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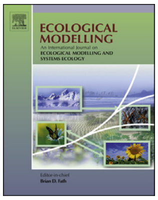

Exploring agricultural production systems and their fundamental components with system dynamics modelling

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ABSTRACT

Agricultural production in the United States is undergoing marked changes due to rapid shifts in consumer demands, input costs, and concerns for food safety and environmental impact. Agricultural production systems are comprised of multidimensional components and drivers that interact in complex ways to influence production sustainability. In a mixed-methods approach, we combine qualitative and quantitative data to develop and simulate a system dynamics model that explores the systemic interaction of these drivers on the economic, environmental and social sustainability of agricultural production. We then use this model to evaluate the role of each driver in determining the differences in sustainability between three distinct production systems: crops only, livestock only, and an integrated crops and livestock system. The result from these modelling efforts found that the greatest potential for sustainability existed with the crops only production system. While this study presents a stand-alone contribution to sector knowledge and practice, it encourages future research in this sector that employs similar systems-based methods to enable more sustainable practices and policies within agricultural production.

1. Introduction

Agricultural production systems undergo rapid changes in response to shifts in production expenses, consumer demands, and increasing concerns for food safety, security, and environmental impact (Hanson et al., 2008; Hendrickson et al., 2008). An overriding concern is the need to develop sustainable production systems that address societal concerns for environmental impacts and nutritional value, while maintaining an economically feasible production system for farmers. Sustainable agricultural production per Sassenrath et al. (2009) is: “an approach to producing food and fibre which is profitable, uses on-farm resources efficiently to minimize adverse effects on environment and people, preserves the natural productivity and quality of the land and water, and sustains vibrant rural communities” (p.266). In aligning with this definition, the five general goals that must be addressed by sustainable production systems are therefore: supplying human needs, enhancing the environment and natural resource base, increasing efficiency of resource use, improving economic viability of farming, and enhancing quality of life for producers and society.

One way to accomplish these sustainability goals has been to employ integrated agricultural production techniques. Integrated agricultural production is a mixed enterprise approach to farming that uses natural resources through the combination of crop and livestock inputs and outputs to promote environmentally beneficial farming practices (Hendrickson et al., 2008; Boller et al., 2004). A major benefit of integrated agricultural production is its inherent ability to distribute, and thereby minimize, farmer risks through the diversification of enterprises, allowing farmers to exploit a higher

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spectrum of marketing channels (Hendrickson et al., 2008). Despite the fact that integrated production can greatly minimize overall risk, it presents a substantial challenge in administering the complex trade-offs of each individual farming component. Examples of these challenges include timing of operations, the type of equipment used and allocated, and the timing of agricultural markets, in concert with a range of other social, environmental, economic and technological considerations (Hendrickson et al., 2008; Archer et al., 2007, 2008; Halloran and Archer, 2008).

At the core, the challenges in both single and mixed-enterprise agricultural production exist in the task of operationalizing the interactions between disparate measures of productivity and sustainability, and necessarily require adequate understanding of the complex interactions between environmental, social, and economic drivers. For example, ecological systems contain a multitude of diverse components, interacting non-linearly and dynamically in both space and time (Wu and Marceau, 2002). As Wu and David (2002) mention, “An obvious challenge in modelling complex ecological systems is, then, to integrate the rigor of reductionism with the comprehensiveness of holism.” Similarly, social drivers are often tenuous, highly changeable, and difficult to quantify (Ramalingham et al., 2008). In addition, environmental drivers that impact farming management choices are not always straightforward, a fact that is exemplified by the substantial loss of Conservation Reserve Program (CRP) lands to greater economic return from corn production for biofuels (Hartman et al., 2011; Fargione et al., 2009).

Past research has approached these complex aspects of agricultural production through the use of modelling. Many models are available that track crop and animal production for decision support, such as GPFARM (Great Plains Framework for Agricultural Resource Management), among others (Rauff and Bello, 2015). These models include mechanistic and statistical approaches to model biophysical processes, and in some cases link these processes to economic or multi-objective optimization to guide management decisions. While these models typically simulate bio-physical processes in great detail, their usefulness is often hampered by the need for large amounts of input data and by requirements for extensive calibration and validation before each use. Also, while these models are often complex, limiting their usefullness, the methods simplify the systemic and dynamic interdependencies necessary for intrinsically complex agricultural systems planning (Ramalingham, 2014). While Tanure et al. (2014) proposed a mathematical model for use in decision support systems for farm management to be applied within dynamic systems models, their models have not yet been applied to real agricultural production systems.

Here we assert that methods within the realm of such fields as complexity science, i.e. “systems thinking”, could be better-fit to holistically understand agricultural system complexity, especially given the added task of considering social drivers and impacts. Complex systems are typically characterized by interconnected and interdependent elements and dynamic feedback processes (also know as “loops”). Through these processes, certain behaviours often emerge that are contrary to what was planned for or expected (Ramalingham et al., 2008; Sterman, 2000). Our approach to agricultural system complexity focuses precisely on these three concepts – namely, (i) the interconnection and interdependence of factors, (ii) dynamic feedback processes between these factors and (iii) the emergent behaviours that result – to study the systemic interaction of factors that influence sustainability. Here we direct our attention to complexities of agricultural production including societal, environmental, and economical aspects. Specifically, we are interested in understanding the structural form of “drivers”, which are key factors that systemically and dynamically interact to influence system sustainability. Of the many methodologies and tools that exist to tackle problems of this type, we elected to use system dynamics modelling because of its ability to explicitly address problems with systemic and dynamic drivers, allowing an improved understanding of emergent problems and behaviours (Churchman, 1968; Sterman, 2000).

Our objective with this study was to make a novel contribution to the sector by developing a preliminary system dynamics-based approach to understand sustainable agricultural production. In doing so, we hope to encourage a dynamic systems-based paradigm shift in agricultural systems analysis. The questions that guided these research efforts were:

1. What drivers influence agricultural production systems?
2. How do these drivers systemically and dynamically interact to influence sustainability?
3. Which type of production enterprise has the greatest chance for sustainability?

To answer these research questions and accomplish our study objective, we use the system dynamics modelling environment, STELLA (isee Systems, 2015) to capture and model the complexities between human (social), environmental, and economic interactions. Of the many software suites (e.g., VENSIM and POWERSIM) or programming languages (i.e., C++ and Java) available for building and simulating system dynamics models, we chose STELLA (isee Systems, Lebanon, NH) because of its low cost, intuitive and user-friendly (no programming is required) interface, and widely recognized modelling iconography. We demonstrate the utility of this approach through a sustainability assessment of three different agricultural production systems (single or mixed enterprise systems) using a qualitative and quantitative systems dynamics model that incorporates various aspects of crop and animal production to output indices of economic, social and environmental sustainability. We present a detailed overview on the data and modelling aspects of this study. We then proceed with an example analysis of model outputs and implications to present a methodology for future modellers to leverage this work and continue building informative models to better understand this complex and important topic of sustainable food production.

2. Data and modelling

This section presents the methodological steps to develop the system dynamics model of three distinct agricultural systems. We begin by providing a brief overview of the systems dynamic modelling approach, highlighting the key modelling aspects that guided our model building process. We then describe the types of data we used to construct a qualitative and quantitative system dynamics model, followed by a synopsis of the key aspects of model development and analysis.

2.1. *The system dynamics modelling approach*

System dynamics modelling presents a means to describe and simulate dynamically complex issues through the structural identification of feedback, and in many cases, delay processes that drive system behaviour (Sterman, 2000; Pruyt, 2013). Since the formation of the modelling concept by Jay Forrester in 1959, the method itself has been used for a broad spectrum of applications including the modelling of complex ecological and economic systems (Costanza and Gottlieb, 1998a; Costanza et al., 1998b; Costanza and Voinov, 2001), many of which address, to some extent, the social implications of system behaviour (Wu and Marceau, 2002; Bossel, 2007; Ford, 1999a). A system dynamics modelling approach was chosen for this research given its proven ability to go beyond