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A modeling framework for the strategic design of local fresh-food systems

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ABSTRACT

The increase in demand for locally grown products over the last couple of decades has created one of the fastest growing sectors within the fresh produce industry. Our hypothesis is that micro and small farmers within local food systems are well positioned to take advantage of existing sustainable and profitable opportunities, specifically in high-value agricultural production. Unearthing these opportunities can entice more micro and small farmers to enter agricultural production, thus expanding the volume, variety and/or quality of products available for local consumption, which are often key factors in farming success. In this study, our objective is two-fold: (1) to demonstrate the hidden production potential that exist within local urban/rural communities and (2) to highlight the importance of supply chain modeling tools in the strategic design of local agricultural systems. As part of this study, we develop an approximation method that estimates a region's potential to produce non-perennial, vegetable items based on simplified yield functions dependent on temporal, temperature patterns. In this case, it is argued that although these estimates may not be exact, they offer practical approximations that help decision-makers identify technologies needed to protect their agricultural production, alter harvesting patterns to better match market behavior, and provide an analytical framework through which external investment entities can assess different production options. These estimates are integrated into a mixed-integer program that identifies an optimal set of small-scale operations (includes backyard-production), fresh vegetables, and wholesale markets to maximize the overall profitability of local agricultural systems. This framework conceptualizes an alternate supply chain structure that targets both internal and external consumption markets through coordinated local fresh food production. By incorporating vegetable yield patterns as a function of environmental and resource variables, the decision-maker can explore harvesting cycles of complementary regions matching market price behavior through a supply chain planning perspective. The methodology framework is applied to the design of a complementary local food system encompassing the states of New Mexico and Arizona in the U.S. Southwest region. This work demonstrates existing opportunities in exploiting complementary production capabilities of local urban communities and sets the basis for future exploration of the probabilistic components of agricultural production related to local fresh food systems.

1. Introduction

The increase in demand for locally grown products over the last couple of decades has created one of the fastest growing sectors within the fresh produce industry. Its growth can be attributed to several social changes in the U.S. – chief among them is an increase in consumer demand for alternative sources of unprocessed foods, an increased availability of safe and healthy food products, and a general consumer desire for full product traceability (Guptill and Wilkins, 2002). In turn, this movement has sparked interest from the research community to assess, from a governance and health perspective, how local food and agricultural production systems can improve consumer access to healthy foods. A topic receiving less attention, however, has been assessing agricultural production capability of local communities from a supply chain planning perspective. This is especially true in areas where production information does not exist either because an area has historically not produced agricultural items (e.g. highly-dense metropolitan areas), current open-field conditions are not ideal (i.e. production window may be too short), or simply, census reporting is not available or inaccurate (e.g. Latin American countries). In these cases, we hypothesize that there are geographical regions with adequate climate patterns to produce high-value agricultural products in a profitable and sustainable manner but whose production capabilities cannot be identified via traditional supply chain assessments. Therefore, in this paper, an agricultural planning framework is developed that seeks to identify these regional opportunities by matching the physiological

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requirements of high, profit-yielding plants (e.g. fresh fruits and vegetables, FVs) to complementary climate characteristics of geographical areas. Moreover, it integrates growth requirements of fresh fruits and vegetables (FVs) into an optimal supply chain planning design of locally sourced production systems. A small case-study in the U.S. Southwest is used to assess its functionality.

The proposed assessment framework seeks to maximize the profitability of identified fresh-food systems by determining an optimal set of wholesale markets, fresh-vegetables, and coordinated, small-scale operations ranging from 2-ha dedicated production to aggregated backyard outputs, whose volume's impact would be negligible on consumer market prices. As part of this framework, a yield approximation method is developed that estimates the production output as a function of basic environmental parameters, such as maximum and minimum temperatures, observed under controlled, production settings. The yield approximation method is used to overcome limited data environments of potential production regions. These yield approximations are then integrated into a mixed-integer programming model that coordinates local, FV production from select geographic regions with complementary climate patterns. The purpose is two-fold: (1) to identify and estimate hidden production potential that may exist within select geographical regions that may not have available historical production information but has recorded weather data and (2) to highlight the importance of using an agricultural supply chain planning perspective in the strategic design of local agricultural systems. This work also serves as a call-to-action for the research community to fill existing gaps in agricultural and supply chain planning literature specifically related to local fresh-food systems.

The inputs to this framework include the environmental characteristics and resource availability within select, geographic regions, as well as historical wholesale market prices of fresh vegetables. The output is a set of planting and harvesting schedules for each individual region, as well as optimally assigned wholesale markets. Considered in these planting and harvesting schedules would be potential opportunities provided by the use of protective planting technologies, such as greenhouse technology. This would allow investors, small farmers, or potential entrants to assess the profitability of specific product, region, and market configurations given different production technologies even when historical production information might not exist. The overall goal is to improve the odds of implementing a successful, local fresh-food operation, encouraging new participants into the agricultural supply chain, and thus, expanding the volume, variety and quality of available products. One should note that the scope of this work is on the exploration and design of a complementary production systems through an agricultural planning perspective for locally-sourced fresh vegetable supply chains.

2. Literature review on yield estimation and integration methods

The scope of this study is dependent on two main components: estimating yield as a function of environmental conditions and integrating production from different geographic regions based on these estimates. Thus, in this review of literature, focus was given to finding examples related to the development of yield estimation methods for assessing a region's potential to produce high-value, agricultural products. Focus was also given to works related to the efficient integration of local food production into established agricultural supply chains. In these works, it was noted that existing yield estimation techniques are mostly geared towards grain crops at a high, global-level perspective. It was also noted that little amount of work has been dedicated to assessing the problem from a supply chain planning perspective: coordinating production systems based on regional yield estimations in situations where actual production information is either limited or does not exist.

2.1. Methods for estimating and integrating yields into local food systems

Over the past few decades, analytical tools have been used to help plan existing production opportunities and explore alternative, land-use options. For example, a common approach to estimate a region's production capability has been the development of land-use exploration models, which are usually structured as a multi-objective programming framework aimed at analyzing large geographical regions. In one of the earliest works related to a land exploration, Barnett et al. (1982) used goal programming with multidimensional scaling to model a Senegalese subsistence farmer's decision problem. In this work, the authors point out that a multi objective approach is particularly relevant for subsistence farmers because they are frequently said to possess conflicting objectives such as profit maximization, risk avoidance, and minimum production thresholds needed for personal consumption. In another early work, Bouman et al. (1998) determine sustainable land use options in the North Atlantic Costa Rican region by quantifying regional trade-offs between socio-economic and biophysical sustainability options. Using a combination of simulation and goal-programming techniques, the authors compare among different land-use options between crops, banana plantation, livestock, and pasture with the objective of maximizing the profitability of agricultural operations in the North Atlantic Costa Rican region.

At the end of the 1990s, changing weather patterns coupled with a growing awareness that current agricultural production levels cannot meet future demand changed the focus of most land-use and exploration models towards incorporating climate change into an integrated assessment framework. These models combine different simulated weather pattern scenarios with recursive goal programming techniques to represent the decision-making process of farmers within a region. The general goal from these works is to improve estimates of current production capabilities and future growth patterns within different geographic regions, especially, under changing climate conditions. However, given the large geographic areas that these models analyze and their wide scope, these models are usually intended for policy-making purposes and geared towards cash-crops and simple technological alternatives. Examples of these works include Lu et al. (2004), who assess scenario exploration of strategic land use options in northern China, Tao et al. (2009) who construct a model through which they examine the impacts of climate variability on crop phenology and yield over large areas, and Neumann et al. (2010) who use econometric-based models along with spatial analysis to explore maximum attainable yield, yield gap and efficiencies of wheat, maize, and rice production. We note that these are only a few examples of the multitude of works that relate to the yield-gap estimation, integrated assessment, and land-use exploration models with general application to current and future productivity estimations. Interested readers can refer to Dinar and Mendelsohn (2011) and van Ittersum et al. (2013) for a more in-depth discussion for this kind of works. Other areas of work relate to farm-level studies on the topic of yield assessments from an agricultural management perspective, in which focus is given to the improvement of current resource management practices. Examples of this type of work include Bindraban et al. (2000), who use land quality metrics to determine time-dependent capacity of a given region for cropping activities, and Mueller et al. (2012), who assess the impact of fertilizers, nutrients, and water management to close estimated yield gaps.

Another approach in estimating agricultural production potential is based on the processing of aerial imagery and geospatial analyses to gauge current and potential land-use within urban communities. For example, Ackerman et al. (2012) provide a detailed assessment of current infrastructure capabilities and unused land space within New York City for potential agricultural production by combining bottom-up approaches with aerial and geographic positioning techniques. Taylor and Lovell (2012) and Erickson et al. (2013) use aerial and geographic positioning tools to quantify the agricultural production opportunity available in urban communities within Chicago's communities and