability. First, if processes can be reasonably assumed to be stochastic, spatial variability can be used to predict regional temporal variability (Hammond & Kolasa, 2014). In other words, if values are independent between locations and between time points, spatial CV and regional temporal CV can be substituted by a factor of $1/n_i^{1/2}$ (Hammond & Kolasa, 2014). In the case of global crop yields however, this assumption does not hold true as forces in nature such as large-scale climate swings could induce synchrony, while differing local climatic conditions and/or technology could induce spatial persistence among countries (Stenseth *et al*., 2002; Lobell *et al*., 2009).

In the second scenario, spatial variability can be used as a precise predictor for its regional temporal variability when there is constant level of synchrony or persistence across variables (Hammond & Kolasa, 2014). Here, synchrony or persistence that is shared by all variables would shift all points equally either up or down from the independent patch dynamics region on the graph. In this case, the rank order of temporal CV's is conserved and can still be predicted from spatial CV using qualitative substitution (Hammond & Kolasa, 2014). In the case of global crop yields, the slight deviation from regression slope of 1 between spatial CV's and regional temporal CV's indicates that spatial persistence in crop yields is not constant and changes as a function of variability. Specifically, a gradient exist where variables with higher variability are slightly more spatially persistent. Nonetheless, the rank order of temporal CV's could still be predicted from spatial CV's if the magnitude of persistence (or synchrony) can be determined and corrected for.

In the last case, variables with similar synchrony and persistence values could also be suitable for space-for-time substitution where using spatial variability to predict temporal variability is concerned. In this case, the influence of synchrony and persistence could cancel each other out, leaving crop variable closer to the independent patch dynamics. There are some crops that have high similarity between their indices of synchrony and persistence (Table 2-2, Appendix A). These include carrots, green peppers, cucumbers, eggplants, maize, onions, potatoes, sorghum, tomatoes and watermelons. Since the index of synchrony and persistence in these crops are similar enough to cancel each other out, they could be good candidates for using spatial data to forecast their temporal variability in yields.

Index of synchrony (ϕ_T) & persistence (ϕ_S)

There were generally high values of index of persistence for most crop yields across all scales (Table 2-2, Appendix A). Spatial persistence is defined as consistent differences between patches from time *k* to *l*, and is calculated by the ratio of temporally aggregated variance to its component spatial variance (Hammond & Kolasa, 2014). By comparison, the values of index of synchrony for most crop yields across all scales were much lower, with mean difference between persistence and synchrony of 41.4%.

Differences in yields of most crops between countries could be quite high due to differing technology advancement and local conditions (Mueller *et al*., 2012). As countries differ in environmental conditions like soil and climate, differences in national crop yields could be quite significant (Lobell *et al.,* 2009). For example, much of Mexico is arid or semi-arid and more than four-fifth of the land cultivated to maize is unsuitable for the improved hybrid varieties (Eakin, 2000). As a result, maize yield in Mexico is only about a quarter of the maize yield averages in United States. In addition, crop management practices such as the amount of fertilizers used, can also widen yield gaps between countries (Lal, 2000). Farmers in developing countries may use less fertilizers due to economic reasons, which could contribute to differences in yields (Mueller *et al*., 2012). Difference in agronomic challenges like pest infestation and level of irrigation, as well as differing agricultural management and levels of investments can also result in great differences in yields between nations (Flores *et al*., 2012; Jensen *et al*., 2010; Lal, 2000). These interacting factors pave way to high spatial persistence for most crop yields. For example, from 1997-1999, the average wheat yields of top performing countries were greater than six times of the worst performing countries.

On the other hand, the effect of synchrony on crop yields was not as dramatic because some countries dominate their production. For example, the main sugarcane producers around the world are Brazil, India, China and USA, which accounts for roughly 70% of the world's sugarcane production (Kamm *et* *al*., 2007). Synchrony among regions in yield of these crops is less likely since high production countries could mask the yields of low production countries. Since the index of synchrony used in this study is defined by the similarity in temporal changes between patches in consideration of their absolute values, it was reasonable to see lower value of synchrony compared to spatial persistence (Loreau & de Mazancourt). Nevertheless, there was still some degree of synchrony for most crop yields, which is likely attributable to long-range synchronization in climatic variables.

It is important to keep in mind that the spatiotemporal scales examined also have an effect on the indices of synchrony and persistence. Index of synchrony for example, could have been underestimated due to the lower temporal scale observed (i.e., 23 years). However, complete longer-term data in crop yields is not available, which may have demonstrated higher synchrony among countries.

Effects of spatial scale

There was a much lower correlation between spatial CV's and aggregate temporal CV's in crop yields at finer scales (i.e., continent, sub-region and general latitude) compared to the global scale. However, these finer spatial scales include progressively fewer countries, which may lower correlation values between mean spatial CVs and mean aggregate temporal CVs. I suspect this effect could have been due to the higher likelihood of sampling errors with smaller number of spatial samples within a region.

However, there were some cases within each spatial scale where the spatial-for-temporal variance approximation shows promise (e.g., Asia - continental scale, 30°N - general latitude scale, and Western Europe – sub-regional scale). In the case of Western Europe (Figure 2-5c), similar level of persistence across crop variables shifted the points somewhat equally down from the independent patch dynamics region of the graphical model. The regression slope of 1 between spatial CV and regional temporal CV indicate that spatial persistence in crop yields within Western Europe was rather constant among crops. The rank order of temporal CV's in this case, may still be recovered from spatial CV via qualitative substitution.

For most crops, index of synchrony was lower at finer scales. This result contrasted our expectation that synchrony would be higher at finer scales due to higher degree of shared geographic and climatic conditions. The lower synchrony value at finer scales could be due to statistical reasons where lower number of countries within a finer region translated into weaker evidence for synchrony. With fewer countries used for analyses at finer scales, crop production could be concentrated in smaller number of countries. High yields in these productive countries could then mask the effects of synchrony at these smaller spatially aggregated regions.

Index of persistence was also found to be lower at finer scales. This result is not surprising given that countries that are closer together likely have more similar environmental and technological conditions and thus more similarity in yields (Stenseth *et al*., 2002; Lobell *et al*., 2009). Having similar yields within finer regions translates into lower degree of spatial persistence.

Limitations

There were several limitations that existed in this study. First of all, temporal scale in the data set was very low compared to spatial scale (i.e., 23 time points versus 212 patches). Due to the inadequacy in record keeping, complete crop yield data was only available from 1990 onward. The limited number of time points most likely led to underestimates of the level of synchrony and overestimates of the level of spatial persistence. Therefore, more temporal data may have resulted in a stronger relationship between temporal and spatial variability.

Also, data on yields of crops in some countries may not be entirely reliable due to the potential irregularity in reported production and harvested area figures by each country's officials. Most estimated national crop yield data referred to crops grown in field and market gardens mainly for sale, which excluded crops grown in kitchen gardens or small family gardens mainly for household consumption. However, the relatively small contribution from family and small gardens were unlikely to play an important part in the estimated crop yields in most countries.

For this analysis, it would have been best if confidence intervals were added to the independent patch dynamic by bootstrapping the data. Including a confidence interval around the independent patch dynamic would allow better assessment on a crop's departure from the null hypothesis of stochastic process (independent patch dynamic). However, as an explorative analysis, leaving the null hypothesis as an absolute value should be sufficient.

It should also be noted that while this analysis has shown that aggregate temporal variance at the global scale could be reasonably predicted by its spatial variance, the prediction has not been tested at the country level. Future work that includes crop yield data from finer scales such as provinces and states within countries should assess the predictability of temporal variance at the country level.

Summary and Conclusions

A strong relationship exists between mean spatial CV and mean regional temporal CV at the global scale for crop yields. Spatial data has good potential in predicting temporal variability via space-for-time substitution. The accuracy of the approximation diminishes however, as the persistence of spatial differences between countries shift the crop variables down from independent patch dynamics and into the persistence region where spatial CV overestimates temporal CV. Some crops are better candidates for the substitution than others, and these are the crops that have similar levels of synchrony and persistence. This potential to forecast temporal stability of food production from its spatial data allows various agencies to improve agricultural polices and production forecasts. Identification of regions with high yield variability can help create strategies to ensure stable crop supply and to reduce food price spikes. Future research in this area can investigate ways to compensate for the high spatial persistence in crop yields to increase accuracy of the space-for-time substitution. Future work should also attempt to investigate the factors that influence crop yield synchrony and persistence. Accounting and combining the effects of those factors may help fine-tuning the approximation such that spatial data can better predict temporal dynamics in crop yields.

Appendix A

Table 2-1. List of countries within each continent.

Continent	Countries
AFRICA	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Côte d Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Ethiopia PDR, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Réunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan (former), Swaziland, Togo, Tunisia, Uganda, United Republic of Tanzania, Western Sahara, Zambia, and Zimbabwe
ASIA	Afghanistan, Armenia, Azerbaijan, Bahrain, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, China, Hong Kong SAR, China, mainland, China, Taiwan Province of, Cyprus, Democratic People s Republic of Korea, Georgia, India, Indonesia, Iran (Islamic Republic of), Iraq, Israel, Japan, Jordan, Kazakhstan, Kuwait, Kyrgyzstan, Lao People s Democratic Republic, Lebanon, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Oman, Pakistan,

	Philippines, Qatar, Republic of Korea, Saudi Arabia, Singapore, Syrian Arab Republic, Tajikistan, Thailand, Timor-Leste, Turkey, Turkmenistan, United Arab Emirates, Uzbekistan, Viet Nam, Yemen, and Sri Lanka
EUROPE	Albania, Austria, Belgium-Luxembourg, Bosnia and Herzegovina, Croatia, Denmark, Estonia, Faroe Islands, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Malta, Netherlands, Norway, Poland, Portugal, Republic of Moldova, Romania, Russian Federation, Serbia and Montenegro, Slovakia, Slovenia, Spain, Sweden, Switzerland, The former Yugoslav Republic of Macedonia, Ukraine, United Kingdom, USSR, Yugoslav SFR, Belarus, Bulgaria, Czech Republic, and Czechoslovakia
NORTH AMERICA	Antigua and Barbuda, Bahamas, Barbados, Belize, Bermuda, British Virgin Islands, Canada, Cayman Islands, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Nicaragua, Panama, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Trinidad and Tobago, and United States of America
OCEANIA	American Samoa, Australia, Cook Islands, Fiji, French Polynesia,

	Guam, Kiribati, Marshall Islands, Nauru, New Caledonia, New Zealand, Niue, Pacific Islands Trust Territory, Papua New Guinea, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wallis and Futuna Islands
SOUTH AMERICA	Argentina, (Plurinational State of) Bolivia, Brazil, Chile, Colombia, Ecuador, French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, and (Bolivarian Republic of) Venezuela

Table 2-2. List of countries within each sub-region.

Sub-region	Countries
AUSTRALIA AND NEW ZEALAND	Australia, New Zealand
CARIBBEAN	Bahamas, Cuba, Dominica, Dominican Republic, Grenada, Guadeloupe, Haiti, Jamaica, Martinique, Montserrat, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, Antigua and Barbuda, Barbados, British Virgin Islands, Cayman Islands
CENTRAL AFRICA	Angola, Cameroon, Central African Republic, Chad, Congo, Democratic Republic of the Congo, Equatorial Guinea, Gabon, Sao Tome and Principe
CENTRAL	Belize, Costa Rica, El Salvador, Guatemala, Honduras,

AMERICA	Mexico, Nicaragua, Panama
CENTRAL ASIA	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan
EASTERN AFRICA	Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Ethiopia PDR, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Réunion, Rwanda, Seychelles, Somalia, Uganda, United Republic of Tanzania, Zambia, Zimbabwe
EASTERN ASIA	China, Hong Kong SAR, Taiwan Province of China, Democratic People s Republic of Korea, Japan, Mongolia, Republic of Korea
EASTERN EUROPE	Hungary, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Ukraine, USSR, Belarus, Bulgaria, Czech Republic, Czechoslovakia
MELANESIA	Fiji, New Caledonia, Papua New Guinea, Solomon Islands, Vanuatu
MICRONESIA	Guam, Kiribati, Marshall Islands, Nauru, Pacific Islands Trust Territory
NORTH AMERICA	Bermuda, Canada, Saint Pierre and Miquelon, United States of America
NORTH AFRICA	Algeria, Egypt, Libya, Morocco, Sudan (former), Tunisia, Western Sahara
NORTHERN	Denmark, Estonia, Faroe Islands, Finland, Iceland, Ireland,

EUROPE	Latvia, Lithuania, Norway, Sweden, United Kingdom
POLYNESIA	American Samoa, Cook Islands, French Polynesia, Niue, Samoa, Tokelau, Tonga, Tuvalu, Wallis and Futuna Islands
SOUTH AMERICA	Argentina, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Ecuador, French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela (Bolivarian Republic of)
SOUTH-EASTERN ASIA	Brunei Darussalam, Cambodia, Indonesia, Lao People s Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, Viet Nam
SOUTHERN AFRICA	Botswana, Lesotho, Namibia, South Africa, Swaziland
SOUTHERN ASIA	Afghanistan, Bangladesh, Bhutan, India, Iran (Islamic Republic of), Maldives, Nepal, Pakistan, Sri Lanka
SOUTHERN EUROPE	Albania, Bosnia and Herzegovina, Croatia, Greece, Italy, Malta, Portugal, Serbia and Montenegro, Slovenia, Spain, The former Yugoslav Republic of Macedonia, Yugoslav SFR
WESTERN AFRICA	Benin, Burkina Faso, Cabo Verde, Côte d Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo
WESTERN ASIA	Armenia, Azerbaijan, Bahrain, Cyprus, Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia,

	Syrian Arab Republic, Turkey, United Arab Emirates, Yemen
WESTERN EUROPE	Austria, Belgium-Luxembourg, France, Germany, Netherlands, Switzerland

Table 2-3. List of countries within each general latitude.

General latitude	Countries
0°	Benin, Brunei Darussalam, Burundi, Cameroon, Central African Republic, Colombia, Congo, Côte d Ivoire, Democratic Republic of the Congo, Ecuador, Equatorial Guinea, French Guiana, Gabon, Ghana, Guyana, Indonesia, Kenya, Kiribati, Liberia, Malaysia, Maldives, Marshall Islands, Nauru, Rwanda, Sao Tome and Principe, Seychelles, Singapore, Somalia, Sri Lanka, Suriname, Togo, Uganda, United Republic of Tanzania
15°N	Antigua and Barbuda, Barbados, Belize, British Virgin Islands, Burkina Faso, Cabo Verde, Cambodia, Cayman Islands, Chad, China, Hong Kong SAR, Cook Islands, Costa Rica, Cuba, Djibouti, Dominica, Dominican Republic, El Salvador, Eritrea, Ethiopia, Ethiopia PDR, Fiji, Gambia, Grenada, Guadeloupe, Guam, Guatemala, Guinea, Guinea-Bissau, Haiti, Honduras,

	India, Jamaica, Lao People s Democratic Republic, Mali, Martinique, Mauritania, Mexico, Montserrat, Mozambique, Myanmar, Nicaragua, Niger, Nigeria, Niue, Pacific Islands Trust Territory, Panama, Philippines, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Senegal, Sierra Leone, Solomon Islands, Sudan (former), Thailand, Timor-Leste, Trinidad and Tobago, Venezuela (Bolivarian Republic of), Viet Nam, Wallis and Futuna Islands, Yemen, Zambia
15°S	American Samoa, Angola, Bolivia (Plurinational State of), Brazil, Comoros, French Polynesia, Madagascar, Malawi, Mauritius, New Caledonia, Papua New Guinea, Peru, Réunion, Samoa, Tokelau, Tonga, Tuvalu, Vanuatu, Zimbabwe 30°N: Afghanistan, Algeria, Bahamas, Bahrain, Bangladesh, Bermuda, Bhutan, China, China, mainland, China, Taiwan Province of, Cyprus, Egypt, Iran (Islamic Republic of), Iraq, Israel, Japan, Jordan, Kuwait, Lebanon, Libya, Malta, Morocco, Nepal, Oman, Pakistan, Qatar, Republic of Korea, Saudi Arabia, Syrian Arab Republic, Tunisia, United Arab Emirates, United States of America, Western Sahara
30°N	Afghanistan, Algeria, Bahamas, Bahrain, Bangladesh,

	Bermuda, Bhutan, China, China, mainland, China, Taiwan Province of, Cyprus, Egypt, Iran (Islamic Republic of), Iraq, Israel, Japan, Jordan, Kuwait, Lebanon, Libya, Malta, Morocco, Nepal, Oman, Pakistan, Qatar, Republic of Korea, Saudi Arabia, Syrian Arab Republic, Tunisia, United Arab Emirates, United States of America, Western Sahara
30°S	Argentina, Australia, Botswana, Chile, Lesotho, Namibia, Paraguay, South Africa, Swaziland, Uruguay
45°N	Albania, Armenia, Austria, Azerbaijan, Belgium-Luxembourg, Bosnia and Herzegovina, Bulgaria, Canada, Croatia, Czech Republic, Czechoslovakia, Democratic People s Republic of Korea, France, Georgia, Germany, Greece, Hungary, Italy, Kazakhstan, Kyrgyzstan, Mongolia, Netherlands, Poland, Portugal, Republic of Moldova, Romania, Saint Pierre and Miquelon, Serbia and Montenegro, Slovakia, Slovenia, Spain, Switzerland, Tajikistan, The former Yugoslav Republic of Macedonia, Turkey, Turkmenistan, Ukraine, Uzbekistan, Yugoslav SFR
60°N	Belarus, Denmark, Estonia, Faroe Islands, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Russian Federation, Sweden, United Kingdom, USSR

Table 2-4. Summary of linear relationships between mean spatial CV and mean aggregate temporal CV of crop yields at regions of different scales.

Region	slope	y-int	F ratio	p	r^2
Global	0.75	-0.88	26.60	<0.0001	0.26
Africa	0.18	-0.94	0.82	0.37	0.01
Asia	0.68	-0.71	13.6	0.0004	0.15
Europe	0.51	-0.71	15	0.0003	0.2
North/Central America	0.06	-0.9	0.16	0.7	0.002
Oceania	-0.04	-0.92	0.13	0.72	0.002
South America	0.13	-0.86	0.64	0.43	0.01
0°	0.3	-0.83	1.48	0.23	0.02
15°N	0.17	-0.9	0.69	0.41	0.01
15°S	-0.08	-1.02	0.27	0.6	0.004
30°N	0.69	-0.72	8.96	0.004	0.11
30°S	0.23	-0.84	4.01	0.05	0.06
45°N	0.53	-0.68	15.6	0.0002	0.20
60°N	0.17	-0.80	0.47	0.5	0.02
Australia and New Zealand	0.09	-0.79	0.53	0.47	0.02
Carribean	0.42	-0.73	7.63	0.01	0.14
Central Africa	-0.03	-0.002	0.19	0.66	0.004
Central America	0.08	0.03	1.08	0.3	0.02
Central Asia	0.46	0.22	7.4	0.01	0.02
Eastern Africa	0.35	-0.77	4.6	0.04	0.06
Eastern Asia	0.09	-0.89	0.34	0.56	0.01
Eastern Europe	0.34	-0.62	5.43	0.02	0.1
Melanesia	0.08	-0.92	0.52	0.48	0.02
Micronesia	-0.09	-0.9	0.36	0.57	0.05
North America	0.17	-0.87	3.4	0.07	0.09
North Africa	0.23	-0.78	3.29	0.07	0.05
Northern Europe	1	-0.62	19.4	0.0002	0.45
Polynesia	-0.5	-0.97	2.29	0.14	0.09

South America	0.13	-0.86	0.06	0.81	0.001
South-Eastern Asia	0.39	-0.72	0.43	0.52	0.01
Southern Africa	0.31	-0.67	8.12	0.01	0.25
Southern Asia	0.22	-0.85	2.14	0.15	0.03
Southern Europe	0.48	-0.62	11.4	0.001	0.17
Western Europe	0.28	-0.83	2.47	0.12	0.05
Western Asia	0.45	-0.64	4.85	0.03	0.07
Western Europe	0.3	-0.57	15.2	0.0004	0.3

Table 2-5. Summary of indices of synchrony and persistence of crop yields at the continental, general latitude and sub-regional scales.

	Continental scale		**General latitude**		**Sub-regional scale**	
Crops	**Synchrony**	**Persistence**	**Synchrony**	**Persistence**	**Synchrony**	**Persistence**
almonds	0.510	0.983	0.598	0.978	0.368	0.972
apples	0.834	0.998	0.741	0.997	0.559	0.983
apricots	0.361	0.987	0.370	0.992	0.119	0.946
asparagus	0.716	0.980	0.659	0.989	0.418	0.944
avocados	0.702	0.897	0.714	0.956	0.488	0.945
bananas	0.518	0.987	0.686	0.994	0.340	0.979
barley	0.839	1.000	0.781	0.997	0.492	0.977
green beans	0.803	0.996	0.695	0.995	0.478	0.968
broad beans	0.422	0.992	0.478	0.988	0.242	0.974
cabbages	0.894	0.997	0.869	0.995	0.713	0.979
carrots and turnips	0.930	0.999	0.890	0.996	0.756	0.984
cassava	0.753	0.990	0.832	0.999	0.645	0.991
cauliflowers and broccoli	0.873	0.998	0.734	0.996	0.588	0.986

cherries	0.393	0.996	0.367	0.995	0.166	0.952
chick peas	0.777	0.978	0.768	0.985	0.621	0.941
green chillies and peppers	0.947	0.987	0.885	0.975	0.829	0.958
cocoa beans	0.558	0.979	0.600	0.991	0.397	0.974
coconuts	0.435	0.974	0.663	0.997	0.322	0.982
green coffee beans	0.173	0.954	0.241	0.990	0.104	0.957
cucumbers and gherkins	0.922	1.000	0.854	0.995	0.776	0.992
eggplants (aubergines)	0.919	0.979	0.930	0.985	0.822	0.977
figs	0.697	0.992	0.721	0.985	0.580	0.980
citrus fruit nes	0.601	0.984	0.724	0.976	0.392	0.893
garlic	0.804	0.991	0.736	0.988	0.501	0.961
grapefruit	0.520	0.979	0.538	0.990	0.369	0.969
grapes	0.675	0.997	0.560	0.990	0.377	0.984
groundnuts	0.596	0.994	0.647	0.995	0.381	0.982
lemons and limes	0.652	0.987	0.624	0.992	0.317	0.976
lentils	0.350	0.939	0.494	0.989	0.232	0.930
lettuce and chicory	0.723	0.998	0.702	0.994	0.501	0.973
linseed	0.268	0.920	0.263	0.924	0.208	0.843
maize	0.917	0.993	0.920	0.996	0.776	0.977
mangoes, mangosteens, guavas	0.629	0.985	0.683	0.992	0.399	0.965
melons (inc.cantaloupe s)	0.777	0.982	0.790	0.988	0.575	0.973
millet	0.646	0.987	0.456	0.976	0.232	0.917
nuts nes	0.753	0.992	0.737	0.979	0.458	0.932
oats	0.715	1.000	0.628	0.997	0.336	0.977
palm fruit oil	0.481	0.992	0.416	0.996	0.395	0.992
dry onions	0.918	0.998	0.894	0.997	0.699	0.984
oranges	0.609	0.987	0.667	0.991	0.396	0.977
papayas	0.618	0.956	0.674	0.979	0.491	0.912
peaches and nectarines	0.807	0.991	0.812	0.996	0.613	0.980

pears	0.740	1.000	0.716	0.998	0.535	0.992
green peas	0.555	1.001	0.303	0.989	0.144	0.950
pineapples	0.451	0.989	0.344	0.991	0.210	0.975
plantains	0.513	0.998	0.634	0.999	0.282	0.992
plums and sloes	0.555	0.992	0.478	0.986	0.303	0.951
potatoes	0.927	0.999	0.908	0.995	0.748	0.987
pulses nes	0.656	0.966	0.578	0.923	0.422	0.873
pumpkins, squash and gourds	0.896	0.997	0.848	0.993	0.686	0.975
rice, paddy	0.842	0.996	0.795	0.996	0.471	0.985
roots and tubers nes	0.458	0.975	0.513	0.995	0.221	0.968
rye	0.717	1.000	0.704	0.998	0.432	0.975
seed cotton	0.344	0.994	0.323	0.991	0.168	0.974
sesame seed	0.821	0.955	0.728	0.951	0.642	0.921
sorghum	0.822	0.900	0.845	0.908	0.641	0.823
soybeans	0.596	0.983	0.677	0.993	0.361	0.971
spices nes	0.453	0.980	0.342	0.935	0.232	0.870
strawberries	0.760	0.985	0.739	0.993	0.536	0.970
sugar beet	0.598	1.001	0.535	0.997	0.256	0.981
sugar cane	0.180	0.998	0.232	0.999	0.066	0.995
sunflower seed	0.657	0.996	0.663	0.996	0.408	0.979
Sweet potatoes	0.543	0.977	0.583	0.994	0.358	0.972
Taro (cocoyam)	0.490	0.990	0.571	0.996	0.308	0.978
Tea	0.726	0.957	0.575	0.890	0.509	0.931
Tobacco, unmanufactured	0.526	0.991	0.436	0.984	0.271	0.961
Tomatoes	0.968	1.000	0.940	0.995	0.861	0.995
Vegetables, fresh nes	0.395	0.991	0.295	0.990	0.144	0.954
Watermelons	0.927	0.992	0.877	0.992	0.747	0.988
Wheat	0.768	0.999	0.693	0.996	0.424	0.980
Yams	0.299	0.990	0.389	0.996	0.207	0.989

LITERATURE CITED

Alexandratos, N., & Bruinsma, J. (2012). World agriculture towards 2030/2050: the 2012 revision. *ESA Work. Pap*, *3*.

Blois, J. L., Williams, J. W., Fitzpatrick, M. C., Jackson, S. T., & Ferrier, S. (2013). Space can substitute for time in predicting climate-change effects on biodiversity. *Proceedings of the National Academy of Sciences*, *110*(23), 9374-9379.

Challinor, A. J., Parkes, B., & Ramirez-Villegas, J. (2015). Crop yield response to climate change varies with cropping intensity. *Global change biology*, *21*(4), 1679-1688.

De Ponti, T., Rijk, B., & Van Ittersum, M. K. (2012). The crop yield gap between organic and conventional agriculture. *Agricultural Systems*, *108*, 1-9.

Eakin, H. (2000). Smallholder maize production and climatic risk: A case study from Mexico. *Climatic change*, *45*(1), 19-36.

Edgerton, M. D. (2009). Increasing crop productivity to meet global needs for feed, food, and fuel. *Plant physiology*, *149*(1), 7-13.

Evans, L. T., & Fischer, R. A. (1999). Yield potential: its definition, measurement, and significance. *Crop Science*, *39*(6), 1544-1551.

Ezeh, A. C., Bongaarts, J., & Mberu, B. (2012). Global population trends and policy options. *The Lancet*, *380*(9837), 142-148.

Flores, F., Nadal, S., Solis, I., Winkler, J., Sass, O., Stoddard, F. L., ... & Rubiales, D. (2012). Faba bean adaptation to autumn sowing under European climates. *Agronomy for sustainable development*, *32*(3), 727-734.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., ... & Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. *science*, *327*(5967), 812-818.

Hammond, M. P., & Kolasa, J. (2014). Spatial variation as a tool for inferring temporal variation and diagnosing types of mechanisms in ecosystems. *PloS one*, *9*(2), e89245.

Johnson, E. A., & Miyanishi, K. (2008). Testing the assumptions of chronosequences in succession. *Ecology Letters*, *11*(5), 419-431.

Jongejans, E., & De Kroon, H. (2005). Space versus time variation in the population dynamics of three co-occurring perennial herbs. *Journal of Ecology*, *93*(4), 681-692.

Kamm, B., Gruber, P. R., & Kamm, M. (2007). *Biorefineries–industrial processes and products*. Wiley-VCH Verlag GmbH & Co. KGaA.

Keyzer, M. A., Merbis, M. D., Pavel, I. F. P. W., & Van Wesenbeeck, C. F. A. (2005). Diet shifts towards meat and the effects on cereal use: can we feed the animals in 2030?. *Ecological Economics*, *55*(2), 187-202.

Lal, R. (2000). Soil management in the developing countries. *Soil Science*, *165*(1), 57-72.

Lambin, E. F., Rounsevell, M. D. A., & Geist, H. J. (2000). Are agricultural land-use models able to predict changes in land-use intensity?. *Agriculture, Ecosystems & Environment*, *82*(1), 321-331.

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop yield gaps: their importance, magnitudes, and causes. *Annual Review of Environment and Resources*, *34*(1), 179.

Lobell, D. B., & Field, C. B. (2007). Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental research letters*, *2*(1), 014002.

Loreau, M., & de Mazancourt, C. (2008). Species synchrony and its drivers: neutral and nonneutral community dynamics in fluctuating environments. *The American Naturalist*, *172*(2), E48-E66.

Minten, B., & Barrett, C. B. (2008). Agricultural technology, productivity, and poverty in Madagascar. *World Development*, *36*(5), 797-822.

Mitchell, D. (2008). A note on rising food prices. *World Bank Policy Research Working Paper Series, Vol*.

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature*, *490*(7419), 254-257.

Ray, D. K., Gerber, J. S., MacDonald, G. K., & West, P. C. (2015). Climate variation explains a third of global crop yield variability. *Nature communications*, *6*.

Shukla, R., & Mallick, S. (2015). Mechanization of Agriculture: Implications for the Farming Community in India. *Perspectives on Global Development and Technology*, *14*(4), 430-447.

Stenseth, N. C., Mysterud, A., Ottersen, G., Hurrell, J. W., Chan, K. S., & Lima, M. (2002). Ecological effects of climate fluctuations. *Science*, *297*(5585), 1292-1296.

Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., ... & Williams, R. (2009). Beneficial biofuels—the food, energy, and environment trilemma. *Science*, *325*(5938), 270.

Turner, M. G. (1990). Spatial and temporal analysis of landscape patterns. *Landscape ecology*, *4*(1), 21-30.

Wang, X., He, X., Williams, J. R., Izaurralde, R. C., & Atwood, J. D. (2005). Sensitivity and uncertainty analyses of crop yields and soil organic carbon simulated with EPIC. *Transaction-American society of agricultural engineers*, *48*(3), 1041.

Chapter 3

Determining the factors of synchrony and spatial persistence in crop yields

ABSTRACT

Based on theoretical model and my earlier research, I believe that spatial CV of crop yields has the potential to predict its regional temporal CV. The accuracy of the approximation increases when the level of synchrony and persistence of spatial variation are low or cancel out each other's effect on the spatiotemporal dynamics. The goal of this study is to uncover possible factors that can predict a crop yield's synchrony and persistence. I analyzed several climatic and economic variables known to affect crops and related them its indices of synchrony and persistence at various scales. I found that a crop's preferred germination temperature, length of growing period and total water need were strong predictors of synchrony between countries at the continental scale. For example, crops' minimum water need and synchrony of yields at the continental scale were well correlated (r^2 = 0.636). This study identified crop's preferred climatic conditions as good predictors for its synchrony between countries. This helps us identify crops that are better candidates for using spatial variability in predicting their temporal variability at a regional scale. These include crops that have high preferred-germination soil temperature, low minimum crop water needs, and low minimum growing period. As total fluctuations in crop yields are expected to increase due to global warming, the results in this study add another supporting evidence to the current notion that climate change has negative consequences on the outlook of global food supply.

Key Words: *Crop yields, synchrony, spatial persistence, variability, temperature, precipitation, climate change, global warming, food security*

RATIONALE AND OBJECTIVES

The previous chapter showed that spatial data has the potential to predict variation in temporal dynamics for crop yields. The accuracy of the spatial CV for temporal CV approximation diminishes however when synchrony between countries and persistence of spatial variation modifies the spatiotemporal relationship. The goal of this paper is to move one step forward in this investigation and find out what may be some factors that can influence a crop's synchrony and persistence. As synchrony implies similar impact over large geographical areas, climate conditions come to mind as likely factors. Therefore, I aim to relate a crop's preferred climatic conditions to its indices of synchrony and spatial persistence. Using the data I have organized, I examined the possible relationships that exist between a crop's synchrony and spatial persistence between countries and its traits that are likely to be responsive to climatic conditions such as the preferred temperature, length of growing period and water need. Overall, I found:

- Mean preferred germination temperature of a crop related positively to its synchrony at the continental scale
- The length of growing period of a crop related negatively to its synchrony at the continental, general latitude, and sub-regional scale
- Total water need of a crop related negatively to its synchrony at the

continental, general latitude, and sub-regional scale

These results suggest some possible factors that can predict a crop's synchrony between countries. Moreover, this study reinforces the negative effects of global warming on global crop yields and stability in crop supply.

INTRODUCTION

Global warming refers to the gradual increase in the overall temperature of Earth's atmosphere due to greenhouse effect (Wood & Vedlitz, 2007). Anthropogenic causes of global warming and climate change is evident by the unusual increase in carbon dioxide in the atmosphere (Houghton *et al*., 2001). Asymmetric molecules like carbon dioxide and ozone near the surface absorbs infrared radiation, thereby trapping heat and increasing the surface temperature on the planet (Mitchell *et al*., 1995). This increase in temperature in turn, causes evaporation and changes in precipitation patterns, leading to increased frequency in droughts and flooding (Dore, 2005).

Carbon dioxide concentration is projected to keep increasing at various rates under different energy-usage scenarios. Under the business-as-usual model, 3°C of average warming is predicted by the end of this century (Hansen *et al*., 2010). Warming is expected to be greatest over land, which is where crop production is conducted (Sitch *et al*., 2007). Projected changes in average rainfall across latitudes suggests that traditionally wet regions near the equator will become wetter, while traditionally dry regions in temperate regions will become drier (Dore, 2005). This means that drought prone regions of the world will experience even more frequent and lengthier droughts.

Some of the direct effects of climate change on crop production are rise in carbon dioxide, rise in temperature, rise in atmospheric pollutants like ozone, and changes in water availability (Kamran & Asif, 2011). Crops utilize carbon dioxide to make carbohydrates and grow. In C3 plants, carbon dioxide is taken up directly through the stomata, and then fixed through the process of photosynthesis into sugars (Morison & Gifford, 1983). For many crops with C3 photosynthesis like rice and potato, rise in carbon dioxide boosts growth as the rate of photosynthesis increases (Mooney *et al*., 1991). Experimentally enriched carbon dioxide concentrations in temperate system have been shown to increase photosynthetic rates and plant biomass production, leading to stimulation in absolute yields (Ainsworth & Long, 2005). However, C4 photosynthetic crops like maize have almost no direct response to increased carbon dioxide since its rate of photosynthesis is already saturated at today's carbon dioxide concentrations (Morison & Gifford, 1983). Also, while carbon dioxide increases the amount of C3 crop produced, nutrient concentration (e.g., nitrogen) within the crop tissues is actually lowered due to dilution effect (Conroy, 1992).

Increased carbon dioxide does not always result in increased yield however as increased temperature could negate the benefits of increased photosynthesis. For example, pollen viability and seed setting are negatively affected by temperature (Prasad *et al*., 2006). The cost of diminished reproductive processes due to increased temperature outweighs the benefits from stimulated photosynthesis by elevated carbon dioxide. Research indicates that even in temperate climates, recent warming trends are associated with overall decreases in crop yields (Ainsworth & Long, 2005; Lal, 2004). For example, rice yields have been shown to decline with higher night temperatures (Peng *et al*., 2004).

Furthermore, stomata conductance (rate of carbon dioxide entering or water vapor exiting through the stomata of a leaf) decreases in crops grown at elevated carbon dioxide concentrations, effectively reducing evaporative cooling (Ainsworth & Rogers 2007). With the reduction in levels of evapotranspiration, this results in elevated canopy temperature for crops (Jackson *et al*., 1977). In areas with moderate amount of droughts, higher carbon dioxide levels can stimulate crop production by retaining more moisture during dry periods. This has been experimentally demonstrated for crops like sorghum, cotton, wheat, soybean and maize (Ainsworth & Long, 2005). However, in severely water-limited areas, raised carbon dioxide level is unlikely to benefit crop production. Therefore, as temperature increases and drought stress exacerbates, the benefits of elevated carbon dioxide may be diminished (Ainsworth & Long, 2005).

In general, most models agree that crop yields will be diminished to varying extents with the projected climate change unless there are new advances in technology (Lal, 2004; Rosenzweig & Parry, 1994). The amount of loss in yields is unclear however and is subjected to debate (Lobell & Field, 2007). The current focus is on attempts to engineer crops to perform better under conditions of increasing environmental stress associated with increased temperature, ozone exposure and changing precipitation patterns (Long *et al*., 2004). With existing genetic variation in crop's response to climate change factors, there are opportunities for biotechnological manipulation to optimize crop productivity and yield by enabling improvement in crop traits (Ainsworth *et al*., 2008).

While there are many studies on how global warming could affect the future absolute yields of crops, its effect on the variability in crop yields is often overlooked in existing literatures. Production of crop commodities has a diverse geographical distribution. Some crops are highly concentrated in few countries, while other could be widely produced (Monfreda *et al*., 2008). Production of crops could also fluctuate from year to year due to variations in climate and environmental factor (Deschenes & Greenstone, 2007). In addition, the economy of a country could also influence the level of agricultural production for a given year (Lal, 2006).

An important aspect of spatiotemporal variability in global crop production is the synchrony of yields among regions or countries. Spatial synchrony is an ecological phenomenon that is common in a variety of natural systems and it usually refers to corresponding changes in time-varying characteristics of geographically distinct populations (Satake & Koizumi, 2008). Abundance of animals has been observed to synchronize among geographically distinct populations (Liebhold *et al*., 2004). Plant species also reproduce in synchrony and experience some degrees of population synchrony (Kelly & Sork, 2002). One mechanism for synchrony is the correlation of external stimuli in different regions. Moran has shown that spatial correlation of environmental disturbances is a big factor in producing population synchrony (Ranta *et al*., 1997). Crop yields may experience some degrees of synchrony among countries with similar climate conditions. Continental drought years for example, could synchronize crop yields of countries within a continent (Ciais *et al.,* 2005; Wright, 1991). Other exogenous factors like temperature or precipitation could also synchronize population dynamics (Post & Forchammer, 2002). Another mechanism for synchrony is dispersal among populations. For example, interactions such as migration and information exchanges could encourage synchrony among populations (Paradis *et al*., 1999).

Aside from synchrony, another important aspect in spatiotemporal variability of crop production is spatial persistence of crop yield differences among countries. Some countries have attained very high yields for particular crops, while others have much lower yields due to different climatic conditions (Neumann *et al*., 2010). The persistence in crop yield differences could be due to differing technology and environmental conditions (Mueller *et al*., 2012). For example, arid countries with little to no irrigation systems have a much lower yield potential and thus persistently have lower yields than other countries (Lobell *et al*., 2009; Mueller *et al*., 2012). Differing agricultural investments and management techniques could also widen the yield gap between countries (Jensen & Hauggaard-Nielsen, 2010). For example, the amount of fertilizers used is positively correlated with crop yields up to a limit. Farmers in developing countries may only be able to afford limited fertilizers, which could contribute to differences in yields compared to developed countries (Mueller *et al*., 2012).

The specific definition of synchrony used in this study is the ratio of aggregate temporal variance to the component temporal variances (Loreau, 2008). In other words, it refers to the similarity in temporal changes of crop yields between countries in consideration of its absolute magnitude. Persistence as defined in this study is the ratio of temporally aggregated variance to its component spatial variances (Hammond & Kolasa, 2014). It refers to the lack of changes in spatial differences between countries from year to year. Due to the unequal balance of synchrony and persistence, accuracy for the substitution between spatial and temporal variation was diminished. It is therefore of great interest to find out what factors influence the indices of synchrony and persistence. I hypothesize that a crop's preference in climatic conditions (i.e., temperature and precipitation) can determine its synchrony and persistence of spatial variation between countries.

METHODS

Data organization

Indices of synchrony and persistence were calculated based on data that was obtained from the statistical database of the Food and Agriculture Organization of the United Nations. Specifically, the organized data set included the crop yields of 77 crops for 212 countries over 23 years from 1990 – 2012. All yields were measured in hectogram per hectare, and computed from detailed harvest area and production data expressed in hectares and hectograms respectively.

Preferred germination temperature data was compiled from the agriculture and forestry ministry of Alberta, 2000. Specifically, the organized data set included minimum germination temperature, mean preferred germination temperature and maximum preferred germination temperature for the following crops: barley, green bean, beet, cabbage, carrot, cauliflower, corn, cucumber, eggplant, lettuce, oats, dry onions, green pea, green pepper, pumpkin, squash, tomato, and wheat.

Crop growing period data were compiled from the statistical database of the Food and Agriculture Organization of the United Nations. Specifically, the organized data set included minimum growing period, mean growing period, maximum grow period, range size of growing period for the following crops:

banana, barley, green bean, cabbage, carrot, citrus, cucumber, eggplant, lentil, lettuce, maize, melon, millet, oats, green onion, dry pepper, potato, rice, sorghum, soybean, squash, sugarbeet, sugarcane, sunflower, tobacco, tomato, and wheat.

Crop water need and sensitivity to drought data were compiled from the statistical database of the Food and Agriculture Organization of the United Nations. Specifically, the organized data set included maximum crop water need, range size of crop water need, sensitivity to drought for the following crops: banana, barley, green beans, cabbage, citrus, maize, melon, millet, oats, onion, dry peas, dry pepper, potato, rice (paddy), sorghum, soybean, sugarbeet, sugarcane, sunflower, tomato and wheat.

Crop average price and average export quantity data were compiled from the statistical database of the Food and Agriculture Organization of the United Nations. Specifically, the organized data set included the crop prices and export quantity across 212 countries in the year 2012 for the following crops: almonds, apples, apricots, asparagus, avocados, bananas, barley, green beans, broad beans, horse beans, cabbages, carrots and turnips, cassava, cauliflowers and broccoli, cereals, cherries, chick peas, chillies and peppers, cocoa beans, coconuts, green coffee beans, cucumbers and gherkins, eggplants, figs, citrus fruit, garlic, grapefruit (inc. pomelos), grapes, groundnuts, lemons and limes, lentils, lettuce and chicory, linseed, maize, mangoes, mangosteens, guavas, melons (inc.cantaloupes), millet, oats, palm fruit oil, onions, oranges, papayas, peaches and nectarines, pears, green peas, pineapples, plantains, plums and sloes, potatoes, pulses, pumpkins, squash and gourds, rice paddy, roots and tubers, rye, seed cotton, sesame seed, sorghum, soybeans, strawberries, sugar beet sugar cane, sunflower seed, sweet potatoes, taro (cocoyam), tea, unmanufactured tobacco, tomatoes, watermelons, wheat, and yams.

Statistical Analysis

All data were analyzed in JMP 12 (SAS Institute Inc., Toronto, Ontario, Canada).

Indices of synchrony and persistence

I quantified synchrony using φ_T, first proposed by Loreau & de Mazancourt (2008) for species synchrony. This index varies from 0 to 1, and it works by comparing the aggregate temporal variance of an ecological variable to its theoretical maximum if all components were perfectly synchronous. I calculated this index as in Hammond & Kolasa (2014). In brief, for each crop I summed its yields across land units (*e.g.,* continents, sub-regions, general latitudes) within a region to get an aggregate yield for the region. The variance of this aggregated series was then divided by the theoretical maximum variance, which is the squared sum of the temporal standard deviations of land units.

I quantified persistence using φ_S, first proposed by Hammond & Kolasa (2014). This index also varies from 0 to 1, and it works by comparing the temporally aggregated spatial variance to its theoretical maximum if the differences between all components persisted perfectly. I calculated this index as in Hammond & Kolasa (2014). In brief, for each crop I summed its yields of each land units (e.g., continents, sub-regions, general latitudes) across all time points (i.e., 1990 – 2012) to get the temporally aggregated yield for the regions. The variance of this aggregated series was then divided by the theoretical maximum variance, which is the squared sum of spatial standard deviations of time points.

The above calculations for indices of synchrony and persistence were performed for each of the 77 crops at the continental, general latitude, and sub-regional scales.

Factors of synchrony and persistence

To quantify the relationship between preferred germination temperature and synchrony, a regression analysis was performed with the predictor (independent variable) being crop's preferred germination soil temperature and the criterion (dependent variable) being the crop's index of synchrony at continental scale. I also conducted this analysis at the general latitude and sub-regional scale, as well as index of persistence. F-tests were then conducted to determine the goodness of fit of the selected model. Residuals were tested for normal distribution using Komogorov-Smirnov tests.

Additional regressions were also tested using other predictor variables: minimum germination soil temperature, mean preferred germination soil temperature, maximum preferred germination soil temperature, range size of preferred germination soil temperature, minimum growing period, mean growing period, maximum grow period, range size of growing period, minimum crop water need, mean crop water need, maximum crop water need, range size of crop water need, sensitivity to drought, average export quantity, and average price (based on 2012 prices).

RESULTS

The approach I adopted generated a number of regression results, one for each variable at each scale (i.e., continental, general latitude, sub-regional) for each of the indices (synchrony and persistence). Of all the regressions, only 3.6% were significant for persistence (see Table 3-1, Appendix B). But many of them (47.6%) were significant for synchrony. Therefore, I focused my attention on synchrony.

Preferred germination temperature was a significant factor in promoting synchrony in yields. Out of minimum, mean, maximum and range size of preferred germination soil temperature, mean preferred germination soil temperature was a significant predictor and had a significant and positive relationship with synchrony at the continental scale (Figure 3-1; slope = 0.011, $F = 5.46$, $p = 0.033$, $r^2 = 0.26$).

Growing period was another significant factor in promoting synchrony in yields. Out of minimum, mean, maximum and range size of growing period, minimum growing period was the best predictor for synchrony at the continental, general latitude and sub-regional scales. Synchrony at the continental scale slightly declined with minimum growing period (Figure 3-2; slope = -0.0023, $F = 20.5$, $p = 0.0001$, $r^2 = 0.43$). Synchrony at the general latitude scale slightly declined with minimum growing period (slope = -0.0019, $F = 6.27$, $p = 0.019$, $r^2 = 0.19$). Synchrony at the sub-regional scale slightly declined with minimum growing period (slope = -0.0014, $F = 7.42$, $p = 0.011$, $r^2 = 0.22$).

Growing period was also broken down into initial, intermediate, mid-stage and late-stag growing periods. Minimum late-stage growing period was the best predictor for synchrony at continental scale (Figure 3-3; slope = -0.0092, $F = 9.96$, $p = 0.0046$, $r^2 = 0.31$).

Crop water need (mm/total growing period) was another significant factor in promoting synchrony in yields. Out of minimum, mean, maximum and range size, minimum crop water need was the best predictor for synchrony at continental, general latitude and sub-regional scales. Synchrony at the continental scale slightly declined with minimum crop water need (Figure 3-4a; slope = -0.00049, $F = 33.2$, $p < 0.0001$, $r^2 = 0.64$). Synchrony at the general latitude scale slightly declined with minimum crop water need (Figure 3-4b; slope = -0.00033, $F = 9.12$, $p = 0.012$, $r^2 = 0.33$). Synchrony at the sub-regional scale slightly declined with minimum crop water need (Figure 3-4c; slope = -0.0014, $F = 7.77$, $p = 0.012$, $r^2 = 0.29$).

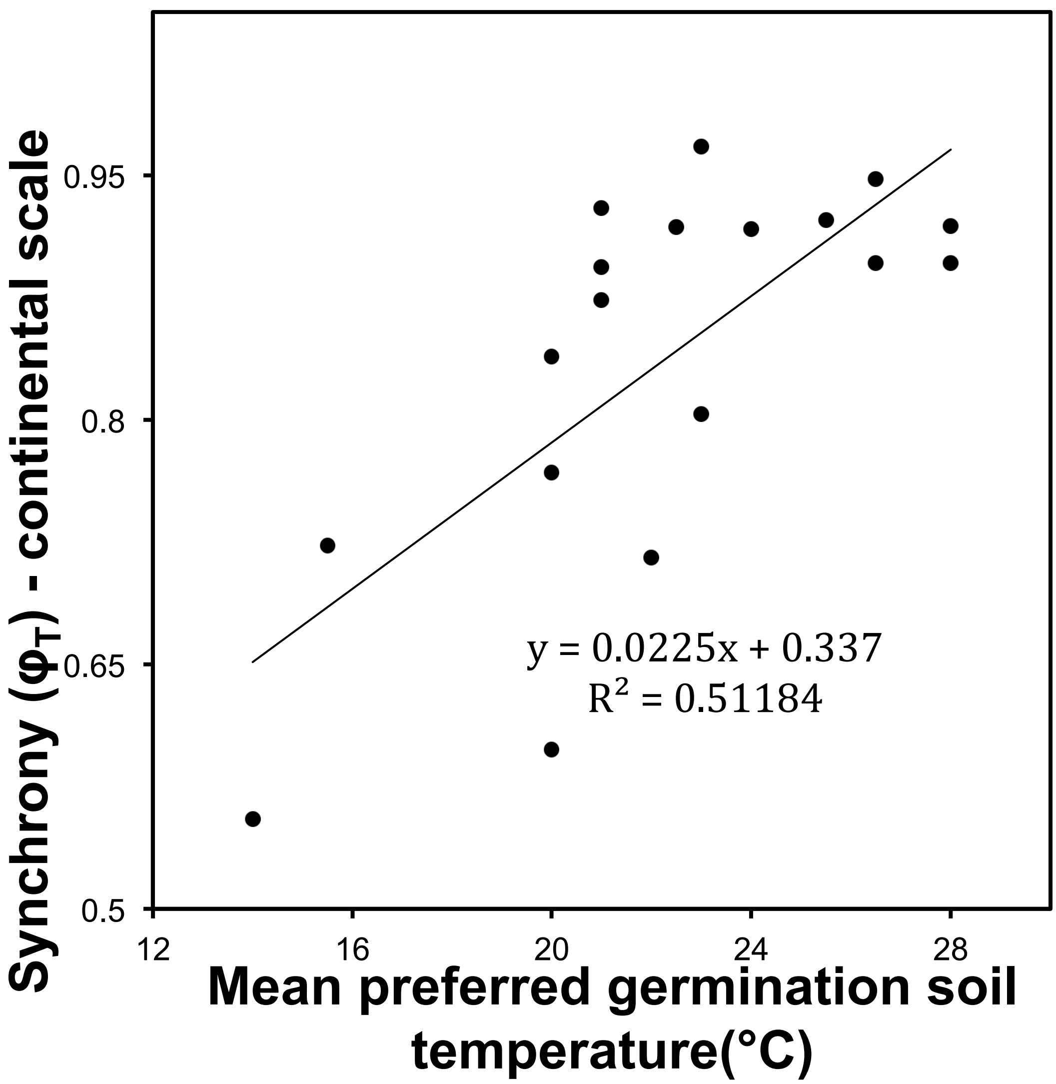

Figure 3-1. Relationship between the mean preferred soil temperature of a crop and its synchrony of yields at the continental scale. Each point represents a crop.

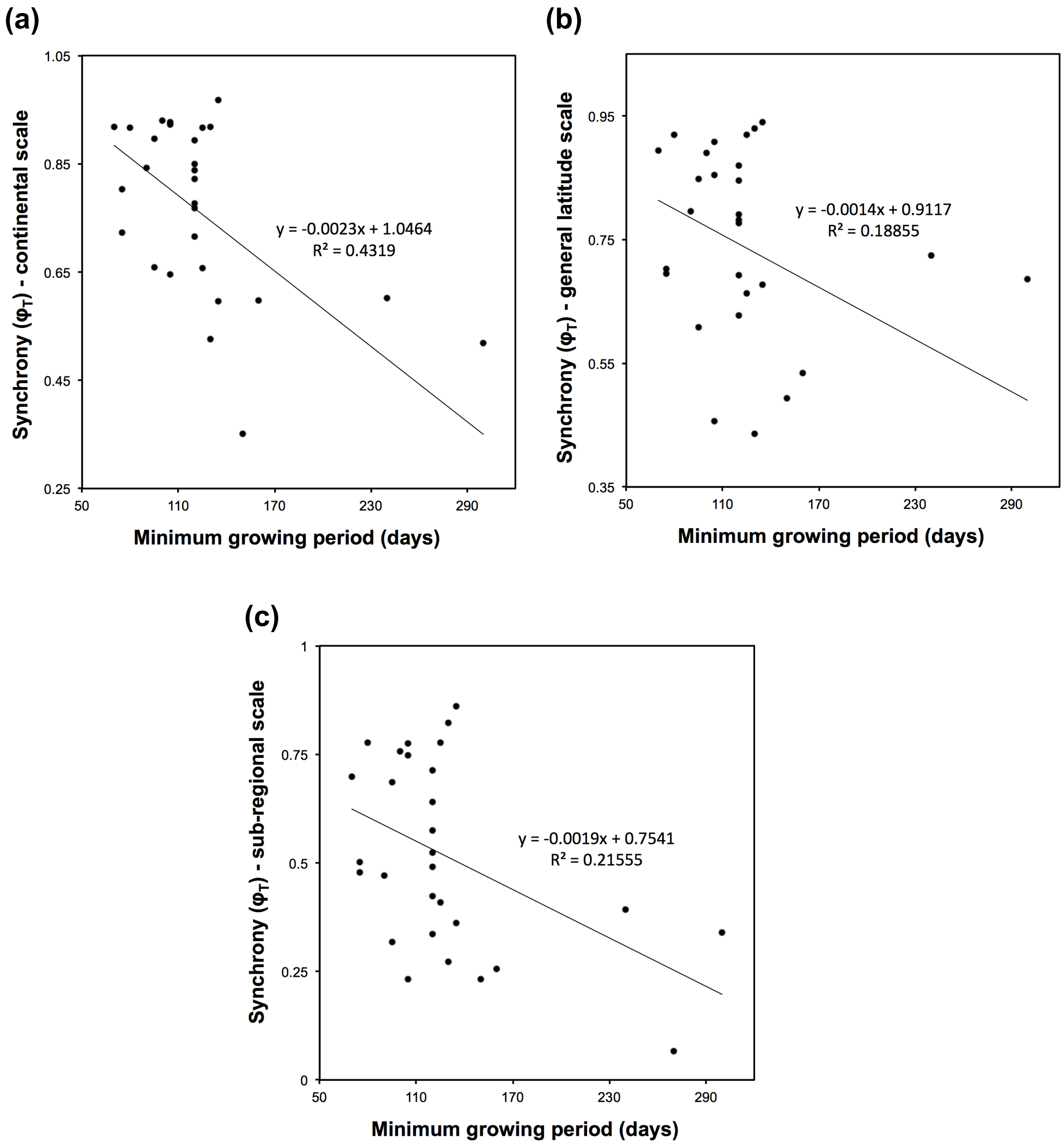

Figure 3-2. Relationship between a crop's minimum growing period and its synchrony of yields at the **(a)** continental scale, **(b)** general latitude scale, **(c)** and sub-regional scale. Each point represents a crop.

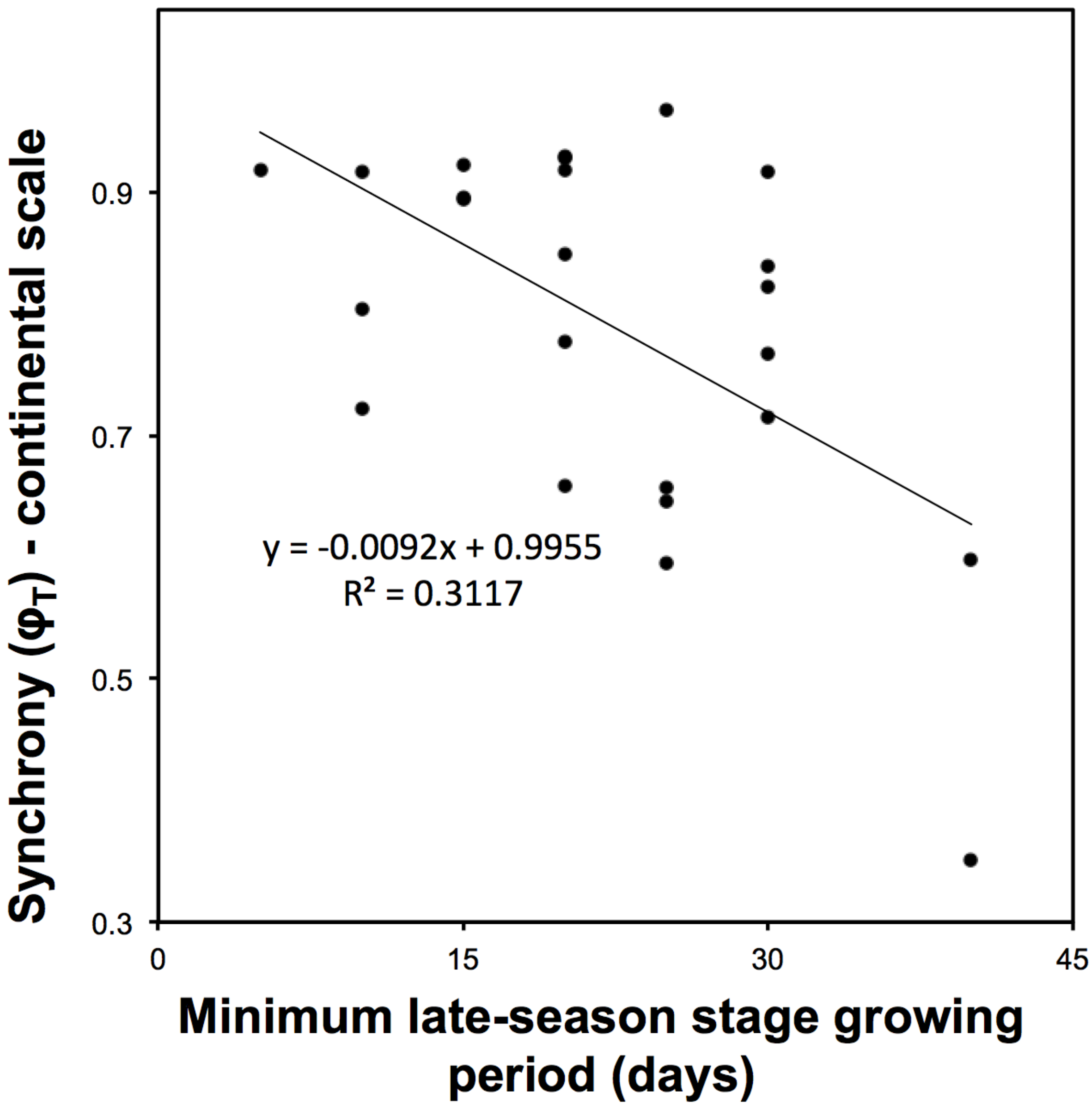

Figure 3-3. Relationship between the minimum late-stage growing period of a crop and its synchrony of yields at the continental scale. Each point represents a crop.

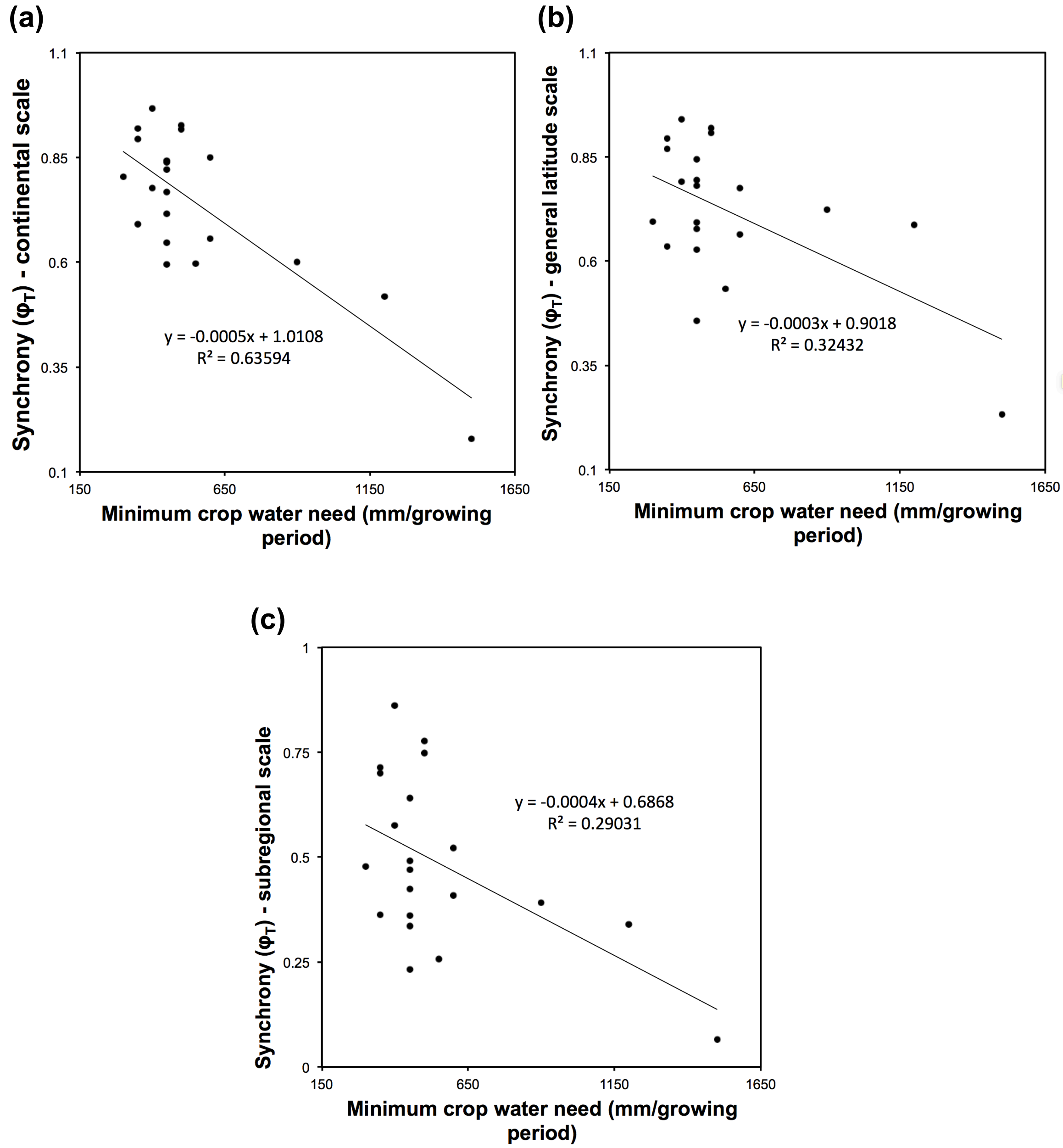

Figure 3-4. Relationship between a crop's minimum crop water need and its synchrony of yields at the **(a)** continental scale, **(b)** general latitude scale, **(c)** and sub-regional scale. Each point represents a crop.

DISCUSSION

This study revealed that preferred germination soil temperature, length of growing period and total water need were strong predictors for synchrony in crop yields between countries. Most crops experience a substantial degree of spatial persistence and varying degrees of synchrony, which resulted in varying degree of overestimation in temporal CV as predicted by spatial CV in a direct substitution. The identification of factors that contribute to the variation in crop yield synchrony allows us to pinpoint to the crops that are better candidates in using spatial variability to predict regional temporal variability. Specifically, these candidates include crops that have high preferred germination soil temperature, low minimum crop water needs, and low minimum growing period.

Temperature has a great effect on a crop's growth productivity. The rates of photosynthesis and respiration of a crop rises with increasing temperature (Ritchie & NeSmith, 1991). As temperature reaches the upper growing limit for the crop, growth is hampered as the rate of sugar used by respiration exceeds the rate of sugar synthesized by photosynthesis (Lafta & Lorenzen, 1995). In general, crops can be separated into warm and cool crops depending on its preferred temperature.

The observation that mean preferred temperature of a crop was positively correlated with synchrony in its yields suggests that warmer climate crops experience higher synchrony in yields, while crops that grow in colder climate conditions experience lower synchrony in yields. Thermal stress related to both temperature extremes can result in lower crop yields due to low germination rates, growth retardation, and reduced photosynthesis (Kai & Iba, 2014). Cold temperatures can for example freeze the cells in a crop, causing damage and interrupt the pathways for nutrients and water intake (Pearce, 2001). Desiccation, sunscald, salt damage, heavy snow break and numerous other injuries are also how cold temperatures can affect crops (Gu *et al.,* 2008; Smillie & Hetherington, 1983). High temperatures on the other hand can cause heat injury in crops including sunburn, scalding and scorching (Zhang *et al*., 2003). In response to higher-than-preferred temperatures, crop growth can also be inhibited due to decreased photosynthesis and increased rate of respiration (Prasad *et al*., 2006). Heat stress can cause problems in mitochondrial functions and can result in oxidative damage (Cross *et al*., 2003). Crop yields are particularly sensitive to brief episodes of hot temperatures if these coincide with critical stages of development. Hot temperatures at the time of flowering can reduce the potential number of seeds or grains that contribute to subsequent crop yields. Therefore, both temperature extremes beyond a crop's preferred temperature can negatively impact its yield (Kai & Iba, 2014).

Cool temperature crops (e.g., lettuce) are only suitable to grow in more temperate countries with lower average temperatures to prevent it from flowering too quickly (Passioura, 2002). This means that there are a few countries that dominate the production of cool temperature crops. The specialization of certain countries on cool temperature crops widens the gap of yields between countries, resulting in lower synchrony in crop yields. On the other hand, warm temperature crops can be grown in just about any countries since technology like greenhouses allow warmer conditions to exist in colder areas. Crops like eggplant for example, can be grown in a wide range of countries (Ozkan *et al*., 2004). Technology makes it easier for warm crops to grow in colder countries, but it is not as easy to grow cool crops in hotter countries. Therefore, it is reasonable to see synchrony of warmer crops to be higher as the difference in yields is not as dramatic between countries.

A crop's growing period is the period from sowing or transplanting to the last day of harvest. It is mainly dependent on the type and variety of the crop, as well as planting date and the climate condition it's grown in (Allen *et al*., 1998). Growing period of a crop is longer when the climate is cool and shorter when the climate is warm (Greenwood *et al*., 1977). The total growing period can also be divided into four growth stages: initial stage, development stage, mid-season stage and late-season stage (Quinn & Kelly, 2011). The initial stage is the period from sowing/transplanting until the crop covers about 10% of the ground. This is then followed by the development stage and lasts until the crop covers about

80% of the ground, but does not necessarily mean the crop is at its maximum height. The mid-season stage usually lasts the longest and it runs from the end of the development stage until the crop's maturity, which includes flowering and grain setting. This is immediately followed by late-season stage, lasting until the last day of harvest (Quinn & Kelly, 2011).

The total length of growing period for a crop was negatively correlated with synchrony in crop yields. This suggests crops that take longer to grow conditions experience lower synchrony in yields, while crops that have shorter growing periods experience higher synchrony in yields. Crops that take longer amount of time to grow have a higher chance of suffering from a major weather event that could decimate or heavily impact its yields. These crops also have a higher chance of facing localized natural disasters such as hurricanes, floods, fires, earthquakes, and tornadoes that could challenge its resulting yields. Crops with longer growing periods are also more prone to biological threats such as pest and disease outbreak. Localized crop failures due to these chance events greatly decrease the synchrony in yields of these crops among countries.

For instance, an impact freeze that lasted for 4 days in 1989 annihilated the entire citrus production in the Florida state (Miller & Downton, 1993). The annual citrus yield in USA subsequently took a big hit that year as Florida produced more than 70 percent of the country's supply of citrus (Gottwald *et al.*, 2001). In fact, citrus takes longer to grow than most crops, with a mean growing period of 302.5 days. With relatively longer growing periods, it is therefore no surprise to see that citrus had one of the lowest indices of synchrony among crops in the study.

I also found that the lengths of later-stage growing periods were more negatively correlated with synchrony than the earlier-stages growing periods. This finding helped narrow down the aforementioned asynchrony-inducing chance events to processes that affected crops at later-stage growing periods. Specifically, this result ruled out indiscriminant chance effects like earthquakes, which affect crops of all stages, and pinpointed to events that later stage crops may have been more vulnerable to. These included events such as severe droughts that usually affect more heavily toward water-demanding matured crops than less water-demanding immature crops (Fereres & Soriano, 2007; Jensen, 1968). Crops with longer late-stage growing periods were more prone to face these localized major weather events, and thus experienced a lower degree of synchrony in yields among countries.

Length of growing season is defined by the number of days temperature remains above 5°C (Lobell & Field, 2007). Crops with longer growing periods are therefore suited to a subset of countries that have growing seasons that are long enough for them. In addition, crops with longer growing periods are generally riskier from an economic perspective since they require more financial investment to cultivate. Crops like bananas are therefore grown by large-scale growers and are concentrated in a few countries that specialize in cultivating them (Raynolds, 2003). Because of the domination of a few countries that produces them, the yield gaps of these long growing period crops are high between countries. This wider difference in mean yields results in lower synchrony between countries.

Water is important to crops for transpiration and photosynthesis. Crop water need is defined by the amount of water needed by a crop to meet its water loss through evapotranspiration and to grow optimally (Allen *et al*., 1998). The amount of water needed mainly depends on the type of crop, the growth stage it is in, as well as the surrounding climate condition (Smith *et al*., 1998). Water hungry crops like rice and sugarcane need more water than drier crops like millet and sorghum. Full-grown crops in its late-stage growing period most often need more water than in earlier-stages. A crop that's grown in sunny and hot conditions likely need more water than the same crop that is raised in a cloudy and cool condition (Allen *et al*., 1998).

Synchrony of a crop yield declined as the crop's minimum water need increased. This means that crops that require more water throughout its growing period experience lower synchrony in yields, while crops that require less water experience higher synchrony in yields. Crops with higher water needs are more vulnerable to fluctuations in local rainfall. This vulnerability translates into higher potential for poor yields when a country is hit by dry spells. As frequencies of dry spells are different from country to country, it could introduce asynchrony in yields (Kogan, 1997). Water availability is projected to change due to climate change where wet areas will become wetter and dry areas will become drier. Crop yields could increase if irrigation is expanded or irrigated areas are expanded, but these come at high costs to the environment considering the strained water supplies around the world (Lobell & Field, 2007).

The global mean temperature will continue to rise in the near future due to global warming. Warmer average temperature means the average number of days between the last spring frost and first fall frost increased, effectively extending the duration of the growing season (Walther *et al*., 2002). Current literature points to both positive and negative consequences of lengthened growing seasons (Linderholm, 2006; Menzel & Fabian, 1999). A longer growing season can for example allow countries to diversify crop production while having multiple harvests from the same growing season (Peltonen *et al*., 2008). Crops with longer growing periods would be suited to more number of countries that have long enough growing season to cultivate them. This closes the yield gaps of long growing period crops between countries. The lower difference in mean yields between countries would then boost synchrony between countries.

My results suggest that as crops adapt to the anticipated higher average temperatures in the near future, synchrony of crop yields will likely increase. As global warming increases crop yield synchrony, the total variability of global food supply increases, which results in lower stability in global food supply and exacerbates food insecurity. Combined with the predicted higher frequencies of climate extremes, the findings in this study reinforce the current notion that climate change will have negative consequences on the global food supply. The results from this study contribute to future yield variability researches, providing insights into the factors that influence a crop's synchrony in yields. This also provides valuable information that policy makers can use to target efforts to stabilize food supply and boost food security around the world.

Despite the clear relationship between a crop's preferred climatic conditions (i.e., preferred soil temperature, length of growing period, and total water need) and its synchrony, my study had several limitations. The preferred temperature data were based on crops that were grown in the province of Alberta, and resembled the values found in crop varieties that are found in temperate regions. Therefore, absolute values of these preferred temperatures were likely lower than varieties found in warmer regions (e.g., tropics).

Nevertheless, the relative differences between crops' preferred temperatures were likely retained and therefore were still valid to resemble variation on the average crop's preferred temperatures worldwide. Crop water need values were also rough estimates and may not be reliable to represent all crop varieties. Crop water need depends on the variety, climate conditions and its current growth stage. A crop grown in hot and dry climate condition for example may need more water than the same crop grown in cool and humid condition. Lastly, future studies should investigate this relationship for synchrony at finer resolution, perhaps at provinces or states level. However, this could be challenging given the difficulty in obtaining constant yield data at these resolutions.

SUMMARY AND CONCLUSIONS

A crop's preferred germination temperature, length of growing period and total water need were strong predictors for its synchrony in yields between countries. These findings should enable identification of crops that are good candidates for which spatial variability could be used to predict regional temporal variability. The results in this study also suggest that synchrony of most crop yields will likely increase due to global warming. This translates into higher fluctuations in global food supply, which increases instability in global food supply and threatens global food security. Policy makers should target efforts to stabilize food supply by focusing on high-risk crops in order to boost food security around the world. This study adds supporting evidence to the current notion that climate change will have negative consequences on the global food supply. Not only is the absolute yield of crops expected to be impacted by climate change, but variability and uncertainty are also likely to increase as a result. Future studies should investigate the factors for synchrony at finer resolutions, which may provide insight to local farmers on the crops that are most vulnerable at the local level.

Appendix B

Table 3-1. Summary of various factors on indices of synchrony and persistence of crops yields at different scales (i.e., continental, general latitude, sub-regional).

Minimum germination soil temperature (°C)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	0.01	0.75	5.46	0.03	0.26
persistence (continental)	-0.001	1	6.86	0.02	0.3
synchrony (subregional)	0.01	0.47	1.27	0.28	0.07
persistence (subregional)	-0.0002	0.98	0.19	0.67	0.01
synchrony (general latitude)	0.005	0.7	0.31	0.59	0.02
persistence (general latitude)	-0.0003	1	7.69	0.01	0.33
Mean preferred germination soil temperature (°C)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	0.02	0.34	16.8	0.001	0.51
persistence (continental)	-0.001	1.02	8.01	0.01	0.33
synchrony (subregional)	0.03	-0.04	4.24	0.06	0.21
persistence (subregional)	0.001	0.97	0.48	0.5	0.03
synchrony (general latitude)	0.02	0.28	3.14	0.1	0.16
persistence (general latitude)	-0.0002	1	1.53	0.23	0.09
Maximum preferred germination soil temperature (°C)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	0.01	0.42	7.96	0.01	0.33
persistence (continental)	-0.0004	1.01	2.52	0.13	0.14
synchrony (subregional)	0.02	-0.03	3.73	0.07	0.19
persistence (subregional)	0.0002	0.97	0.18	0.67	0.01
synchrony (general latitude)	0.01	0.4	1.47	0.24	0.08
persistence (general latitude)	-0.0002	1	1.11	0.31	0.06
Preferred germination soil temperature range size (°C)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	0.002	0.8	0.43	0.52	0.03
persistence (continental)	0.0001	1	0.12	0.74	0.01
synchrony (subregional)	0.01	0.48	0.7	0.42	0.04
persistence (subregional)	0.0001	0.98	0.03	0.86	0.002

synchrony (general latitude)	0.001	0.72	0.05	0.83	0.003
persistence (general latitude)	-0.00001	0.99	0.02	0.89	0.001
Minimum growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.002	1.05	20.5	0.0001	0.43
persistence (continental)	-0.00003	0.99	0.18	0.68	0.01
synchrony (subregional)	-0.002	0.75	7.42	0.01	0.22
persistence (subregional)	-0.00004	0.97	0.11	0.75	0.004
synchrony (general latitude)	-0.001	0.91	6.27	0.02	0.19
persistence (general latitude)	- 0.000004	0.99	0.004	0.95	0.0002
Maximum growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.002	1.01	14.5	0.001	0.35
persistence (continental)	0.00001	0.99	0.03	0.87	0.001
synchrony (subregional)	-0.001	0.73	6.32	0.02	0.19
persistence (subregional)	-0.00002	0.97	0.03	0.87	0.001
synchrony (general latitude)	-0.001	0.89	5.08	0.03	0.16
persistence (general latitude)	0.00001	0.99	0.05	0.83	0.002
Mean growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.002	1.03	17.5	0.0003	0.39
persistence (continental)	- 0.000005	0.99	0.01	0.94	0.0002
synchrony (subregional)	-0.002	0.75	6.99	0.01	0.21
persistence (subregional)	-0.00003	0.97	0.06	0.81	0.002
synchrony (general latitude)	-0.001	0.9	5.74	0.02	0.18
persistence (general latitude)	0.00001	0.99	0.01	0.92	0.0004
Range size of growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.002	0.83	2.46	0.13	0.08
persistence (continental)	0.0002	0.98	1.63	0.21	0.06
synchrony (subregional)	-0.002	0.59	1.81	0.19	0.06
persistence (subregional)	0.00005	0.96	0.04	0.85	0.001
synchrony (general latitude)	-0.001	0.78	1.24	0.27	0.04
persistence (general latitude)	0.0001	0.99	0.5	0.49	0.02
Minimum crop water need (mm/growing period)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**

synchrony (continental)	-0.0005	1.01	33.2	<0.0001	0.64
persistence (continental)	0.000003	0.99	0.03	0.87	0.001
synchrony (subregional)	-0.0004	0.69	7.77	0.01	0.29
persistence (subregional)	0.000005	0.96	0.03	0.88	0.001
synchrony (general latitude)	-0.0003	0.9	9.12	0.01	0.32
persistence (general latitude)	0.000004	0.99	0.08	0.77	0.004
Maximum crop water need (mm/growing period)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.0003	0.97	25.9	<0.0001	0.58
persistence (continental)	0.000002	0.99	0.06	0.81	0.003
synchrony (subregional)	-0.0002	0.64	5.79	0.03	0.23
persistence (subregional)	0.00001	0.96	0.24	0.63	0.01
synchrony (general latitude)	-0.0002	0.87	7.27	0.01	0.28
persistence (general latitude)	0.000004	0.99	0.21	0.65	0.01
Mean crop water need (mm/growing period)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.0003	0.99	28.8	<0.0001	0.6
persistence (continental)	0.000003	0.99	0.05	0.83	0.002
synchrony (subregional)	-0.0002	0.66	6.52	0.02	0.26
persistence (subregional)	0.00001	0.96	0.14	0.72	0.01
synchrony (general latitude)	-0.0002	0.88	7.99	0.01	0.3
persistence (general latitude)	0.000004	0.99	0.16	0.69	0.01
Range size of crop water need (mm/growing period)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.001	0.9	15.9	0.001	0.46
persistence (continental)	0.00001	0.99	0.11	0.75	0.01
synchrony (subregional)	-0.0003	0.59	3.42	0.08	0.15
persistence (subregional)	0.00003	0.96	0.78	0.39	0.04
synchrony (general latitude)	-0.0003	0.82	4.73	0.04	0.2
persistence (general latitude)	0.00001	0.99	0.42	0.52	0.02
Minimum initial stage growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	0.01	0.56	2.77	0.11	0.11
persistence (continental)	-0.0004	0.99	0.001	0.97	0.0001
synchrony (subregional)	0.02	0.07	8.41	0.01	0.28
persistence (subregional)	0.002	0.92	1.56	0.23	0.07
synchrony (general latitude)	0.02	0.43	7.12	0.01	0.24
persistence (general latitude)	0.0001	0.99	0.01	0.92	0.0005

maximum initial stage growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	0.001	0.76	0.07	0.79	0.003
persistence (continental)	0.0005	0.98	0.51	0.48	0.02
synchrony (subregional)	0.01	0.42	0.9	0.35	0.04
persistence (subregional)	0.001	0.93	1.77	0.2	0.07
synchrony (general latitude)	0.002	0.7	0.33	0.57	0.01
persistence (general latitude)	0.0004	0.98	0.56	0.46	0.03
Mean initial stage growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	0.005	0.68	0.7	0.41	0.03
persistence (continental)	0.0004	0.98	0.2	0.66	0.01
synchrony (subregional)	0.01	0.26	3.01	0.1	0.12
persistence (subregional)	0.002	0.92	1.94	0.18	0.08
synchrony (general latitude)	0.01	0.59	1.92	0.18	0.08
persistence (general latitude)	0.0004	0.98	0.28	0.6	0.01
Ratio of initial stage to total growing period	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	1.38	0.54	4.75	0.04	0.18
persistence (continental)	0.09	0.97	0.77	0.39	0.03
synchrony (subregional)	2.29	0.14	7.85	0.01	0.26
persistence (subregional)	0.2	0.93	1.43	0.25	0.06
synchrony (general latitude)	1.48	0.5	5.98	0.02	0.21
persistence (general latitude)	0.05	0.98	0.34	0.57	0.02
Minimum developmental stage growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	0.004	0.68	0.32	0.58	0.01
persistence (continental)	-0.0003	1	0.11	0.74	0.01
synchrony (subregional)	0.01	0.18	2.2	0.15	0.09
persistence (subregional)	0.001	0.93	0.62	0.44	0.03
synchrony (general latitude)	0.01	0.52	1.72	0.2	0.07
persistence (general latitude)	-0.0001	0.99	0.01	0.91	0.001
Maximum developmental stage growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.001	0.81	0.03	0.87	0.001
persistence (continental)	0.0002	0.98	0.16	0.7	0.01
synchrony (subregional)	0.001	0.52	0.05	0.83	0.002

persistence (subregional)	0.001	0.94	0.69	0.41	0.03
synchrony (general latitude)	0.0001	0.76	0.001	0.97	0.0001
persistence (general latitude)	0.0002	0.98	0.14	0.71	0.01
Mean developmental stage growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	0.001	0.78	0.01	0.92	0.0005
persistence (continental)	0.0001	0.98	0.02	0.89	0.001
synchrony (subregional)	0.005	0.4	0.5	0.49	0.02
persistence (subregional)	0.001	0.93	0.78	0.39	0.03
synchrony (general latitude)	0.003	0.68	0.27	0.61	0.01
persistence (general latitude)	0.0001	0.99	0.05	0.83	0.002
Ratio of developmental stage to total growing period	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	0.85	0.57	2.44	0.13	0.1
persistence (continental)	0.06	0.97	0.42	0.52	0.02
synchrony (subregional)	1.26	0.23	2.96	0.1	0.12
persistence (subregional)	0.09	0.94	0.4	0.53	0.02
synchrony (general latitude)	0.83	0.54	2.45	0.13	0.1
persistence (general latitude)	0.02	0.99	0.07	0.8	0.003
Minimum mid-season stage growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.01	1.01	7.07	0.01	0.24
persistence (continental)	-0.0003	1	0.77	0.39	0.03
synchrony (subregional)	-0.01	0.82	4.97	0.04	0.18
persistence (subregional)	-0.0002	0.97	0.12	0.73	0.01
synchrony (general latitude)	-0.004	0.94	4.34	0.05	0.17
persistence (general latitude)	-0.00002	0.99	0.01	0.93	0.0003
Maximum mid-season stage growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.001	0.88	0.78	0.39	0.03
persistence (continental)	0.00005	0.99	0.03	0.86	0.001
synchrony (subregional)	-0.002	0.69	0.95	0.34	0.04
persistence (subregional)	0.0002	0.95	0.31	0.58	0.01
synchrony (general latitude)	-0.001	0.84	0.66	0.43	0.03
persistence (general latitude)	0.0001	0.98	0.28	0.6	0.01
Mean mid-season stage	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**

growing period (days)					
synchrony (continental)	-0.004	0.97	3.09	0.09	0.12
persistence (continental)	-0.0001	0.99	0.08	0.78	0.004
synchrony (subregional)	-0.005	0.79	2.74	0.11	0.11
persistence (subregional)	0.0001	0.96	0.04	0.85	0.002
synchrony (general latitude)	-0.003	0.91	2.18	0.15	0.09
persistence (general latitude)	0.0001	0.99	0.09	0.77	0.004
Ratio of mid-season stage to total growing period	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.58	1.01	1.51	0.23	0.06
persistence (continental)	-0.003	0.99	0.001	0.97	0.0001
synchrony (subregional)	-0.94	0.9	2.2	0.15	0.09
persistence (subregional)	-0.005	0.97	0.002	0.97	0.0001
synchrony (general latitude)	-0.59	0.98	1.65	0.21	0.07
persistence (general latitude)	0.02	0.98	0.09	0.77	0.004
Minimum late-season stage growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.01	1	9.96	0.005	0.31
persistence (continental)	-0.001	1.01	3.09	0.09	0.12
synchrony (subregional)	-0.01	0.8	7.16	0.01	0.25
persistence (subregional)	-0.001	0.99	1.79	0.19	0.08
synchrony (general latitude)	-0.01	0.93	6.65	0.02	0.23
persistence (general latitude)	-0.0004	1	0.84	0.37	0.04
Maximum late-season stage growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.01	0.93	3.23	0.09	0.13
persistence (continental)	-0.0004	1	0.62	0.44	0.03
synchrony (subregional)	-0.01	0.76	3.92	0.06	0.15
persistence (subregional)	-0.0005	0.98	0.44	0.52	0.02
synchrony (general latitude)	-0.01	0.9	3.29	0.08	0.13
persistence (general latitude)	-0.0001	0.99	0.16	0.7	0.01
Mean late-season stage growing period (days)	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-0.01	0.97	5.95	0.02	0.21
persistence (continental)	-0.001	1	1.56	0.22	0.07
synchrony (subregional)	-0.01	0.79	5.54	0.03	0.2
persistence (subregional)	-0.001	0.98	0.98	0.33	0.04

synchrony (general latitude)	-0.01	0.92	4.9	0.04	0.18
persistence (general latitude)	-0.0003	1	0.42	0.52	0.02
Ratio of late-season stage to total growing period	**Slope**	**y-int**	**F ratio**	**p**	**Rsquare**
synchrony (continental)	-1.15	1	4.42	0.05	0.17
persistence (continental)	-0.13	1.01	2.27	0.15	0.09
synchrony (subregional)	-1.75	0.88	5.9	0.02	0.21
persistence (subregional)	-0.24	1.01	3.19	0.09	0.13
synchrony (general latitude)	-1.17	0.98	4.99	0.04	0.19
persistence (general latitude)	-0.08	1	1.47	0.24	0.06

LITERATURE CITED

Agriculture and Forestry Ministry of Alberta. (2000). *Agri-facts – Practical information for Alberta's agriculture industry*. Retrieved from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1203

Ainsworth, E. A., & Long, S. P. (2005). What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2. *New Phytologist*, *165*(2), 351-372.

Ainsworth, E. A., & Rogers, A. (2007). The response of photosynthesis and stomatal conductance to rising [CO2]: mechanisms and environmental interactions. *Plant, cell & environment*, *30*(3), 258-270.

Ainsworth, E. A., Rogers, A., & Leakey, A. D. (2008). Targets for crop biotechnology in a future high-CO2 and high-O3 world. *Plant physiology*, *147*(1), 13-19.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO, Rome*, *300*(9), D05109.

Berger, A., Loutre, M. F., & Laskar, J. (1992). Stability of the astronomical frequencies over the Earth's history for paleoclimate studies. *Science*, *255*(5044), 560-566.

Canadell, J. G., Le Quéré, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., ... & Marland, G. (2007). Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the national academy of sciences*, *104*(47), 18866-18870.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., ... & Valentini, R. (2005). Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, *437*(7058), 529-533.

Conroy, J. P. (1992). Influence of elevated atmospheric CO2 concentrations on plant nutrition. *Australian Journal of Botany*, *40*(5), 445-456.

Deschenes, O., & Greenstone, M. (2007). The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. *The American Economic Review*, 354-385.

Dore, M. H. (2005). Climate change and changes in global precipitation patterns: what do we know?. *Environment international*, *31*(8), 1167-1181.

Fereres, E., & Soriano, M. A. (2007). Deficit irrigation for reducing agricultural water use. *Journal of experimental botany*, *58*(2), 147-159.

Flores, F., Nadal, S., Solis, I., Winkler, J., Sass, O., Stoddard, F. L., ... & Rubiales, D. (2012). Faba bean adaptation to autumn sowing under European climates. *Agronomy for sustainable development*, *32*(3), 727-734.

Friis-Christensen, E., & Lassen, K. (1991). Length of the solar cycle: an indicator of solar activity closely associated with climate. *Science*, *254*(5032), 698-700.

Gottwald, T. R., Hughes, G., Graham, J. H., Sun, X., & Riley, T. (2001). The citrus canker epidemic in Florida: the scientific basis of regulatory eradication policy for an invasive species. *Phytopathology*, *91*(1), 30-34.

Greenwood, D. J., Cleaver, T. J., Loquens, S. M. H., & Niendorf, K. B. (1977). Relationship between plant weight and growing period for vegetable crops in the United Kingdom. *Annals of Botany*, *41*(5), 987-997.

Hansen, J., Ruedy, R., Sato, M., & Lo, K. (2010). Global surface temperature change. *Reviews of Geophysics*, *48*(4).

Houghton, J. T., Ding, Y. D. J. G., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., ... & Johnson, C. A. (2001). Climate change 2001: the scientific basis.

Jackson, R. D., Reginato, R. J., & Idso, S. B. (1977). Wheat canopy temperature: a practical tool for evaluating water requirements. *Water resources research*, *13*(3), 651-656.

Jensen, E. S., Peoples, M. B., & Hauggaard-Nielsen, H. (2010). Faba bean in cropping systems. *Field Crops Research*, *115*(3), 203-216.

Kamran, A., & Asif, M. (2011). Climate Change and Crop Production. *Crop Science*, *51*(5), 2299-2300.

Kelly, D., & Sork, V. L. (2002). Mast seeding in perennial plants: why, how, where?. *Annual Review of Ecology and Systematics*, 427-447.

Lafta, A. M., & Lorenzen, J. H. (1995). Effect of high temperature on plant growth and carbohydrate metabolism in potato. *Plant Physiology*, *109*(2), 637-643.

Lal, R. (2006). Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation & Development*, *17*(2), 197-209.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, *304*(5677), 1623-1627.

Lean, J., & Rind, D. (1996). The sun and climate. *Consequences*, *2*(1), 27-36.

Liebhold, A., Koenig, W. D., & Bjørnstad, O. N. (2004). Spatial synchrony in population dynamics. *Annual Review of Ecology, Evolution, and Systematics*, 467-490.

Linderholm, H. W. (2006). Growing season changes in the last century. *Agricultural and Forest Meteorology*, *137*(1), 1-14.

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop yield gaps: their importance, magnitudes, and causes. *Annual Review of Environment and Resources*, *34*(1), 179.

Lobell, D. B., & Field, C. B. (2007). Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental research letters*, *2*(1), 014002.

Long, S. P., Ainsworth, E. A., Rogers, A., & Ort, D. R. (2004). Rising atmospheric carbon dioxide: plants FACE the Future. *Annu. Rev. Plant Biol.*, *55*, 591-628.

Menzel, A., & Fabian, P. (1999). Growing season extended in Europe. *Nature*, *397*(6721), 659-659.

Miller, K. A., & Downton, M. W. (1993). The freeze risk to Florida citrus. Part 1: Investment decisions. *Journal of Climate*, *6*(2), 354-363.

Mitchell, J. F. B., Johns, T. C., Gregory, J. M., & Tett, S. F. B. (1995). *Climate response to increasing levels of greenhouse gases and sulphate aerosols*. *Science*, *219*(2673), 1022-1031.

Monfreda, C., Ramankutty, N., & Foley, J. A. (2008). Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global biogeochemical cycles*, *22*(1).

Mooney, H. A., Drake, B. G., Luxmoore, R. J., Oechel, W. C., & Pitelka, L. F. (1991). Predicting ecosystem responses to elevated CO2 concentrations. *BioScience*, 96-104.

Morison, J. I., & Gifford, R. M. (1983). Stomatal sensitivity to carbon dioxide and humidity a comparison of two C3 and two C4 grass species. *Plant physiology*, *71*(4), 789-796.

Neumann, K., Verburg, P. H., Stehfest, E., & Müller, C. (2010). The yield gap of global grain production: A spatial analysis. *Agricultural systems*, *103*(5), 316-326.

Oppenheimer, C. (2003). Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. *Progress in physical geography*, *27*(2), 230-259.

Paradis, E., Baillie, S. R., Sutherland, W. J., & Gregory, R. D. (1999). Dispersal and spatial scale affect synchrony in spatial population dynamics. *Ecology Letters*, *2*(2), 114-120.

Peltonen-Sainio, P., Jauhiainen, L., & Hakala, K. (2008). Climate change and prolongation of growing season: changes in regional potential for field crop production in Finland. *Agricultural and Food Science*, *18*(3-4), 171-190.

Peng, S., Huang, J., Sheehy, J. E., Laza, R. C., Visperas, R. M., Zhong, X., ... & Cassman, K. G. (2004). Rice yields decline with higher night temperature from global warming. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(27), 9971-9975.

Porter, J. R. (2005). Rising temperatures are likely to reduce crop yields. *Nature*, *436*(7048), 174-174.

Post, E., & Forchhammer, M. C. (2002). Synchronization of animal population dynamics by large-scale climate. *Nature*, *420*(6912), 168-171.

Prasad, P. V., Boote, K. J., & Allen, L. H. (2006). Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum [Sorghum bicolor (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. *Agricultural and forest meteorology*, *139*(3), 237-251.

Quinn, J., & Kelly, D. (2011). Crop growth stages. *Australian Cotton Production Manual*, 44-47.

Raynolds, L. T. (2003). The global banana trade. *Banana Wars: Power, Production, and History in the Americas*, 23-47.

Rosenzweig, C., & Parry, M. L. (1994). Potential impact of climate change on world food supply. *Nature*, *367*(6459), 133-138.

Ranta, E., Kaitala, V., Lindström, J., & Helle, E. (1997). The Moran effect and synchrony in population dynamics. *Oikos*, 136-142.

Richard, A. (2012). A new estimate of the average earth surface land temperature spanning 1753 to 2011. *Geoinformatics & Geostatistics: An Overview*.

Ritchie, J. T., & NeSmith, D. S. (1991). Temperature and crop development. *Modeling plant and soil systems. Agron. Monogr*, *31*, 5-29.

Rosenzweig, C., & Parry, M. L. (1994). Potential impact of climate change on world food supply. *Nature*, *367*(6459), 133-138.

Satake, A., & Koizumi, I. (2008). Population synchrony in ecological systems. *Population ecology*, *50*(4), 325-327.

Shackleton, N. J. (2000). The 100,000-year ice-age cycle identified and found to lag temperature, carbon dioxide, and orbital eccentricity. *Science*, *289*(5486), 1897-1902.

Sitch, S., Cox, P. M., Collins, W. J., & Huntingford, C. (2007). Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature*, *448*(7155), 791-794.

Smith, M., Allen, R., & Pereira, L. (1998). Revised FAO methodology for crop-water requirements.

Solomon, S., Plattner, G. K., Knutti, R., & Friedlingstein, P. (2009). Irreversible climate change due to carbon dioxide emissions. *Proceedings of the national academy of sciences*, *106*(6), 1704-1709.

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, *108*(50), 20260-20264.

Walther, G. R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J., & Bairlein, F. (2002). Ecological responses to recent climate change. *Nature*, *416*(6879), 389-395.

Wood, B. D., & Vedlitz, A. (2007). Issue definition, information processing, and the politics of global warming. *American journal of political science*, *51*(3), 552-568.

Wright, S. J. (1991). Seasonal drought and the phenology of understory shrubs in a tropical moist forest. *Ecology*, 1643-1657.

Chapter 4

Conclusion

CONCLUSION

Summary and Conclusions

For my thesis, I took on an integrative and comprehensive approach in the investigation of spatiotemporal dynamics in crop yields. Although a previous study have quantified a link between spatial and temporal variability (Hammond & Kolasa, 2014), the research presented here took the relationship to a macro-ecological scale in the context of global crop yields. My study evaluated whether it is possible to use spatial variation of crop data to predict regional temporal variation in crop yields. Moreover, this study was one of the first to determine factors that may be able to predict synchrony and spatial persistence of crop yields between countries. Through this, I was able to identify crops that are better candidates than others to use spatial variability to predict regional temporal variability.

Based on the results from this study, I concluded that spatial data of crop yield has good potential in predicting its temporal variability via space-for-time substitution. The accuracy of the approximation diminishes however, as the persistence of spatial differences between countries shift the crop variables down from the independent patch dynamics and into the persistence region where spatial CV overestimates temporal CV. Persistence is the lack of changes in spatial differences between patches from time point to time point (Hammond &

Kolasa, 2014). Since yield of most crops within a country does not fluctuate much from year to year, spatial persistence of most crop yields can be quite high due to consistent differences in yields between countries. Some crops are better candidates for the space-for-time substitution than others, and they are crops that have levels of synchrony and persistence similar enough to cancel out each other's effect on the crop's spatiotemporal dynamics.

The spatiotemporal correspondence in crop yields was much lower at finer scales (i.e., continent, sub-region and general latitude) compared to global scale. The fewer countries within the regions at these scales translated into lower correlation between mean spatial CVs and mean aggregate temporal CVs. However, there were some cases within each spatial scale where the space-for-time substitution for variance showed promise. Western Europe for example, had similar level of persistence across crop variables, which displaced the points somewhat equally down from the independent patch dynamics. The rank order of temporal CV's in this case, could still be predicted from spatial CV via qualitative substitution.

I also found that a crop's preferred germination temperature, length of growing period and total water need were strong predictors for its synchrony in yields between countries for most crops. The identification of these factors provided insights on the type of crops that are good candidates in using spatial variability to predict regional temporal variability. Specifically, these include crops that have high preferred germination soil temperature, low minimum crop water needs, and low minimum growing period. The accuracy of the approximation are higher in these crops as the level of synchrony and persistence of spatial variation are more similar than others and can cancel out each other's effect on the spatiotemporal dynamics.

This study also suggested that as crops adapt to the anticipated higher average temperatures in the near future, synchrony of crop yields will likely increase. As global warming increases crop yield synchrony, the total variability of crop production increases, which results in lower stability in global food supply and exacerbates food insecurity. Combined with the predicted higher frequencies of climate extremes, the findings in this study reinforce the current notion that climate change will have negative consequences on the global food supply.

Limitations and Future Directions

My study had several limitations. First, the temporal scale in my data set was quite limited compared to the spatial scale (i.e., 23 time points vs. 212 patches). Due to the gap in record keeping between countries, complete crop yield data were only available from 1990 onward. The low number of time points likely underestimated the level of synchrony and overestimated the level of spatial persistence. Therefore, more temporal data would have likely resulted in stronger relationship between temporal and spatial variability.

Also, data on yields of crops in some countries may not be entirely reliable due to the potential irregularities in reported production and harvested area figures by each country's officials. Most estimated national crop yield data only referred to crops grown in field and market gardens mainly for sale, excluding crops cultivated in kitchen gardens or small family gardens mainly for household consumption. However, the relatively small contribution from family and small gardens are unlikely to play an important part in the estimated crop yields in most countries.

Furthermore, while this analysis has shown the feasibility in using spatial variance to predict regional temporal variance at the global scale, the prediction has not been tested at the country level. Future work that includes crop yield data from finer scales such as provinces and states within countries should enable the assessment of predictability of temporal variance at the country level.

The preferred climatic conditions of each crop may have also exhibited some degrees of error. For example, the preferred temperature data was based on crops grown in the province of Alberta, and resembled the temperature preferences of crop varieties that are found in temperate regions. Therefore, absolute values of these preferred temperatures were likely lower than varieties found in warmer regions (e.g., tropics). Nevertheless, the relative differences between crops' preferred temperatures were likely retained and therefore were still valid to resemble variation on the average crop's preferred temperatures worldwide. Crop-water need values were also rough estimates and may not be reliable to represent all crop varieties. Crop-water need depends on the variety, as well as the climate conditions and growth stage it is in. A crop grown in hot and dry climate condition for example may need more water than the same crop grown in cool and humid condition.

Future studies should investigate this relationship for synchrony at finer resolution, perhaps at provinces or states level. This may provide insight to local farmers on the crops that are most vulnerable at the local level. However, this could be challenging given the difficulty in obtaining consistent yield data at these resolutions. Understanding the factors that influence crop yield synchrony and persistence can provide insights into the spatiotemporal dynamics of crop yields. Accounting and combining the effects of those factors may help fine-tune the approximation such that spatial data can better predict temporal dynamics in crop yields. Future studies, therefore, should investigate other factors that may influence crop yield synchrony and persistence at broader scales.

Implications for policy makers

Global food security continues to be under threat due to a number of fundamental factors (Gilland, 2002; Parry, 2004; Pimentel, 1973). By 2050, food demand is expected to almost double from the levels in 2005 (Tilman *et al*., 2011). Suitable land and natural resources are becoming limited; future expansion for agriculture areas will incur a significant risk to remaining forests and savanna (Mueller *et al*., 2012). Continued yield improvements will therefore be key factor in raising crop production in the near future. The potential to forecast temporal stability of crop yields from its spatial data allows various agencies to improve agricultural polices and production forecasts. Identification of regions with high yield variability can help creating strategies to ensure crop supply stability and prevention of food price spikes.

Given the committed trajectory of global temperature increase, the results in this study also suggest that synchrony of crop yields will likely increase due to climate change. This translates into higher fluctuations in global food supply, which increases instability in global food supply and threatens global food security. Policy makers should target efforts to stabilize food supply by targeting high-risk crops in order to boost food security around the world. The results in this study add another supporting evidence to the current notion that climate change will have negative consequences on the global food supply. Not only is the absolute yield of crops expected to be impacted by climate change, but also total production variability and uncertainty are likely to increase as a result.

LITERATURE CITED

Gilland, B. (2002). World population and food supply: Can food production keep pace with population growth in the next half-century?. *Food Policy*, *27*(1), 47-63.

Hammond, M. P., & Kolasa, J. (2014). Spatial variation as a tool for inferring temporal variation and diagnosing types of mechanisms in ecosystems. *PloS one*, *9*(2), e89245.

Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science*, *333*(6042), 616-620.

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature*, *490*(7419), 254-257.

Parry, M. L., Rosenzweig, C., Iglesias, A., Livermore, M., & Fischer, G. (2004). Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change*, *14*(1), 53-67.

Pimentel, D., Hurd, L. E., Bellotti, A. C., Forster, M. J., Oka, I. N., Sholes, O. D., & Whitman, R. J. (1973). Food production and the energy crisis. *Science*,*182*(4111), 443-449.

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, *108*(50), 20260-20264.