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Grass-Based Dairy in Vermont: Benefits, Barriers, and Effective Public Policies

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GRASS-BASED DAIRY IN VERMONT: BENEFITS, BARRIERS, AND EFFECTIVE PUBLIC POLICIES

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ABSTRACT

A comprehensive literature review was undertaken in order to define and assess the sustainability and resiliency characteristics associated with grass-based and confinement dairy farming. Primarily as a result of reduced input costs, grass-based dairy farming often enhances profitability over confinement systems, especially on small farms. Further, conversion of tilled soil to permanent pasture has been shown to significantly reduce harmful sediment and nutrient transport into waterways. Perennial forage also acts as a carbon sink, curtailing or even negating a grass-based farm's carbon footprint. Finally, social benefits derived from enhanced nutrition and higher quality of life are also associated with grass-based dairy farming. Given that policy goals of the State of Vermont include both bolstering farm viability and reducing farm-related runoff, two questions are then raised. What is the most effective way to incentivize the adoption of rotational grazing in Vermont? And what types of farms are best suited to its use?

A series of interviews with dairy experts and farmers was conducted as a preliminary investigation into these questions. This qualitative evidence suggested that farmers generally adopted grass-based dairying after observing a peer's success with the method, suggesting that a key leverage point may be peer-based learning.

A behavioral economics game was developed to evaluate the role of peer networks in facilitating decision-making under conditions of uncertainty. A computerized game platform simulated networks of small dairy farm enterprises, with participants acting as farm managers. Treatments varied the size of peer networks, as well as the inclusion of a perfectly-performing automated "seed player." Participants could base their decisions upon the successes of their peers. They received a cash incentive based on their farms' performance. Results indicated that players with higher numbers of peers made better economic decisions on average. The inclusion of a "seed player" within a network, which modeled the ideal behavior, also facilitated better decision-making. Both of these correlations were statistically significant. Furthermore, the shape of the "diffusion curve" of new adoptees confirmed literature on the dynamics of innovation diffusion. Public policy implications from this work include an increased focus on facilitating peer-to-peer learning among farmers where Best Management Practice adoption is a policy goal.

To further evaluate the potential for peer learning to facilitate positive change, the Dairy Farm Transitions Agent Based Model (DFTABM) was developed. The model was calibrated using existing datasets along with the qualitative and quantitative results described above. It forecasts effects on farm profitability, attrition, and soil loss arising from varying assumptions about peer network connectivity, peer emulation, macroeconomic trends, and agri-environmental policy. Nine experimental treatments were assessed. Overall, it was found that high rates of emulation coupled with high rates of connectivity—especially targeted connectivity among smaller farms—yielded the best balance of farm viability and reduction in soil loss. The establishment of a performance-based tax credit had no clear correlation with the resulting soil loss figures predicted by the model. Policy implications from this study include the finding that direct payment schemes for reduction in environmental harm may not always have their intended effects, whereas policies that enhance peer-to-peer learning opportunities, especially among the proprietors of smaller farms, may present an effective and relatively affordable means by which to bolster farm profitability while also reducing environmental degradation.

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CHAPTER 1: INTRODUCTION, PROJECT OVERVIEW, AND LITERATURE REVIEW

1.1. Introduction

1.1.1. Grass-Based Dairy Farming: A Primer

Over the past several decades, the economic squeeze of higher feed costs and lower milk prices has prompted dairy farmers to adapt and experiment with new ways to maintain profitability. Many farmers have followed the “get big or get out” path, buying extra land to produce more feed, increasing the size of their milking herds, implementing the latest science-based animal nutrition, and harnessing economies of scale to maintain profitability despite diminishing per-animal returns (USDA NASS, 1992b; 1997b; 1997c; 2002b; 2002c; 2007b; 2007c; 2012b; 2012c). Other farmers have focused on cost cutting rather than production volume maximization. One way this has been actualized is through a renaissance in pasture- or grass-based production methods. Managing cattle on perennial forages requires something of a paradigm shift in land use management and planning, but agricultural economists and early adopters have demonstrated that in many cases, well-managed grass-based systems are a viable alternative to confinement dairying.

A great deal of research has been conducted on the economic, ecological, and social benefits associated with grass-based agriculture. A common theme that emerges from the literature is that a specialized system of pasture management known as rotational grazing offers significant productivity advantages over continuous grazing, while also providing important ecosystem services (Murphy, 2002). Research shows that dairy farmers who use rotational grazing are more likely to maintain steady profitability—even at the smaller scale of many traditional family farms—and report higher average levels of success and satisfaction than do confinement farmers (Dartt et al, 1999; Winsten, Parsons, & Hanson, 2000; Kriegl, 2001; 2005; Conneman et al., 2006; Hanson et al., 2009; Benson, 2009; Colby, 2012; Karszes et al., 2012). Additionally, cultivating perennial forages in place of row crops has the potential to sharply cut or even reverse net greenhouse gas emissions, while also stabilizing soil and reducing the quantity of phosphorus, nitrogen, and sediment that runs off into waterways (Conant et al., 2001; Six et al., 2002; Guo and Gifford, 2002; Gilker, 2005; Rotz et al., 2009; 2010; Schwarte et al., 2011). Finally, hillsides dotted with grazing cows epitomize the look and feel of traditional working landscapes, and flourishing small family farms are a boon to rural community development (Donham et al, 2007; Lyson et al, 2001). As a result of logistical challenges, switching to rotational grazing will not be feasible for all dairy farmers, but where possible, it has been suggested that grass-based dairying—specifically the use of rotational grazing—should be considered an environmental Best Management Practice (BMP) for dairy production (Gilker, 2005). Details about the sustainability and resiliency characteristics of grass-based and confinement dairy production will be discussed at length in Section 1.3 below.

1.1.2. If It's So Great, Why Isn't Everyone Doing It?

Despite its potential advantages, as of 2006, only 13% of northeast U.S. dairy producers were using rotational grazing (Winsten et al., 2011). To understand why more dairy managers have not switched from confinement dairying to grass-based methods will require an inquiry into farmers' motivations and decision-making patterns. A number of studies have suggested perceived barriers which prevent farmers from adopting BMPs in general, and grass-based dairying in particular (Winsten et al., 2011b; Zia, 2014). In these studies, factors such as uncertainty and a perceived lack of control over outcomes emerge as the strongest barriers to adoption. If increased adoption of grass-based dairy farming is to be a policy goal, policy interventions will need to build on existing knowledge about perceived barriers, while also introducing systematic stakeholder input and rigorous analysis to determine which policy options may represent effective and efficient uses of public resources.

1.1.3. Why Study Dairy in Vermont?

The State of Vermont represents an excellent case study to assess both dairy industry production trends and agri-environmental public policy interventions. Dairy accounts for the large majority—about 70-80%—of Vermont's annual agricultural revenue, and despite its small size, the state's 135,000 milkers produce enough milk to position Vermont at 16th in the nation for overall dairy production. But despite ever-increasing milk production—both per cow and aggregated to the state level—many Vermont dairy farms teeter on the brink of economic failure. Whereas in 1965 there were over 6000 operating dairy farms in Vermont, the latest census figures indicate that as of 2012 only 934 farms were still selling milk, with the rate of attrition in the industry showing no signs of slowing (Parsons, 2010; USDA NASS, 2012d).

While farm profitability and viability are certainly worthy policy goals, it is important to realize that agriculture impinges upon more than just Vermont's bottom line;

in fact, agricultural production represents less than 2% of Vermont's total GDP (Altendorfer et al., 2010). It is the multifunctional nature of agriculture (Boody et al., 2005)—its impacts upon Vermont's working landscape, rural communities, and natural environment—that make farming in general, and dairy farming in particular, such a cornerstone issue in Vermont politics. The recent political wrangling over efforts by environmental regulators to clean up Lake Champlain—which have pinpointed dairy farming as a major nonpoint source of Phosphorus runoff—is a case in point (State of Vermont, 2014). Vermont policymakers must grapple not only with the economic aspects of dairy farming, but how it affects the State's commitment to healthy communities, environmental sustainability, and other key policy goals.

Structurally, Vermont's dairy industry is marked by somewhat smaller than average farms, averaging 125 cows, compared to the national average of 144 (USDA NASS, 2012f). This is important because, in general, it is smaller dairy farms that have been forced out of the industry in the face of mounting economic pressures (Parsons, 2010). As of 2010, about 11.5% of Vermont dairy farmers were using rotational grazing as a primary feed source (Winsten, Parsons, & Hanson, 2000). This is in line with a 2006 figure of 13% using rotational grazing in the northeast U.S. region (Winsten et al., 2011), but quite low when compared to a 1999 figure indicating that 21.8% of Wisconsin dairy farmers use the technique (Undersander et al., 2014).

Due to Vermont's twin agricultural policy goals of farm viability and agricultural runoff reduction, as well as the structural characteristics of its dairy industry, the State represents an excellent environment in which to pose questions concerning the future of the dairy industry. Specifically, this study aims to uncover the conditions under which farmers would—or would not—choose to adopt novel farm management practices like rotational grazing, and to use that information to pinpoint smart public policy solutions which address both farm viability and environmental sustainability.

1.1.4. Project Goals

The primary goals of this research project are:

1. *To demonstrate through a comprehensive literature review that grass-based dairying should be considered a Best Management Practice for many farmers*
2. *To determine the common factors underlying farmers' decisions to switch to grass-based dairy production, and the perceived barriers blocking its use*
3. *To identify public policy interventions which may effectively mitigate perceived barriers by examining farmers' motivations and decision-making strategies*
4. *To predict the effects of proposed policies upon dairy farm viability, state finances, and key metrics of ecological sustainability*

1.2. Project Overview

This project focuses on utilizing stakeholder input, experimental research, and computational analysis to determine which public policy options would most-effectively incentivize the use of grass-based dairy production. Qualitative data were collected in the form of stakeholder interviews with dairy farmers and other dairy industry experts. An original behavioral economics experiment was then undertaken to determine the dynamics by which novel techniques such as BMPs may diffuse through peer networks.

These qualitative and quantitative data were combined with existing statistical datasets using a Knowledge Management approach and used to calibrate an agent-based computer model. The model forecasts likely results—at the level of one key Vermont watershed—of user-input setup conditions pertaining to macroeconomic trends, farmer decision-making strategies, and public policies aimed at addressing agri-environmental goals. This section gives a brief overview of the methods employed in this study; a comprehensive methodological review will follow in Section 1.4.

1.2.1. Initial Expert Interviews

Semi-structured expert interviews were performed with agricultural economists and dairy industry leaders in order to identify (a) what typologies of Vermont farmers may benefit from switching to grass-based dairying, (b) barriers to switching to grass-based dairying faced by these farmers, (c) realistic policy incentives which may overcome these barriers, and (d) individual farmers who may be available for in-depth interviews. The initial expert input phase informed the creation of interview schedules to be used in the structured farmer stakeholder interviews to follow.

1.2.2. Structured Farmer Interviews

Eight structured interviews were conducted during the summer of 2014. These interviews were stratified across three farmer stakeholder groups: (a) farmers who are successfully using rotational grazing; (b) farmers who are successfully using modern confinement systems, and (c) farmers who at some point have transitioned between confinement and grass-based dairy management. Standardized interview schedules were created for each farmer typology. These schedules first posed a series of questions concerning characteristics identified in the expert input phase which may influence the choice to switch to rotational grazing, such as operator demographics, land attributes, management attributes, economic data, and success/satisfaction. Next, the interviews addressed perceived barriers to switching to rotational grazing, probable responses to specific incentive programs designed to overcome those barriers, and, for farmers who had personally made management transitions, factors underlying the choice to do so. Results of this qualitative analysis were used to generate the structure of the behavioral economics game, and used to inform the decision rules to be implemented in the agent-based model.

1.2.3. Behavioral Economics Experimentation

Results of qualitative interviews strongly suggested that learning from other farmers, specifically concerning their peers' management decisions and resultant levels of financial success, played a major role in farmers' decisions to switch production methods. In order to rigorously analyze this observation, a multi-round social contagion behavioral economics experiment was developed to ascertain whether the structure and density of peer networks affects the adoption rate of ecologically-beneficial Best Management Practices for farmers operating in a simulated agricultural commodity market.

Participants were randomly selected from a cohort of University of Vermont undergraduate volunteers, and were compensated based on the financial success of a simple simulated farm enterprise over ten farming seasons. During each season, players decided whether to adopt a new production method or maintain their current production method. In order to replicate an environment of uncertainty, the financial outcomes of these choices were not made directly available to participants, but they did have access to the management choices and financial outcomes of one or more peers also playing the game. Treatments varied primarily based on the peer network size, or degree, in order to ascertain whether larger networks facilitated learning faster or more robustly than smaller networks.

1.2.4. Agent-Based Computer Simulation

Because the prevalence of barriers and efficacy of public policies are likely to be linked to multiple factors—such as farm typology characteristics, land use patterns, geographic limitations of specific sites, peer connections between farmers, federal and state tax and subsidy policies, and macroeconomic price trends for agricultural products—optimizing overall state-level policy regarding dairy Best Management Practices represents a complex, nonlinear problem: there are too many “cogs in the wheel,” and their actions too closely intertwined, to be able to confidently predict cause-and effect without the aid of advanced techniques. In order to assess the probable results of proposed public policies upon complex systems, computational modeling can be a valuable tool. Agent-based, Coupled Human and Natural Systems (CHANS) models such as the one developed for this project can distill complex interactions between human rationality, macroeconomic trends, and environmental conditions into simplified projections which are relevant to policymakers and analysts.

The Dairy Farm Transitions Agent Based Model’s agents are initialized using a series of functions to assign real-world farm characteristics based on statistical distributions of farm typologies identified by USDA Census of Agriculture data. The agents are then located within a Global Information System (GIS) environment based on current land use data from the Vermont Center for Geographic Information. Partly to save on computational requirements, the model's environment is limited to Franklin County, Vermont. This region was chosen because a key policy goal addressed by this project is phosphorus loading of the Missisquoi River watershed, a major tributary of Lake Champlain which is located primarily within Franklin County. Ecological and economic effects of changing agricultural land use, including the use of grass-based production and organic certification, were calibrated using data from peer-reviewed academic studies and government reports. Calibration of the model's economic forecasting engine was performed by correlating model outcomes with trendlines apparent in real-world data. County-level predictions are generated which indicate the effect of changes in land use and farm management on farm viability and resiliency, milk production, and levels of agricultural runoff. The model amalgamates current land use data, farmland geographic factors, and probable farmer responses to policy incentives, specifically those aimed at increasing the use of grass-based dairy production by strengthening opportunities for peer-to-peer learning.

A setup screen allows the user to select the policies she wishes to implement, as well as adjusting baseline assumptions such as feed and milk price trends, and agent decision-making behavior. The model runs for several years, during which the farm agents within the model react to economic conditions and policy incentives, making farm management decisions based on heuristics codified from identified motivational attitudes of actual farmers and participants in the behavioral economics simulations. Land-use changes of individual farm agents, along with county-level economic and ecological effects, are displayed in real time as the model runs. This model allows policymakers a glimpse into the future in order to more accurately and wisely choose policy paths which best utilize limited resources to accomplish agri-environmental policy aims.

1.3. Literature Review

1.3.1. Literature Review Overview

The purposes of this literature review are as follows:

1. *To briefly address the history and current patterns of dairy farming in Vermont*
2. *To outline the basic distinctions between confinement and grass-based dairy production, specifically focusing on the rotational grazing technique*
3. *To examine academic research on the benefits and drawbacks of each system regarding key indicators of sustainability*
4. *To review current and proposed agri-environmental legislation in Vermont*
5. *To examine literature which addresses perceived and actual barriers to the adoption of BMPs in general, and grass-based dairying in particular*
6. *To lay the methodological foundation under the research methods here proposed:*
    a. *Qualitative interviews with expert informants and stakeholders*
    b. *Behavioral economics of decision making under conditions of uncertainty*
    c. *Knowledge Management*
    d. *Agent-based computer modeling*

1.3.2. Dairy Production in Vermont: History and Current Production Trends

Vermont has a rich agricultural history which has largely centered on the production of animal-derived products. In the early 1800s, the forests were cleared for lumber, and Vermont became home to thousands of sheep which grazed its hillsides. Dairy production took over starting around the 1850s and has continued as the state's primary agricultural export to this day. Vermont was the dominant producer of milk, butter, and cheese for east coast population centers throughout the late 19th and early 20th centuries, but economic pressures beginning in the 1950s began to take their toll on Vermont's small dairy operations, the majority of which have since folded (Parsons, 2010; Vermont Agency of Agriculture, 2014). The squeeze of volatile milk prices, coupled with higher feed costs, has continued and even intensified in the 21st century. Net earnings per hundredweight (CWT) of milk have fluctuated significantly in recent decades, punctuated by periodic years in which net losses are reported across dairy producers (VSJF, 2013: Figure 3.3.1). Factoring in the value of unpaid operator labor, dairy profitability dropped every year between 1988 and 2004 (USDA, 2007). Smaller-scale, traditional Vermont dairy farms are the most likely to fall prey to this cost-price squeeze because many have not captured operational efficiencies associated with recent developments in dairy management.

To remain profitable, farms must either increase in size, drawing their profits from economies of scale and overall production volume, cut costs, find ways to sell their milk for a higher price, or a combination of these approaches. The sections below discuss two primary ways dairy farmers have adapted to maintain solvency in the face of economic pressures: large modern confinement systems and grass-based rotational-grazing systems. Both system typologies offer dairy farmers the opportunity to maintain profitability in the face of significant economic challenges.

1.3.3. Definitions of Dairy Production Methods As Used in This Project

Confinement Dairying

Confinement dairying has been the dominant method of dairy farming since about the middle of the 20th century. Nutrition on confinement farms is managed through the formulation of a Total Mixed Ration (TMR), which generally includes corn silage and haylage (both often produced on site), along with purchased protein supplements, vitamins, and minerals. Cows are housed in either a stall barn (stanchion or comfort stall), or increasingly a free stall setup, and milked either two or three times per day. Cows on many confinement farms rarely if ever leave the barn: the TMR is delivered to a feed bed, and waste is removed mechanically and stored for later use as fertilizer. While most Vermont farms are much smaller, confinement farms can have milking herds of well over 1000 cows. Advances in nutrition, better environmental conditions in barns, and more frequent milking have increased yields on well managed confinement dairies. Milk production per cow in a confinement system can be as high as 25,000 pounds per year (Karszes et al., 2012).

Grass-Based Dairying

Grass-based dairy production relies on pasture forage for the majority of cows' nutrition. Because overall caloric intake is lower and energy expenditure higher, cows raised on pasture are generally milked only twice per day and produce up to 30% lower milk yields than cows in a confinement operation (Kolver & Muller, 1998). It is important to note that, due to Vermont's winter season, year-round grass-based production is not feasible. Vermont graziers' average grazing season in 2010 began May 5th and ended November 13th (Colby, 2012).[1] During the remainder of the year, cows are fed hay, haylage, and silage produced on site; and/or purchased feed grain. A minority of farmers dry their cows off in the winter and synchronize calving to resume milking in the spring season in an effort to save on winter feed.

An Introduction to Rotational Grazing

Rotational grazing, variously called Management-Intensive Grazing (MIG), Management-Intensive Rotational Grazing (MIRG), rational grazing, or short-term grazing, is a method of grass-based livestock management which regulates the movement of animals through a series of paddocks rather than turning them out on a single continuous pasture. A French agronomist named Andre Voisin developed the principle of rotational grazing, which he called "rational grazing," in the late 1950s (Voisin, 1959). Due to the herd's frequent rotation from paddock to paddock, cows are afforded a steady supply of grasses which are at their optimum growth point for bovine nutrition, rather than becoming overgrazed in some spots and overgrown in others. Rotational grazing also facilitates an even distribution of manure on the field and prevents soil compaction from cows congregating in certain favorite areas (Murphy, 2002). For these reasons, rotational grazing offers livestock managers significant advantages over continuous pasturing.

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[1] This figure is for all pasture-raised animals in Vermont. The grazing season for dairy cows may be somewhat shorter, depending on weather and pasture management techniques.

Efficiently managing a grass-based system requires an intimate knowledge of grass species, regrowth timing, and nutritional content of pasture forage at different points in the growth cycle. Grasses must be grazed at the vegetative stage before they go to seed for optimum nutritional value. To ensure even grazing, cows must be moved at a minimum every three days, although the best managers may move their cows daily or even multiple times per day (Colby, 2012). Plants re-bitten after three days may have already started to regrow and will therefore suffer longer-term damage, resulting in less overall forage production. Despite its somewhat technical nature, rotational grazing has the potential to produce much more forage from a given area of land than continuous grazing, and therefore represents a smart management choice where pasture forage is to be used as a primary feed source (Murphy, 2002).

Grass-Based Dairying in Vermont

Much of Vermont's land was once cleared to accommodate grazing animals, but around the mid-20th century, grazing gradually fell out of favor as confinement dairying became the norm. In recent years, grass-based agriculture has enjoyed a resurgence as farmers have searched for ways to cut costs associated with corn silage production and feed grain purchases. The acreage of permanent pastureland in Vermont shows a corresponding jump from 6.6% of total agricultural land in 1997 to 11.2% as of 2012 (USDA NASS, 1997d; 2012e). While only 11.5% of Vermont's dairy farms use rotational grazing as a primary feed source, continuous pasturing is common on Vermont's traditional dairies, with more than 47% of farmers employing grazing to some extent, often for dry cows, heifers, and feeder calves (Winsten, Parsons, & Hanson, 2000;

Parsons, 2003). In his 1831 book, *A History of the State of Vermont*, Nathan Hoskins observed of the state, “The soil is such and the seasons are so uncertain for the perfection of crops of grain, that grazing is the most sure and profitable branch of agriculture which the farmer of Vermont can carry on with success” (Hoskins, 1831). Despite advances in agricultural technology, we shall see that Hoskins’ statement still largely rings true to this day.

1.3.4. Sustainability and Resilience of Dairy Production Systems: The “Three Legged Stool” Model

There exist a number of disparate bodies of literature related to the ecological, economic, and social benefits of managed grasslands in general and grass-based dairy in particular. These three elements make up the “three legged stool” model of sustainability. This project takes a transdisciplinary stance, weaving together established research in farm management, agricultural economics, plant and soil sciences, natural resource ecology, rural sociology, and nutrition and food science to address systems-level impacts of the two dairy production paradigms laid out above on key indicators of sustainability and resiliency.

Economic Sustainability

For a farm to be economically sustainable, it must at the very least be solvent, and ideally be profitable enough to comfortably support its proprietors. Agricultural economists have undertaken a number of case studies and experiments looking into the profitability of grass-based vs. confinement dairy production. A retrospective cohort study by Dartt et al. (1999) indicated that Michigan dairies using rotational grazing captured more profit on average than conventionally-managed dairy farms. Data from Cornell University's Dairy Farm Business Summary and Analysis Project indicated that grazing farms in New York averaged a net income of $467 per cow annually, whereas confinement farms averaged $365. The additional profits were driven by lower operating costs, fewer feed purchases, decreased machinery costs, lower veterinary bills, and other factors (Benson, 2009). An economic analysis of over 100 rotational grazing farms in the great lakes region concluded that graziers had higher Net Farm Income from Operations (NFIFO) both per cow and per CWT than did their confinement counterparts. Interestingly, graziers with fewer than 100 cows had the highest level of NFIFO per cow (Kriegl, 2005).

Hanson et al. (2013) analyzed the tax returns of 62 dairy farmers milking 200 or fewer cows from the mid-Atlantic region of the U.S. over a 15 year period. Their research revealed that operators using rotational grazing were more profitable than their counterparts using confinement methods based on a number of indicators of profitability. The profits of grazing operations were also less volatile, meaning that these farms faced less risk and operated with more certainty in the marketplace. In light of grass-based operations' established environmental benefits, especially concerning erosion and nutrient runoff, the authors concluded that greater environmental regulations upon dairy farms may further increase the attractiveness of grass-based dairying in the future.

Gillespie et al. (2009) assessed 1815 responses from 24 states to the 2005 Agricultural Resource Management Survey (ARMS) administered by the National Agricultural Statistics Service (NASS) of the United Sates Department of Agriculture

Economic Research Service (USDA ERS). Data from this survey were weighted so that results could be accurately extended to the overall national commercial dairy sector. Researchers used regression analysis to correlate farm characteristics with measures of both dairy enterprise and whole-farm profitability. They found that conventional and semi-pasture based farms were larger and produced more milk per cow, but also had higher debt to asset ratios than fully pasture-based operations. While conventional farms had higher dairy enterprise returns, fully pasture-based operations proved the most profitable on a whole-farm basis, which includes factors such as opportunity costs for unpaid labor and land, revealing that pasture-based farmers may have more free time and resources to devote to other profitable activities.

Based on 1999 survey data of 124 Connecticut dairy farms sampled across all sizes and production methods, Foltz and Lang (2005) used economic modeling to determine how a farmer’s decision to adopt rotational grazing would affect measures of cost, production, and profit. Overall, adoption of rotational grazing did not statistically correlate with changes in milk production per cow, cost of production, or profit. The results did show, however, that full adoption of rotational grazing resulted in greater profitability than partial adoption.

It is important to note that there is great variability in the data on dairy farm profitability. While grazing farms may have demonstrable economic advantages in some contexts, many variables affect profitability, and well-managed systems of both types can be profitable (Kriegl, 2001). It is also important to recognize that transitioning from one production system to another will likely give rise to significant transitional costs as the systems require somewhat different equipment, knowledge, and possibly livestock breeds. At the end of the day, the literature clearly demonstrates that grass-based dairy farms are an economically-viable alternative to modern confinement operations for many farmers, and especially so for farmers whose operations are too small to compete on size alone.

At its core, profitability in dairy production is a direct function of input costs, milk price, and milk production. The following sections will therefore examine each factor in turn to see how grass-based and confinement-based production systems stack up. The final section will look at how these factors influence the risk and resiliency associated with each system.

Input Cost

One of the main economic advantages to rotational grazing systems over both traditional dairies and large modern confinement operations is cost savings. A 2005 comparison of rotational grazing vs. non-grazing farms in New York revealed per-cow cost savings on labor, purchased feed, medicine, and machinery; as well as reduced crop production expenses per hundredweight (Conneman et al., 2006).

i. Labor:

Savings in hired labor costs on rotational grazing farms were driven by farm scale, less labor-intensive feed production, and less frequent milking. Labor is generally a larger component of total expenses on larger farms because primary operator and family labor must be supplemented with hired labor. Large confinement operations had the highest labor costs of any dairy production system, estimated at about $2.82 per hundredweight in 2012 (Karszes et al., 2012).

ii. Feed:

Feed represents the largest cost on most dairy farms. Research shows that feed costs are lowest on rotational grazing farms, but the data reveal important differences between specific grazing practices. When comparing farms which report any form of pasture use to those that do not, a significant difference in feed costs is not reported (Kriegl, 2005). However, reduced feed production and purchase costs are observed on farms which use rotational grazing techniques. An analysis of farm enterprise budgets concluded that rotational grazing systems experienced the lowest direct costs per unit of equivalent nutritional value when compared with hay or corn-silage cropping programs (Hanson, 1995). In the northeast, feed savings on grass-based farms were driven largely by reduced production of corn: 12 of 41 grazing farms polled by the 2006 Cornell Dairy Business Summary did not grow a corn silage crop at all, whereas the average forage production across grazing farms was about one quarter corn and three quarters hay. Large confinement farms, on the other hand, grew about equal ratios of corn and hay (Conneman et al., 2005). In Vermont, farms employing grazing of any type grew an average of 0.97 acres of corn per cow, whereas confinement-based operations averaged 1.22 acres per cow (Parsons et al, 2004).

It is important to consider the within-group differences between the rotational grazing farms and the other farms represented in these data which use grazing only in certain circumstances. While farms that graze only their dry cows and heifers, for example, probably spend about the same percent of their budget on feed production as large confinement farms, the 25% of grazing farms in the 2005 Conneman et al. study which grew no corn at all likely had significantly reduced feed production costs. This helps explain why rotational grazing farms have been shown to achieve high profitability, while traditional small farms which use grazing to some extent but do not manage their pastures for optimum forage yield do not (Foltz and Gillis, 2005). Farms that use grazing, but do not manage their pastures using rotational grazing, will probably still be reliant on significant amounts of corn silage or purchased grain feed.

An additional consideration is the high variability in feed grain prices over the last decade (Thraen and McNew, 2007). Since 2006, incentive programs for corn ethanol production at the national level have both raised the price of corn and increased price volatility, with prices ranging from a low of $2.20 per bushel in 2006 to a high of $5.17 in 2008 (Parsons, 2010). As discussed in the resiliency section below, this feed cost variability may have negative impacts on long-term farm viability.

iii. Fuel:

While fuel does not represent a primary cost of dairy farming as do feed and labor, a large differential has been reported between the fuel use of typical grass-based farms and typical confinement-based farms. This savings is driven mainly by the equipment-intensive nature of corn silage production. The University of Wisconsin's Center for Dairy Profitability estimates fuel costs of $29.01 per acre to raise corn silage, versus only $4.81 per acre to manage a perennial pasture, including one cut of hay (Center for Dairy Profitability, 2008). In Vermont, it is very likely that more than one cut of hay would be required on most grass-based dairies, which would increase the actual cost per acre to some extent. Nevertheless, it is probable that there is generally at least some degree of fuel savings associated with grass-based dairying.

Milk Price

i. Historical Milk Price Trends

In 2011, organic milk sold at the farm gate for an average price of $30.64 per CWT, while the price for conventional milk averaged $20.93 per CWT (Maltby, 2013). While the price of conventional and organic milk both show upward trends over the past half century, the most significant trend in milk prices is the increasing intensity of cyclic price fluctuations over the last 20 years (Gould, 2015b). In the case of conventional milk, in particular, these price cycles, peaking roughly every three years, have become quite drastic: as of 2013, the coefficient of variation for the 5-year moving average of U.S. conventional farm gate milk prices was nearly 18%, whereas organic milk varied by only about 6% over the same time period (Su & Cook, 2015). A similar analysis reveals that, between 2004 and 2012, annual price change for conventional milk ranged from -23% to 52%, whereas organic milk prices changed only -4% to 10% per year (Su, 2013). For farmers operating on tight margins, these fluctuations can create a “cost price squeeze” which may significantly impact farm viability.

ii. Product Differentiation and Value-Added Products

Organic dairy certification now requires that cows receive at least 30% of their nutrition from pasture during a minimum 120-day grazing season (USDA Organic, 2011). Coupling grass-based production with organic certification may represent a way to earn higher returns per unit of milk without purchasing a great deal of expensive organic feed. Many Vermont farms have taken advantage of the added value associated with certifying organic, with the number of certified organic dairy farms in Vermont increasing from only two in the early 1990s to more than 200 in 2010 (Parsons, 2010). Higher returns from organic milk sales are probably a significant factor in the high average profitability of grass-based farms.

A potential for increased profitability may also exist for dairy products differentiated as “Grass-Fed”. This type of product differentiation has been important for producers of beef and other meat products, for example through the third party American Grassfed Association’s “American Grassfed” designation (Steiner & Franzluebbers, 2009). While not yet widespread, a similar potential for added value may eventually exist for grass-fed dairy products as well.

Milk Production

Whereas grass-based production has demonstrable advantages regarding input costs, these savings come at the expense of lower milk production per cow. In a controlled experiment, Kolver and Muller (1998) compared the dry matter intake and milk production of similar Holsteins fed either high-quality pasture forage or Total Mixed Rations. They found that the pasture feed provided 19% less dry matter, organic matter, and net energy for lactation. Milk production per cow was also reduced from an average of 44.1 kg per day to 29.6 kg per day.

Several other factors should also be considered when considering milk production on grass-based dairies. For example, sometimes a small amount of concentrate is fed in addition to the pasture forage to increase dry matter intake. Supplementing cows on pasture with a ration of concentrate has been found to increase milk production by about 1 kg milk per kg of concentrate (Bargo et al., 2003). Milk production results are also complicated by specifics of breeding. For example, Grainger et al. (2009) found that Holstein cows with a higher proportion of northern hemisphere genes produced more milk on pasture-based diets than did their counterparts with fewer northern hemisphere genes.

Overall, while it is clear that in most cases milk production is lower on grass-based systems, the economic data reveal that this reduction is often more than compensated by the corresponding reduction in input costs, and therefore farm-level profitability is not generally diminished (see Economic Sustainability section above). However, the reduction in milk production is important because, as discussed in Section 1.3.6 below, it may serve as a significant perceived barrier among farmers considering switching to grass-based production.

Resiliency and Risk Management

We have seen that rotational grazing offers lower production costs and capital investments than confinement-based production. Fewer capital investments mean these farms may be more adaptable to changes in environment or market forces, and less risky overall. Cannella (2009) used Monte Carlo simulations to model economic risks associated with three dairy production systems, finding that, while they have a strong profitability potential, large confinement operations present more financial uncertainty than do traditional or rotational grazing farms.

Profits on large confinement farms are highly susceptible to changes in both input costs and farm gate milk prices, both of which have proven very volatile in recent years (Thraen & McNew, 2007; Su & Cook 2015; Su, 2013). Feed grain represents the largest portion of dairy farm budgets, with confinement farms purchasing the most feed grain per cow, and grass-based farms purchasing the least (Hanson, 1995). This suggests that grass-based farms may be more resilient in the face of volatile global grain market conditions, which show no signs of stabilizing. Similarly, the farm gate price of conventional milk has been quite volatile since about 1990, and it seems to be getting more so (Su & Cook, 2015; Su, 2013). Grass-based dairy farmers selling on the organic market may experience less market fluctuation, leading to steadier profitability and bolstering economic resiliency. Overall, because they are likely somewhat more shielded from macroeconomic fluctuations, grass-based dairy farms—particularly those that are certified organic—will likely exhibit a higher degree of resiliency than large confinement operations.

Ecological Sustainability

Because they are not perpetually disrupted by agricultural machinery or heavily sprayed with agrochemicals and fertilizers, grassland forages, or pastures, have a number of ecological advantages over tilled cropland. Here we will focus on two: (a) the capacity of grassland forages to maintain high levels of soil organic matter (SOM), thus sequestering carbon into the soil; and (b) the potential of grassland forages to ease erosion and nutrient runoff, lessening agricultural non-point source pollution of waterways.

Greenhouse Gases and Climate Change

The buildup of atmospheric carbon and other greenhouse gases, leading to global climate change, is a huge concern for researchers and policymakers alike. To understand the role of plants and soil in the carbon cycle will require a brief discussion of carbon dynamics. Photosynthesis converts CO_2 and H_2O into glucose ($C_6H_{12}O_6$), plants' structural building block, and oxygen. Plants generally grow both above and below the ground in approximately equal proportions, in the process removing carbon from the atmosphere. While most of the carbon in the above-ground portion of the plant eventually oxidizes back into the atmosphere through decomposition, much of the carbon in the roots and the microorganisms that feed on them becomes sequestered underground. When soil is tilled, carbon trapped underground is exposed to the air and oxidizes, returning to the atmosphere. Soil can therefore act as either a carbon source or a carbon sink, depending on land use. The carbon sequestration rate and carbon-carrying capacity can be increased by additional soil organic matter, soil biodiversity, and superior soil structure (Guo and Gifford, 2002).

Various theoretical models have been put forth to explain and predict soil carbon dynamics, generally positing a number of "pools" of soil carbon, some of which are more labile (that is, readily oxidized and returned to the atmosphere), whereas some are more recalcitrant, staying in the ground for years due to chemical or physical properties of the soil. Whereas disruption of soil aggregates under mechanical tillage, for example, increases the labile pool of soil carbon, grasslands are particularly adept at increasing the recalcitrant pools, potentially trapping carbon in the soil for generations (Six et al., 2002).

Guo and Gifford (2002) conducted a meta-analysis of 537 observations from 74 publications addressing land use change in relation to soil carbon stocks. Across studies, soil carbon decreased by an average of 59% when pasture was converted to cropland. Conversely, conversion from cropland to pasture increased soil carbon levels by 19%. Newly-formed perennial pastures have been found to continue to sequester carbon each year until they reach an equilibrium after 20–40 years, depending on soil type (Hutchison et al., 2007). Similar findings have been corroborated by other studies. Richard Conant's 2001 review compiled data from 115 journal articles investigating the impact of land use on soil carbon, concluding that converting from other land uses to managed grassland significantly increases both soil carbon content and long-term storage (Conant et al., 2001).

Bearing in mind that any increase in soil carbon corresponds with an equal decrease in atmospheric carbon, this body of research suggests that increasing pasture acreage may significantly mitigate the effect of greenhouse gases on global climate change. A 2010 study demonstrated a greenhouse gas offset of 10–22% where confinement dairy systems were converted to pasture-based systems (Rotz et al., 2010). Overall, the review above clearly demonstrates the advantages of incentivizing grass-based dairy for any policymaker interested in increasing air quality and decreasing Vermont's greenhouse gas footprint.

Hydrodynamics and Agricultural Runoff

Compared to cropland soil, pasture soil is more porous and has better structure because it is not repeatedly compacted by agricultural machinery, and because it is bound together by a network of roots. These factors lead to superior water infiltration, meaning heavy rains are less likely to pool up and run into nearby waterways, carrying away fertilizers, nutrients, chemicals, and sediment. Soil's water infiltration rate is also a major factor in floodwater mitigation.

Gilker (2005) collected groundwater and surface-water samples on mid-Atlantic rotational grazing dairy farms for a period of three years. No detectable levels of nitrogen or phosphorus were detected in streams adjacent to pastures, except in one instance when a farmer had allowed cattle to remain by the stream bank for a long period of time over the winter. It is often assumed that urine from grazing cattle leaches nitrates into groundwater, however this conclusion was not borne out in the groundwater sampling. The study concludes that rotational grazing should be considered an "environmental Best Management Practice" for dairy farms (Gilker, 2005).

Bishop et al. (2005) used a paired watershed study on a farm located in the Cannonsville Reservoir watershed in upstate New York to evaluate the effects of implementation of key BMPs on phosphorus runoff. The BMP treatment specifically focused on manure management and conversion to rotational grazing. An automated stream monitoring station recorded water quality for two years pre-treatment, and for four years after implementation of the BMPs. Following implementation of the BMPs, load reductions of 43% for dissolved phosphorus and 29% for particulate phosphorus were recorded.

It has also been found that the use of rotational grazing in particular is preferential when compared with other forms of grass-based production. In a two-year field trial, Schwarte et al. found that rotational grazing of livestock reduced sediment and phosphorus loading compared with continuous stocking (Schwarte et al., 2011).

Grass-based dairying is not completely without environmental consequence, however. Research shows that grazing animals should not be given free access to stream banks, because they will congregate, causing water quality problems (Bilotta et al., 2007). For this reason, fencing animals off from waterways is critical to achieving the water quality advantages associated with grass-based agriculture. Additional research may also be required to determine the differential dynamics of dissolved versus particulate phosphorus under pasture versus annual crop land use.

There is a large body of scientific research examining the biological mechanisms underlying the superior hydrological properties of grazed grasslands. Studies in Serengeti National Park have found that the presence of grazing animals modulates excess soil phosphorus and accelerates plants' uptake of nitrogen and phosphorus, both increasing animal nutrition and limiting phosphorus runoff (Anderson et al., 2007; Anderson, Ritchie, & McNaughton, 2007). The presence of earthworms has been suggested to improve soil's water infiltration by physically aerating and loosening the soil. Earthworms also allow legumes to fix more nutrients so that plant roots can grow deeper, facilitating better soil structure and less runoff (Amador & Gorres, 2007). Pasture soils generally contain three to four times as many earthworms as tilled soils, measured at 1.2 million/acre for pastures vs. 400,000/acre in tilled soils (Schmidt et al., 2001). This may be one reason for their superior performance with regard to runoff and water infiltration.

Various computer modeling approaches have also shown lower phosphorus loading and erosion to correlate with the use of grass-based dairying. Rotz et al. (2009) simulated four management scenarios on a typical 250 acre Pennsylvania dairy farm. The researchers used an established farm system computer simulation called the Integrated Farm System Model to generate their predictions. In general, the team found that converting cropland to perennial grassland significantly reduced phosphorus runoff and soil erosion. In the rotational grazing scenario in which all cropland was converted to pasture, erosion was reduced by 87%, sediment-bound P losses reduced by 80%, and soluble P runoff reduced by 23%. Belflower et al. also used the Integrated Farm System Model to analyze differentials in runoff and soil loss between two dairy farms in the southeast USA, one confinement and one pasture-based. A primary finding from that study was that erosion and phosphorus runoff from the confinement farm were much greater due to the large area of land tilled to produce annual crops for feed (Belflower et al., 2012). A 2000 study simulated a representative 200-acre Pennsylvania dairy farm over a 25 year period and found that use of rotational grazing was predicted to achieve long-term phosphorus balance (Winsten et al, 2000). Winsten and Stokes used stochastic dynamic programming to model a hypothetical dairy farm. Financial disincentives for excess phosphorus accumulation were predicted to cause farmers to switch to rotational grazing, reducing soil test phosphorus to acceptable levels within 5 years (Winsten and Stokes, 2004).

Finally, a number of government-sponsored studies confirm that grass-based land use offers large reductions in soil loss compared with continuous row-cropping. Ontario, Canada's Ministry of Agriculture and Food used the Universal Soil Loss Equation to generate its agricultural land use recommendations. Their study concluded that land in permanent pasture offers soil loss reductions of 93% when compared with land in continuous corn or bean production (Stone, 1996; see Table 1 below).

Table 1: Reduction in Soil Loss Compared to Continuous Corn or Beans (Stone, 1996)

Land Use	Percent Reduction
Mixed grain or winter wheat	40
Rotation of 1 yr. corn, 1 yr. grain, 2 yrs. hay pasture or 3 yrs. corn, 3 yrs. hay pasture	60
Rotation of 2 yrs. corn, 4 yrs. hay pasture	70
Hay pasture	87
Permanent pasture	93

These findings are roughly echoed in a publication issued by the Vermont Department of Environmental Conservation, Water Quality Division, which indicates soil losses from land in active pasture at 2-4 tons per acre per year, and losses from land in row crops at 8-15 tons per acre per year (Vermont Department of Environmental Conservation, 2006).

Currently, Vermont is facing a limit on phosphorus loading of waterways to be imposed by the EPA in the near future. Mitigating runoff of agricultural nutrients is therefore a major policy goal. Additionally, in the wake of a series of devastating floods, policymakers are focused on ways to mitigate the risk of large-scale flooding events (State of Vermont, 2014). This literature review has demonstrated that perennial forages have superior water infiltration and reduced nutrient runoff compared with tilled land. Incentivizing the increased use of grass-based dairying in Vermont may represent an efficient way to address both of those policy aims while maintaining profitability in the agricultural sector.

Social Sustainability

In addition to the economic and ecological factors discussed above, grass-based dairy production has been shown to offer social and health advantages when compared to other dairy production systems. These benefits fall into three categories: (a) rural community development; (b) farmer satisfaction; and (c) human health benefits.

Effects on Rural Communities

As we have seen, grass-based farms are able to succeed economically without significantly scaling up, whereas moving to a large modern confinement model entails increased scale and farm consolidation. Fewer, larger farms means fewer farm operators, which can dismantle rural communities. Research has shown that larger numbers of smaller farms is correlated with a higher quality of life, more equitable economic distribution, and lower crime rates (Donham et al, 2007; Lyson et al, 2001). Moving increasingly to grass-based dairy production would therefore likely help to keep Vermont's traditional small towns and rural economies vibrant.

Effects on Farmers: Success and Satisfaction

Research shows that grass-based farming may be associated with a higher quality of life and greater farmer satisfaction than competing dairy production typologies. Cornell University's Dairy Farm Business Summary regularly polls northeast dairy farmers on economic and social issues. In a recent survey, over 80% of respondents answered the following question positively: "Has the adoption of grazing impacted your family's quality of life?" Reasons given included reduced chore time, healthier cows, positive comments from neighbors and tourists, and more opportunity to involve their children (Benson, 2009). A survey issued to dairy farmers in Vermont, Virginia, and Pennsylvania indicated that farmers using rotational grazing were significantly more satisfied with their operations than other groups, especially in the areas of feed costs, machinery repair expenses, levels of anxiety and stress, and financial progress (Winsten, Parsons, & Hanson, 2000). A 2010 study posed 7-point Likert-scale questions asking farmers to subjectively rate their feelings of success and satisfaction. Results indicate that 71.2% of Vermont's pasture-based farmers feel somewhat to highly successful, and 93.3% are somewhat to extremely satisfied (Colby, 2012).

Effects on Human Health and Nutrition

Nutritionists have shown that milk from cows raised on pasture has tangible health benefits over milk produced in confinement systems. For example, key vitamins and antioxidants are less concentrated in milk from grain-fed cows when compared with milk from grass-fed cows (Jensen et al, 1999). Milk from pastured animals has also been found to have a healthier ratio of essential fatty acids than that from non-grass-fed animals (Dhiman et al, 1999). In light of these findings, increasing the availability and consumption of grass-fed milk and dairy products will likely have positive impacts upon human health and wellbeing.

1.3.5. Water-Quality Related Agri-Environmental Policy

Current Policy in Vermont

In order to understand how incentive-based regulation may be used to curtail environmentally harmful practices in the agricultural sector, it is first necessary to be familiar with the array of existing and currently proposed policies in this area. The first phase of the Vermont/Lake Champlain Phosphorus TMDL Implementation Plan has been submitted to the EPA for approval (State of Vermont, 2014), preceding the phase II development of watershed-specific policies. The report concludes that agriculture contributes up to forty percent of the phosphorus load into Lake Champlain (State of Vermont, 2014). As per the Governor's summary of the implementation plan provided to the EPA (Shumlin, 2014), the State will:

1. Increase inspections and compliance efforts for all farms with a focus on small farms which have been largely unregulated in the past;
2. Implement a requirement that will strengthen livestock exclusion from perennial waters through regulation and incentives;
3. Update current agricultural regulations to increase management of buffers, gullies and ditches;
4. Update requirements for and increase investment in nutrient management planning.

To summarize, the State intends to achieve its phosphorus load reduction goals primarily through increased inspections, licensing, and more stringent management standards.

Vermont’s annual investment in incentive-based nutrient management planning is significant. Between the beginning of fiscal year 2005 and the end of fiscal year 2013, the total investment made in agri-environmental projects was $29,026,594 (State of Vermont, 2014, pp. 21–22). The largest percentage (50.5%) of this total was dedicated to cost-sharing program incentives for the implementation of Best Management Practices (BMPs). The Vermont Department of Environmental Conservation (VDEC) Watershed Management Division (WSMD) Ecosystem Restoration Program (ERP) also managed numerous outreach and implementation programs that were funded through Clean Water Act Section 319 grants. Nevertheless, the revised TMDL models developed by the EPA indicate that Vermont still needs to reduce its phosphorus load to Lake Champlain by 39%, with a 5% margin of safety (State of Vermont, 2014, p. 29). For the agricultural sector, the overwhelming majority of phosphorus reduction is proposed to take place through the regulation of nonpoint source pollution, such as through the Best Management Practices Program (State of Vermont, 2014, p. 45). While grass-based dairying is not currently listed as a Best Management Practice under this program, it does have similar potential to mitigate agricultural runoff, and has been considered a BMP by various scholars (see e.g. Gilker, 2005).

Factors Affecting BMP Adoption Rates

In order to analyze the efficacy of potential new policies, it is necessary to review the research concerning factors which influence farmers’ adoption rates of BMPs. In their quantitative meta-analysis of the BMP adoption literature, Baumgart-Getz, Prokopy, and Floress (2012) isolate the handful of variables that have the largest impact on farmers' decisions to adopt BMPs. These were found to be, "access to and quality of information, financial capacity, and being connected to agency or local networks of farmers or watershed groups" (Floress, 2012, p. 17).

These variables are presaged in Baerenklau's (2005) analysis of 34 pasture-based dairy farmers in Wisconsin. His study identified risk preferences, uncertainty regarding profitability, and observation of peers' decisions to adopt as factors influencing adoption. Additionally, McCann et al. (2014) conducted a mail survey of over 3,000 livestock producers in Missouri and Iowa. Their analysis of the 1,000+ responses found that the relative level of observability and the complexity of the technique are further indicators that predict adoption.

Finally, Zia (2014) surveyed 80 farmers in Vermont, using the Theory of Planned Behavior framework (Ajzen, 1985) to assess linkages between farmer motivations and their propensity to adopt BMPs. The study found that perceived behavioral control had the largest effect on BMP adoption rates. This finding suggests that policies which aim to increase farmers' agency and their sense of control, such as technical assistance concerning BMP implementation, may be a valuable driver of positive behavior change in the form of increased BMP adoption.

Assessing the Effectiveness of Agri-Environmental Policy

Environmental and agricultural policymakers continue to seek ways to mitigate the negative environmental externalities of agricultural production, such as water quality issues caused by phosphorus runoff. This section of the literature review summarizes several articles that are aimed at this problem, focusing on research that privileges increased citizen (i.e., farmer) participation and agency. This focus is aimed at discovering policy tools that are guided by the empirical research regarding farmer adoption of BMPs.

Premised upon the argument that cost-sharing and similar policies do not encourage farmers to be either cost-effective or innovative with respect to farming operations, Winsten et al. (2011a) focused on performance-based incentives, specifically those where farmers are rewarded for achieving pollution-reduction goals. Common performance-based incentives include direct payments, tax credits, liability protection (i.e., safe harbor), public recognition, or penalties. Performance-based incentives are focused on outcomes rather than any specific BMP or combination of BMPs. As a result, farmers are encouraged to learn, innovate, and determine the best set of practices to adopt in order to achieve the desired environmental outcome.

Along similar lines, Bosch, Pease, Wieland, and Parker (2013) developed economic and empirical models to test the relative benefit of performance versus practice incentives in nitrogen abatement agri-environmental policy. While both performance and practice incentives were associated with specific costs and challenges such as intensive compliance monitoring and direct financial incentive payments, the authors found that performance incentives hold the potential for cost minimization where nitrogen abatement is a policy goal. However, performance incentive policies are also prone to policy-specific moral hazards and target-related inefficiencies. For example, policies that provide incentives for decreased levels of nitrogen are susceptible to “baseline shifting,” a practice wherein farmers temporarily increase pollution-causing practices during baseline periods in order to increase incentive payments during the incentive period. Baseline shifting is both a moral hazard as well as counterproductive with respect to goals for nitrogen abatement. The authors suggest that performance incentive policies could be structured based upon attainment of specified levels of nitrogen loss per acre, for example, rather than through measurement of reduction (i.e., change of nitrogen loss over time). While the level-attainment incentive structure would be less cost-effective than the reduction incentive—because of the inability to provide different levels of incentive for higher and lower levels of reduction relative to baselines—it would avoid the moral hazard and inefficiencies posed by the problem of baseline shifting.

Finally, Reimer (2014) states that "top-down approaches, particularly ones that focus only on the tools of conservation (e.g., BMPs) rather than real environmental outcomes, have been largely unsuccessful at solving our most pressing environmental problems" (p. 60a). Rather than, for example, mandating the use of specific BMPs across all farms, Reimer points to bottom-up solutions which rely on the localized knowledge of farmers and experts within a certain geographical region or who use similar management methods. For the reasons discussed in the preceding paragraphs, this study focuses primarily on policies that strengthen individual farmer agency rather than command and control regulation.

1.3.6. Barriers to the Adoption of Grass-Based Production

Despite the profitability and sustainability advantages associated with rotational grazing, as of 2006, only 13% of dairy producers in the northeast region were using the technique (Winsten et al, 2011). In order to incentivize its increased use, researchers must identify the barriers preventing farmers from adopting this useful technology. Winsten et al. (2011b) analyzed almost 1000 northeast large confinement, traditional, and rotational grazing farmers' perceptions of 11 barriers to switching to rotational grazing. The top barriers perceived by farmers were related to income, land, and work, specifically "decrease in milk production", "decrease in farm profits", "decrease in cash flow", "difficulty producing enough feed for winter", "lack of land for grazing", "amount of work to start rotational grazing", and "amount of work to manage rotational grazing." It is commonly assumed that farmers perceive high barriers concerning lack of technical assistance and information, but Winsten's research suggests that these are not major factors, indicating that perhaps incentive programs should focus elsewhere.

A Wilcoxon Signed Rank Test of farmers' perceptions both before and after switching to rotational grazing revealed that most of the barriers they perceived to be significant before switching ended up being much less significant after they had made the transition. Whereas before switching farmers were concerned about decrease in milk production, decrease in cash flow, decrease in farm profits, and skepticism from family members, after establishing rotational grazing systems these factors did not represent significant concerns (Winsten et al., 2011b). This suggests that, despite the finding that technical information about rotational grazing is not a key perceived barrier, contact with experienced farmers who are successfully employing rotational grazing may allay concerns and act as an incentive to increase adoption. If this analysis holds, it would suggest that the biggest barrier to the adoption of grass-based methods is simply the uncertainty associated with adopting an unfamiliar practice. This corroborates Zia's

(2014) analysis, which points to perceived behavioral control—or familiarity with the technical specifics and likely outcomes of a novel agricultural practice—as strongly correlated with the adoption of other novel BMPs.

1.3.7. Proposed Public Policy Interventions to Incentivize Grass-Based Dairying

Agricultural public policy incentives can be broadly categorized into positive incentives, which provide money, goods, or services to farmers in exchange for actions which work toward policy goals; and disincentives, which impose a cost if farmers use practices which contradict policy goals. Both types of incentive are briefly discussed below. Another category of incentives are targeted incentives, which analyze which farmers should be targeted by incentive programs to optimize the use of resources and effect the greatest change. Finally, a category of public policy programs which aim at increasing farmer connectivity in an attempt to foster behavior change through peer-to-peer learning is discussed.

Positive Incentives

Subsidies for rotational grazing adoption could come in the form of cash payments, free or low cost insurance programs, grants, tax credits, or other mechanisms. Based on their analysis of barriers to rotational grazing adoption, Winsten et al. (2011a) suggest three possible policy interventions with relevance for Vermont. One is a “green payment” approach which links carbon sequestration and water quality improvements from conversion to perennial forage with debt relief assistance. The next is a debt restructuring program which targets highly-leveraged farms. The third is a revenue assistance program which assures minimum profitability during the transition to rotational grazing.

Disincentives

A stochastic dynamic programming model for a hypothetical dairy farm showed that financial disincentives for phosphorus accumulation led farmers to reduce herd sizes and switch to seasonal rotational grazing, but it also cost farmers an average of $524 per hectare per year (Winsten and Stokes, 2004). Direct financial disincentives like this may effect change, but they may also work against other policy goals, since they would financially burden already-struggling small farmers and likely lead to attrition. This topic needs further study.

A possible non-financial disincentive relates to the pending GMO labeling legislation in Vermont. The current legislation exempts conventional dairy producers who use GMO feed from labeling requirements. However, if this loophole were removed, market forces may incentivize farmers to look for ways to feed their cows that do not rely on GMO corn, prompting increased interest in rotational grazing.

Targeted Incentives

Farmers currently using large confinement systems perceive far higher barriers to the adoption of rotational grazing, especially when it comes to “decrease in farm profits” and “not enough land for grazing” (Winsten et al., 2011b). This is likely due to the heavy investment and asset fixity associated with their large herds and specialized equipment; and the correspondingly-high levels of debt which large confinement operators often carry (Cannella, 2011). Because large confinement farmers are both less able and less likely to switch to rotational grazing, and also because they may already be running profitable operations, it probably does not make sense to focus incentive programs on these farmers. A primary aim of this project is to conduct further research into targeted policy incentive optimization, including determining which types of farmers would benefit most from transitioning to rotational grazing.

Peer-Based Policies

A number of peer-learning based approaches have historically been implemented in an attempt to increase the use of Best Management Practices in agriculture. Model farms were commonly established in the 19th century as centers of both agricultural research and education. Their methods were designed to be replicable or emulable, and they served as learning hubs for the community, in order to enhance overall agricultural efficiency and productivity (Wade, 2002). Farmer Field Schools (FFS) are a group-based approach which have successfully been used to teach best management and other beneficial practices to farmers around the world. They rely on bottom-up, largely peer-derived knowledge rather than centrally-designed, “one size fits all” messaging, and are often held at participants’ own farms. In this way, information may be shared between farmers concerning techniques that work for specific farm typologies, but may be glossed over by hegemonic recommendations (Sustainable Agriculture Information Initiative, 2010). Farmer Field Schools have proven effective in promoting the adoption of BMPs, most notably the technique of Integrated Pest Management (Feder, Murgai, & Quizon, 2004; Rebaudo & Dangles, 2013). The observation that many rotational grazing farmers are already encouraged to adopt the technique through existing peer networks suggests that peer-based approaches may be effective in this context.

1.3.8. Conclusions from Literature Review

As traditional small-scale dairy farms are increasingly pressured by the cost-price squeeze of fluctuating milk prices coupled with higher feed production and purchase prices, they must increase the efficiency of their production systems to maintain profitability. The above literature review has demonstrated that increased use of intensively-managed grass-based dairy production offers the opportunity to enhance indicators of ecological and social sustainability while maintaining or augmenting profitability in Vermont's dairy sector. While large confinement farms can certainly be profitable as well, all else being equal this type of management may have negative effects on important policy goals such as phosphorus runoff and rural community development. This study contends that it would therefore be in policymakers' best interest to incentivize the increased use of grass-based dairy production, and to consider rotational grazing a Best Management Practice, especially for smaller-scale dairy operations.

Recognizing that peer learning may play a pivotal role in farmers' decisions to adopt new innovations, a series of methods which aim to discover the mechanisms behind these adoption dynamics, along with the theoretical justification for their use in this project, are discussed in the following section.

1.4. Review of Methodology

1.4.1. Expert Input

To determine key farm and farmer attributes and policy incentive options, a series of expert interviews were initially conducted with agricultural economists and dairy experts. Expert interviews have been shown to be an excellent way to gather structuring information before delving into more comprehensive methods. Keeney et al. (1990) describe a method called the “Public Value Forum”—variously also called a “Delphi Group”—which has been successfully used to elicit public input when faced with complex policy decisions. The first step in this process is to carry out “structuring activities” which narrow a complex problem down to a defined set of attributes by consulting with experts and representatives of stakeholder groups. There is no doubt that a paradigm change such as shifting dairy production models is a complex problem, spanning across academic disciplines, and imbued with diverse preexisting beliefs and perceptions amongst the target population of Vermont dairy farmers. This project used expert stakeholder input to inform a range of attributes of the decision problem at hand, such as identifying barriers and suggesting policy interventions. This structuring information informed the creation of the interview schedule used to assess Vermont dairy farmers’ motivational attitudes and decision-making patterns, the experimental design of the behavioral economics game, and finally the calibration of the agent-based model.

1.4.2. Structured Farmer Interviews

Davis and Wagner (2004) posit that local knowledge is an important and often overlooked element of resource management decisions, which are often informed from a top-down perspective by institutional insiders. They suggest identifying “alternative” experts who have a more embedded type of expertise which better reflects “on the ground” realities. The authors advocate corroborating information across at least three local knowledge experts to assure that their expertise reflects systemic realities. As part of a Knowledge Management approach, this study endeavored to seek out local knowledge experts, specifically farmers with on-the-ground experience interacting with state policy concerning agriculture and the environment.

Original in-depth interview research was stratified across three key dairy farmer stakeholder groups: confinement farmers, grass-based farmers, and farmers who had transitioned between the two. A total of 8 structured interview sessions were conducted with 10 Vermont dairy managers, stratified across these typologies to as great a degree as was feasible considering the relatively low number of interviews. Stratified sampling in interview-based research has been shown to be an effective way to capture multiple viewpoints when there is clear theoretical rationale for assuming that the groups will differ in meaningful ways (Robinson, 2014). Interview schedules were crafted specific to each stakeholder group which addressed barriers and incentives identified through the expert input phase. Interviews were transcribed and analyzed thematically, with particular attention to perceived barriers, characteristics of innovation diffusion, and potential incentive efficacy. The differential motivational attitudes of farmers were compared across the stratified typologies. This qualitative analysis was used to inform both the behavioral economics experiment and the decision rules of agents in the ABM.

1.4.3. Behavioral Economics Experimentation: Assessing the Role of Information Uncertainty in Economic Decision-Making

Farmers considering implementing a new practice or switching from one production paradigm to another operate under conditions of information uncertainty. In fact, farmers always operate under uncertainty due to incomplete information concerning costs of inputs and farm-gate prices of agricultural goods, weather, market trends, and other factors. Decision making under such conditions has been referred to as “bounded rationality” (Simon, 1982), and may take on features not observed in economic environments in which optimization is an available strategy. A behavioral economics experiment was designed to analyze the extent to which lack of complete information and/or uncertainty about outcomes following the implementation of a new practice or method may affect farmer decision making surrounding BMP implementation. This experiment assessed whether decreasing information uncertainty, for example by facilitating access to the economic choices and outcomes of other actors in the marketplace, may increase perceptions of personal agency and lead to increased BMP adoption behavior.

Based on observations of economic actions which are generally regarded as aberrations from standard economic behavior, Alchian (1950) proposed an analytical model within which uncertainty of foresight and incomplete information render meaningless the concept of profit maximization, instead giving rise to adaptive, imitative, and trial-and-error behaviors. Alchian hypothesized that under these conditions, successful actions are selected not through a calculable optimum, but by the various actions actually tried by the economic actor and/or other visible actors making similar decisions in the marketplace. Despite the actors themselves being oblivious to the optimal course of action—thereby making a true Nash equilibrium impossible—this theory explains why economic behaviors are still often observed to converge upon a predictable optimum course which appears to approximate the Nash equilibrium.

Building upon the work of Alchian (1950), Rhode and Stegeman (2001) aimed to discover whether and when imitation is a rational decision and what effects imitation has on equilibrium in a relatively more realistic and dynamic Darwinian model of economic competition. In realistic settings, profit maximization is meaningless and payoff is uncertain. Under these conditions, imitation may be considered a rational choice. "If computation is costly, then imitators can prosper among a population of optimizers" (Conlisk, 1980 as cited in Rhode & Stegeman, 2001, p. 418). In information-uncertain environments, backwards-looking imitation may be more fruitful than forwards-looking optimization, while offering more certainty than a random trial-and-error decision. This is especially true in highly complex and dynamic situations. As imitators adopt the relatively more successful strategies of their rivals, decisions converge upon a non-Nash equilibrium, namely, relative payoff maximization. In instances in which other actors' behaviors are observable, the authors determined that the Darwinian price is lower than Bertrand-Nash and Cournot-Nash prices, because the spiteful behavior of imitators affects the ability of rational agents to maximize profit effectively. This paper is well-suited to this project because the authors assume that the Darwinian dynamics present in this kind of behavior—relative payoff maximization—is most likely to be present in small groups of strategically-related agents. Nevertheless, this model of competition may not be ideally suited to the population of small dairy farmers, who collectively comprise a rival producer of dairy products. It may be the case that we would need to consider the case of the small dairy farmer in aggregate versus other dairy producers, but then the applicability to the case of BMP adoption is unclear.

Contra Friedman's (1953) claim that profit maximization is a rational survival strategy in a Darwinian economic model, Schaffer (1989) applies Hamilton's (1970) "spite" evolutionary biological theory to this model and finds that profit maximizers are only "fittest" under conditions of perfect competition. However, under conditions of market power, the fittest firms would be those who exercise spite, that is, those that choose to hurt themselves so as to hurt their rivals more. By lowering prices and *not* maximizing profits, firms with less market power demonstrate greater fitness by decreasing rival and more powerful firms' profit by a greater amount than their own. Spiteful, non-maximizing firms are thereby more likely to survive, that is, they demonstrate superior fitness. It is unclear how this model will apply to the situation that we will be attempting to test, namely, the market for small dairy farms. In this situation, small dairy farmers are not attempting maximum growth. Rather, they are attempting to minimize costs and maximize profit while the size of their business remains relatively stable. This article is possibly applicable in an aggregate analysis of small dairy farms versus other forms of dairy farming.

Cabrales et al. (2007) ran a coordination game (game with multiple equilibria) under which participants operated with various degrees of uncertainty about true payoff potentials. The researchers observed that behavior generally converges upon the theoretical prediction after sufficient experience has been gained. In a baseline treatment of incomplete information, it took roughly 50 rounds before behavior converged. The authors suggest that subjects arrived at this equilibrium not by careful introspection, but by observation of the behavior of other players. Suri and Watts (2011) ran a public goods game in which treatments were varied based on network typology, finding that network typology did not significantly correlate with differences between subject contributions in that experimental context.

Our experiment follows up on the studies presented above, empirically testing whether imitative behaviors are an important facilitator of the adoption of novel practices in the context of an agricultural commodity market, like that for milk, when firms operate under information uncertainty. This experiment measures the rate of adoption among socially networked "farmers" under varying levels of information uncertainty based on proximity and access to information about other players' successful behavior. In a series of computer-based experiments, 12 participants per session played a "social learning" game within peer network topologies of varying degree, and with the presence or absence of a perfectly-performing automated model peer. We hypothesize that rotational grazing is adopted more quickly in more highly informed and/or larger networks.

1.4.4. Knowledge Management

The selection of raw information used to calibrate a computer model is crucial to the accuracy and relevance of the knowledge that emerges when the model is run; thus the adage, "garbage in, garbage out." A structured knowledge management and in-depth interview process will ensure that the information upon which the Dairy Farm Transitions Agent Based Model rests captures on-the-ground realities for Vermont farmers and policymakers. The first step in this process is to identify the set of inputs required for the model (North & Macal, 2007). These input requirements, based on which factors will be endogenous to the model, determine the set of data necessary for model calibration.

Knowledge Management (KM) takes a multi-disciplined approach to effectively capture, code, store, and use available knowledge. The approach focuses on merging existing datasets with human input, evaluating both tacit and explicit knowledge about a subject (Alavi & Leidner, 2001). Data used to assign decision rules to agents in an ABM are often drawn from a variety of existing sources (North & Macal, 2007). In this case, such sources include the USDA Census of Agriculture, Vermont Center for Geographic Information, survey data from previous academic studies on Vermont dairy farmers (e.g. Colby, 2012; Cannella, 2009), and original qualitative and quantitative research conducted as part of this project.

1.4.5. Agent-Based Modeling of Coupled Human and Natural Systems

Agent-based simulations have been widely used to model complex systems in which humans interact with the natural environment, each influencing the state of the other. Agent-based modeling can incorporate the influence of human decision-making on land use in a mechanistic, formal, and spatially explicit way, taking into account social interaction, adaptation, and decision-making at different levels. Agent-based models are especially adept at incorporating non-monetary influences on decision making and linking social and environmental processes (Matthews et al., 2007). A 2012 review of coupled human and natural systems (CHANS) agent-based models showed the efficacy of the methodology, concluding that calibration of human decision-making patterns should be a primary consideration for future research (An, 2012). Filatova et al. (2013) identify four challenges to agent-based CHANS modeling: (1) design and parameterizing of agent decision models, (2) verification, validation and sensitivity analysis, (3) integration of socio-demographic, ecological, and biophysical models, and (4) spatial representation. These challenges must be considered and addressed as a model is developed.

Multi-agent system models of land-use/cover change (MAS/LUCC models) are a subset of agent-based models which combine a geographically-situated landscape model with agent-based representations of decision making. In this way, the interaction between agents and their environment can be represented. MAS/LUCC models have proven particularly effective at modeling complex spatial interactions under heterogeneous conditions, and for modeling decentralized, autonomous decision making (Parker et al., 2003). For example, a number of MAS/LUCC ABMs have been developed to model the landscape-level impacts associated with human settlement patterns (Kohler et al., 2000; Sanders et el., 1997). MAS/LUCC models have also been developed with a specific focus on the impacts of agriculture upon the natural and built environment. Such approaches have addressed issues such as the diffusion of novel agricultural practices which impinge upon agricultural investment, production, and land renting (Balmann 1997; Balmann et al., 2002; Berger 2001); and cropping decisions with environmental sustainability impacts such as tropical deforestation (Lim et al., 2002; Lynam, 2002).

The ABM project undertaken here, which is titled the Dairy Farm Transitions Agent Based Model (DFTABM), incorporates elements of previous MAS/LUCC ABM research, and applies them toward the specific policy problem outlined in the literature review above, namely the diffusion of grass-based production in the Vermont dairy industry. The DFTABM incorporates a farmer network model, which facilitates the spread of novel technologies according the patterns observed in the qualitative phase of this research, as well as those derived from the results of the experimental economics game outlined above. The DFTABM model is calibrated to reflect present on-the-ground realities in Vermont such that experiments with relevance for Vermont policymakers may be carried out. The model also serves as a scalable backbone which can be re-calibrated to address the diffusion of other agricultural practices, providing a basis for future research in this area.

1.4.6. Conclusions from Methodology Review

The above review of methodology was meant to provide a theoretical basis upon which this project may be carried out. It has outlined three primary research methods: (a) qualitative interview research, (b) behavioral economics experimentation, and (c) the development of an agent-based computer model. Results from these research endeavors will be discussed in Chapters 2 and 3 to follow. These chapters take the form of academic journal articles intended for publication in early 2016. Chapter 2 will present the behavioral economics experiment, while Chapter 3 addresses the development of the DFTABM.

CHAPTER 2: SIZE MATTERS: INNOVATION DIFFUSION IN AN OFFLINE CLUSTERED SOCIAL NETWORK EXPERIMENT

Experiment undertaken in collaboration with:
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2.1. Abstract

A behavioral economics game was developed in order to test the way participation in peer networks of varying degrees and configurations facilitates or hinders decision-making under conditions of information uncertainty. The specific decision modeled was a farmer deciding whether to implement a new, environmentally-beneficial management practice. A web-based computer platform was developed using the Python language, which simulated networks of small dairy farm enterprises. Participants operated as farm managers, playing a series of three ten-round computerized games in groups of 10-11 players. Players were networked in either pairs, trios, groups of six, or groups of twelve. All but one treatment also included an automated "seed player" who made optimal decisions in every round, such that in all "seeded" treatments, participants theoretically had access to the same information quality. After each round, information about the farm management decisions and financial outcomes of all other players in a given network, including the automated "seed," was made available to the other participants in the network. Participants were paid based on their farm's financial performance over the three games. Results indicate that players in networks with higher numbers of peers made better economic decisions on average. The inclusion of an automated "seed player" within a given network configuration also facilitated better decision-making. Both of these correlations are statistically significant. Furthermore, the shape of the "diffusion curve" of new adoptees confirms other literature on innovation diffusion dynamics. Public policy implications from this work include an increased focus on facilitating peer-to-peer learning among farmers where Best Management Practice adoption is a policy goal.

2.2. Introduction

Given the pressing need to reduce or eliminate the environmental externalities that arise from certain agricultural practices, there has been increasing interest among policymakers and network theorists to understand the processes by which farmers decide to adopt environmentally sustainable Best Management Practices (BMPs). Social learning has proven to be an effective model for understanding the ways in which the adoption of new agricultural management techniques diffuse through natural social networks (Ryan & Gross, 1943; Foster & Rosenzweig, 1995; Conley & Udry, 2001; Munshi, 2004; Young, 2009; Rebaudo & Dangles, 2013). Other studies affirm the centrality of social learning for farmers' adoption of BMPs (Baerenklau, 2005; Baumgart-Getz, Prokopy, & Floress, 2012; McCann et al., 2014; Zia, 2014). While it has been found that observing the successes one's peers aids in overcoming barriers to adoption that arise from uncertainty about new agricultural technologies, what is not known is what impact the size of a farmer's social network may have upon the diffusion dynamics which lead to increased BMP adoption.

This study aims to address this question by empirically testing the diffusion of agricultural BMP adoption in a controlled laboratory environment using a custom behavioral economics game. Our goal is to verify theorized dynamics associated with the adoption of novel behaviors, and specifically to identify the social network size that provides the most effective level of positive information externalities under conditions of information uncertainty (Shampine, 1998; Eksin et al., 2013). A real-life application of a game such as ours might include the development of peer learning networks by agricultural extension offices for the purpose of disseminating target BMPs. In such a case, understanding optimal network size and diffusion dynamics would increase the efficiency and effectiveness of agri-environmental policy implementation (Beaman et al., 2014).

We designed a three-round, offline network game in which participants were randomly assigned to clustered social networks of varying sizes, or total degrees (Walker & Muchnik, 2014). Participants made decisions about whether to adopt a new or maintain a current agricultural management practice over the course of ten "years," and were allowed perfect ex-post monitoring of their own and the decisions of peers within their networks after each year of play. Additionally, four out of five network typologies tested in our experiment, unbeknownst to the other network members, included an automated "seed" player who made individually optimal decisions for each round of play.

Because payouts for the decision to adopt a new or maintain a current management practice varied in each game, and participants were only given information regarding the continued profit they would receive from maintaining their current management practice, participants were forced to rely upon the information that they received from monitoring the results of their own and their peers' management decisions. Monitoring has been shown to improve overall performance in economics experiments (Deck & Nikifourakis, 2012). In this experimental context, careful monitoring of peers' decisions and outcomes provided the ability for a player to make management decisions that resulted in high profitability for her own farm enterprise.

In the literature on network modeling, the relative complexity and risk related to the decision to adopt a new technology influences the effectiveness of social networks of varying degrees and length of network ties (Centola & Macy, 2007; Centola, 2010). For riskier and more complex behavioral adoption, social learning in clustered networks proves to be the most successful means of diffusion. Additionally, it has been theorized that in the context of information uncertainty, optimization ceases to be a viable strategy for profit maximization, and instead bounded rationality in the form adaptive behaviors informed through trial-and-error and imitation step in to guide decision-making (see, e.g., Alchian, 1950; Rhode & Stegeman, 2001).

Previous experimental economics research into information uncertainty suggests that, in the context of a coordination game, decision-making eventually converges upon a theoretical equilibrium as players observe the behavior of their peers (Cabrales et al., 2007). The question is then whether or not socially derived information improves results in the context of a price-taking commodity market. It seems that this has been demonstrated empirically in the dissemination of complex agricultural techniques. For example, Farmer Field Schools (FFS) have proven effective in encouraging the adoption of BMPs, though the complexity of the BMPs sometimes provided a barrier to the spread of the new behavior beyond the FFS networks (Feder, Murgai, & Quizon, 2004; Rebaudo & Dangles, 2013). The need to understand the optimal size for network development is, once again, especially crucial to the successful implementation of agricultural policy where contagion and the observability of neighbors' behaviors are limited by the technical complexity of target BMPs.

For the purposes of studying the dissemination of behavior like environmentally-sustainable BMPs, it is necessary to design games that do not include mechanisms such as equilibria under cooperation, or even public goods scenarios. This is because, in an agricultural commodity market, the implementation of target BMPs may bolster profitability on individual farms without significantly affecting these farms' competitiveness with respect to their neighbors' conventional output. The target BMP assessed by this experiment is known as grass-based dairy farming. On smaller farms in particular, grass-based production has been found to generally improve the profitability of the farms on which it is implemented, while also achieving environmental goals (Bishop et al., 2005; Foltz & Lang, 2005; Gillespie et al., 2009; Hanson et al., 2009; Rotz et al., 2009). To assess the dynamics associated with such a scenario, we would benefit from the development of games that test decision making in networks where the goal is one's own individual optimum, and where providing information to peers and stimulating social learning are externalities of the decision making process; a case in which the "rising tide lifts all boats." Such an experiment would be valuable in illuminating the relationship between network structures and information diffusion characteristics, in particular the network size best suited to individual success and optimal information externalization.

Research has shown that social learning through adult peer interaction can be an effective driver of behavior change (e.g. Milbrath, 1989; Keen et al., 2005; McKenzie-Mohr, 2011). It has been suggested that under conditions of information uncertainty, as modeled in this experiment, economic actors assume a constrained model of self-interest based on bounded rationality, relying on strategies other than optimization—namely adaptation via trial-and-error and imitation—to achieve favorable economic outcomes (Alchian, 1950; Selten, 1990; Simon, 1957, 1982). Further, under conditions of bounded rationality, backwards-looking imitation is a computationally-inexpensive method of decision-making which is often superior to simply guessing (Conlisk, 1980 as cited in Rhode & Stegeman, 2001). These are the assumed characteristics of the participants in our game, whom we then placed into social networks in order to observe the ways in which good information diffused amongst and influenced the members of these networks.

Finally, Rogers (2010) provides a mechanism, called "Social Diffusion of Innovation," which helps to explain the dynamics at play here, postulating a sigmoid diffusion curve that encompasses early, middle, and late adopters. Rogers suggests that, to facilitate optimal diffusion of innovation, networks should have both a level of homophily and of heterophily. This effect has also been described in the network theory literature, which contends that the stabilization of linkages over time leads to homophily (Burt, 1992), whereas heterophily results when a central actor forms a bridge between two dissimilar actors (Granovetter, 1973, 1983; Burt, 1992). The level of homophily and heterophily within a networked system has also been found to correlate with network outcomes (Burt, 2000). In this experimental context, we assume that, given a random set of participants, a larger sample will tend to encompass a larger degree of heterogeneity among participants. Accepting this assumption, it follows that when participants are assigned into network groupings at random, a network of higher total degree will tend to result in a greater level of network heterophily. In other words, under conditions of random assignment, in larger networks it is more likely that players will be in contact with peers who have made decisions that are both similar to and different from their own.

Following work by Suri and Watts (2011), who did not find significant differences between subject contributions in a public goods game based on network typology, we aimed to explore whether network connectivity influences the decision-making quality of participants operating under information uncertainty in a simulated commodity (price taking) market. Our study contributes to the literature by analyzing the innovation diffusion effects associated with (1) the presence or absence of perfect information within a network, and (2) the size, or total degree, of a network. We hypothesize that the inclusion of a single automated player providing a model of perfect play should promote better decision-making among the other actors in a given network by increasing the quality of information available within that network. We also hypothesize that, in an information uncertain marketplace, the ability to monitor the performance of higher numbers of networked peers should lead to better average decision making within a given network, although there may be a size limit beyond which higher numbers of peers ceases to facilitate more efficient diffusion. Network performance in this experiment can be assessed by examining the innovation diffusion dynamics within a given network throughout the ten-round experiment, as well as the average level of profitability achieved by players in each network.

Our research questions are thus as follows:

RQ1: *Under conditions of information uncertainty, to what extent does the inclusion of a single well-informed peer impact the decision-making quality of the other individuals located within a network?*

RQ2: *Under conditions of information uncertainty, is there a relationship between average decision making quality and network total degree?*

2.3. Methods

We developed a multi-round, offline game designed to ascertain the extent to which the size of peer networks and/or the inclusion of a perfectly-performing peer within a network affects the quality of decision making for actors in a marketplace in which information uncertainty is a constraint. The game was developed using the Python programming language, and was based on the Willow experimental economics platform (Weel & McCabe, n.d.). Participants were randomly selected from a cohort of University of Vermont (UVM) student volunteers. Recruitment of participants was accomplished through direct outreach to undergraduate students in two UVM courses, postings on the UVM graduate student email list, and advertisements at the UVM student union. Recruits scheduled their sessions via confidential web-based Doodle polls. Sessions were held under the auspices of the Social Ecological Gaming and Simulation (SEGS) lab at the University of Vermont during late 2014 and early 2015. A total of 85 participants completed the game in a series of 8 experimental sessions. In each session, between 10 and 12 participants at a time were provided with desktop computers loaded with our network-based software. Each experimental session was comprised of three separate games, and lasted roughly 45 minutes. In order to provide a payoff dominant incentive, the sessions were designed such that players could earn between $13.50 and $28.50, depending on their performance.

In each of three games, participants began with zero dollars and were asked to make a series of ten management choices, one per round (called “years” in the game), that could influence the profitability of their simulated farm enterprises. At the outset of each round, participants made a simple decision: they chose either to (a) continue their current management method and earn a known profit, or (b) adopt a new management method with unknown financial consequences. If a participant chose to adopt the new management method in any given round, he or she was committed to that choice for the remainder of the ten-round game.

On the main interface screen of the game (see Appendix 1 for a screenshot), participants were provided with a self-updating table that allowed for perfect ex-post monitoring of the management decisions and resultant financial outcomes of each of the other players within their peer networks. Participants were given scratch paper and a pen to do their own arithmetical calculations, if desired. At the end of each session, participants were issued U.S. dollars equivalent to the sum of the cumulative profits over all three games of their own farm enterprises. Participants were only allowed to participate for a single session, and were instructed to keep any information they learned about the experimental design confidential. All information in this paragraph (but no additional information) was given to participants via an instruction sheet and verbal directions at the beginning of each session.

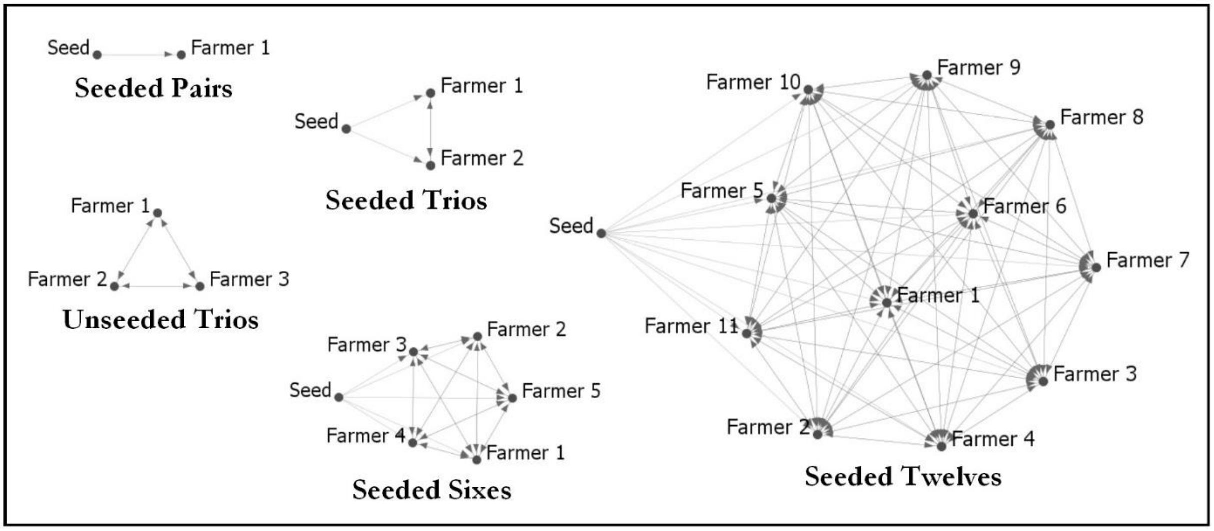

Figure 1: Schematic Representations of Peer Network Configurations. Arrows Indicate the Direction of Information Flow. Figures were Generated Using ORA Network Analysis Software.

Five treatments, varying by peer network typology, were tested in this study (Figure 1). In seeded treatments, players were not aware that the seed was an automated player, so that they would not treat the information gleaned from this source preferentially over human peers. The purpose of the seed was to control for information quality within each network. The inclusion of a seed ensured that participants in all seeded treatments had access to the same ideal information, allowing us to assess the diffusion dynamics arising from differential peer network total degrees. Network treatments ranged in size from one to eleven human players. For example, in the Seeded Pairs treatment, our smallest network, each player was connected only to the seed, whereas in the Seeded Twelves treatment, our largest network, each player was connected to ten human players in addition to the automated seed. Eleven Seeded Pairs networks were tested, totaling eleven players. Seven Seeded Trios networks were tested, totaling 14 players. Four Seeded Sixes networks were tested, totaling 20 players. Two Seeded Twelves networks were tested, totaling 22 players.

The Unseeded Trios treatment differed from the others in that it did not include an automated seed player. Comparing the performance of the Seeded Trios network to the Unseeded Trios—a network with an equivalent degree, but lacking the perfect-quality information provided by the seed—allowed us to analyze the diffusion dynamics associated with the presence or absence of a single agent operating ideally. Six Unseeded Trios networks were tested, for a total of 18 players.

Each participant completed three subtreatments, or versions of the game, which varied based upon the financial consequences of adoption of the new management method versus maintenance of the current management method. In two subtreatments, it was individually optimal to adopt the new management method immediately, whereas in the remaining subtreatment, it was individually optimal to maintain the current management method throughout the duration of the ten-round game. The ordering of the subtreatments was held consistent for all sessions in order to ensure that whatever information players may have gleaned about the game itself from subtreatment to subtreatment was a consistent factor. Players were unsure in any given game of the individually optimum decision, thus maintaining within-subjects information uncertainty over the course of the three subtreatments each player completed.

In each subtreatment, players earned a set profit per year if they chose to maintain the status quo (P_{sq}). An upfront payment, or investment, was required in order to adopt the new method (I_{bmp}), reflected as a negative profit immediately following the year the adoption decision was made (A). In subtreatments 1 and 3, players ultimately earned more profit after adoption ($P_{bmp} > P_{sq}$), meaning that adopting early in those subtreatments represented the best financial decision. In subtreatment 2, $P_{bmp} = P_{sq}$, so switching to the new method resulted in a net loss in profit (the investment did not pay off). It is common that when changing management methods, farmers may experience a time lag before the management method becomes profitable. To model this dynamic, subtreatments 1 and 2 included a one-year lag, such that in the second year following adoption (A+1), the player earned zero profit ($P_{y2} = 0$). After the one-year profitability lag, the farm returned to profitability, earning an unwavering profit (P_{bmp}) during all remaining years (A+2 … 10). Subtreatment 3 differed in that it did not include a profitability gap, with the farm enterprise returning to profitability (P_{bmp}) the year after the adoption decision was made (A+1). Using the payoff dynamics variables for each subtreatment (Table 2 below), and where A represents the round a player makes the choice to adopt (if it is made at all), the cumulative profit for an individual player from a ten-round game can be determined using the following formula:

$$P_{cumulative} = \begin{cases} \left(\sum_{1}^{A-1} P_{sq}\right) - I_{bmp} + P_{y2} + \left(\sum_{A+2}^{10} P_{bmp}\right) & if\ 1 \leq A \leq 7 \\ (P_{sq} \times 8) - I_{bmp} + P_{y2} & if\ A = 9 \\ (P_{sq} \times 9) - I_{bmp} & if\ A = 10 \\ P_{sq} \times 10 & otherwise \end{cases}$$

Table 2: Payoff Dynamics for Each Subtreatment

	P_{sq}	I_{bmp}	P_{y2}	P_{bmp}	**Individually Optimal Decision**
Subtreatment 1	$0.50	$1.50	$0.00	$1.50	Adopt New Method at Round 1
Subtreatment 2	$0.75	$1.00	$0.00	$0.75	Never Adopt New Method
Subtreatment 3	$0.50	$3.00	$1.50	$1.50	Adopt New Method at Round 1

Data from each session were retrieved from the Python output files and imported into IBM SPSS 22 software for statistical analysis. For analysis of innovation diffusion characteristics, including innovation diffusion curves, data were aggregated by subtreatment, and the ratio of adoptees to non-adoptees at each round was tabulated for each network configuration. For analysis of network performance, the optimum profit was calculated for each subtreatment, and the distance to optimum profit, in dollars, was generated for each player in each subtreatment. As the distance to optimum was determined to be distributed non-normally, non-parametric significance tests were utilized. A Mann-Whitney test was used to determine the effect on player performance of the presence or absence of a seed within the trio networks. A Spearman's rho correlation was performed in order to analyze whether the total degree of a social network was a statistical predictor of the performance of its players, based on distance to optimum profit. Note that for all statistical analyses, the automated decisions of the non-human seed players were not included in the data.

2.4. Results

Alchian's (1950) decision-making heuristics, as well as Rogers' (2010) observations on innovation diffusion, are both supported by our experimental data.

Firstly, our data show clear evidence of trial-and-error behavior through the dynamics of early adoption. Overall, we find that an average of 50.6% of participants adopted in round 1 of each game, before any ex-post monitoring of peer actions was possible. Early adoption behavior in this experiment can be explained in two ways. In the first game, it would appear that early-adopters relied purely on the trial-and-error heuristic. However, with one or two games under their belts, early adopters in the second or third game could have been using either trial-and-error or backwards-looking imitation, relying upon the successes of peers in previous games to guide their behavior. In this experimental context, due to game-to-game differences in payoff dynamics, backwards-looking imitation may have enabled some degree of economic success, since the individually-optimal behavior in subtreatments 1 and 3 were identical. However, forwards-looking imitation based on ex-post monitoring of peer decisions, while more computationally-costly, enabled better decision making in Subtreatment 2, which did not have a payoff-analogous game upon which to base backwards-looking imitation.

2.4.1. Results for Seeded and Unseeded Trio Networks: Significance of the Availability of Perfect Information within a Social Network

Our data strongly suggest that many participants did successfully use a strategy of adaptation based on forward-looking imitation to inform their decisions. Within-game information diffusion can be seen clearly by examining the diffusion curves of the Seeded and Unseeded Trios (Figures 2-4). Players in subtreatments 1 and 3 (in which adoption of the new method was economically beneficial) achieved very high levels of diffusion by round 10. By contrast, the innovation curves for subtreatment 2, in which adoption was not ideal, plateaued around 65-70%, after which players who had not yet adopted generally refrained from doing so for the remainder of the game. We can assume that this behavior is based largely on the ex-post monitoring and subsequent imitation of their non-adopting peers.

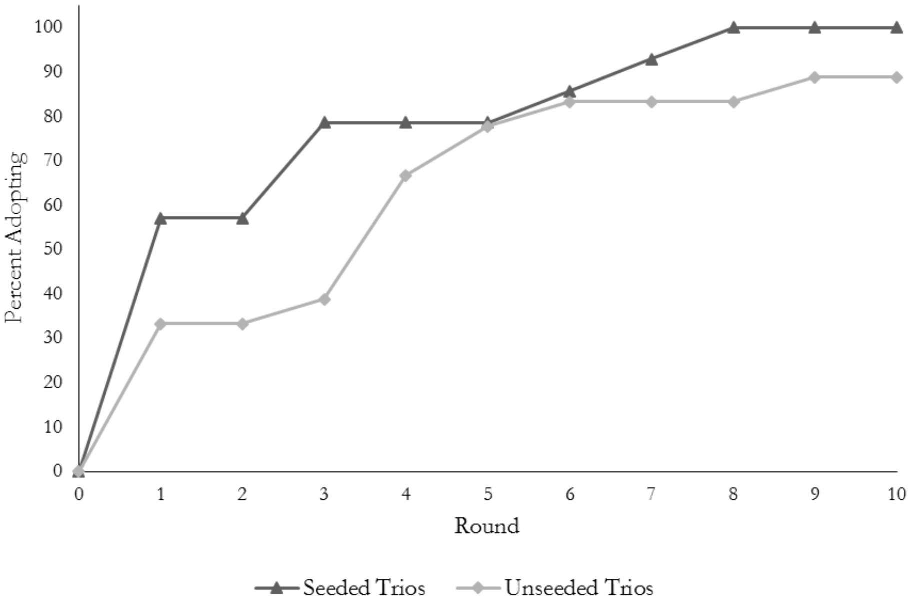

Figure 2: Subtreatment 1 Diffusion Curve for Seeded Trios and Unseeded Trios.

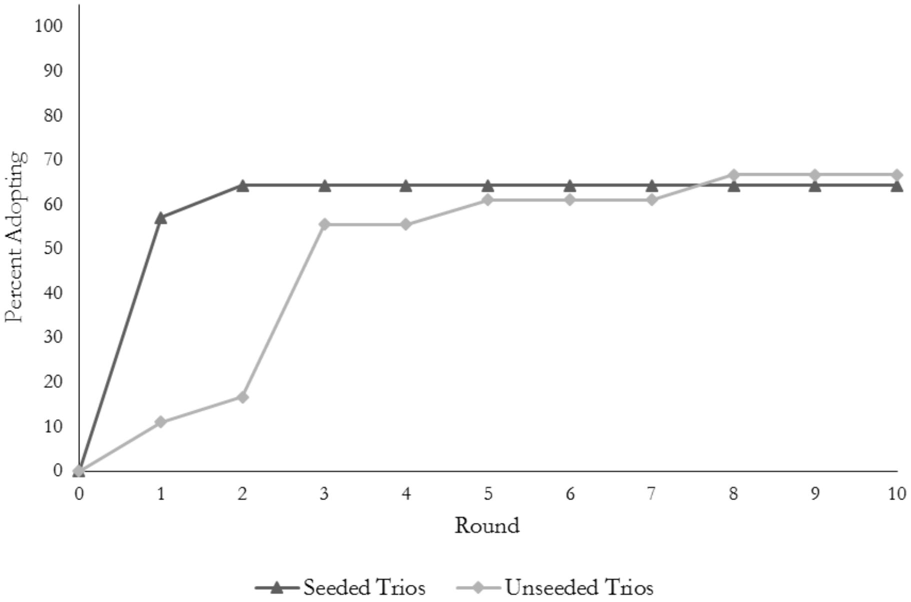

Figure 3: Subtreatment 2 Diffusion Curve for Seeded Trios and Unseeded Trios.

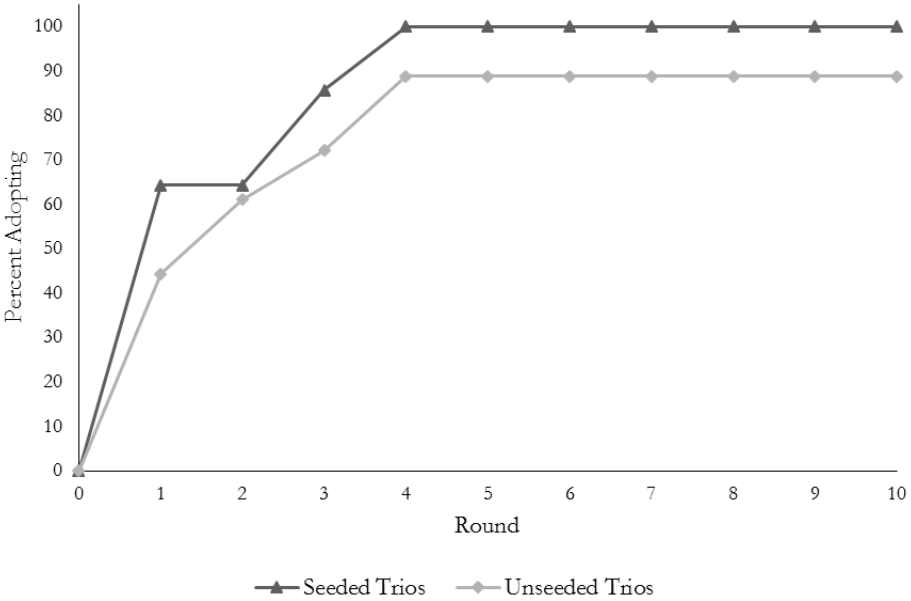

Figure 4: Subtreatment 3 Diffusion Curve for Seeded Trios and Unseeded Trios.

It is interesting to note that in subtreatment 3, which did not include the unprofitable lag year in its payoff dynamics, the diffusion curve proceeds much more quickly. Players could see the investment into the new management method pay off for their peers after only two rounds, rather than having to wait three rounds in subtreatment 1. Thus, while the Seeded Trios achieved 100% adoption in each case, in subtreatment 3 we observe complete adoption as early as round 4, whereas in subtreatment 1 this plateau did not occur until round 8. This observation corroborates theories from the field of system dynamics, which suggest that the rapidity of information feedback within a system can have profound effects on how that system evolves and changes (Wright & Meadows, 2012). Observing this effect in an experimental setting is a powerful corroboration of those theories.

The diffusion curve for subtreatment 2 provides a glimpse into the diffusion characteristics associated with high quality information in a network in more depth. Recall that in subtreatment 2 the individually-optimal decision was to never adopt the new management method. Not knowing at the time that it was a bad economic decision, we observe that 57% of the players in the Seeded Trios networks adopted early in this subtreatment. However, the diffusion curve for this subtreatment suggests that the other players learned very quickly from the mistakes of their peers. The ability to weigh the poor results of early adopters against the relative success of non-adopters, such as the ideally-behaving seed, may explain why the diffusion curve plateaus at 65% adoption and does not increase throughout the remaining duration of the game. Among the Unseeded Trios players, we observe that social learning did not proceed nearly as efficiently.

Despite having a much lower rate of early adoption, players in the unseeded networks continued to adopt—a poor economic decision in this case—such that instead of plateauing, the unseeded players ultimately surpassed the adoption level of the seeded players. These observations support the hypothesis that the insertion of high-quality information within a peer network, for example by training and equipping specific farmers to serve as peer models, may bolster the decision-making performance of others in their peer networks due to the imitation effects seen in this experimental context.

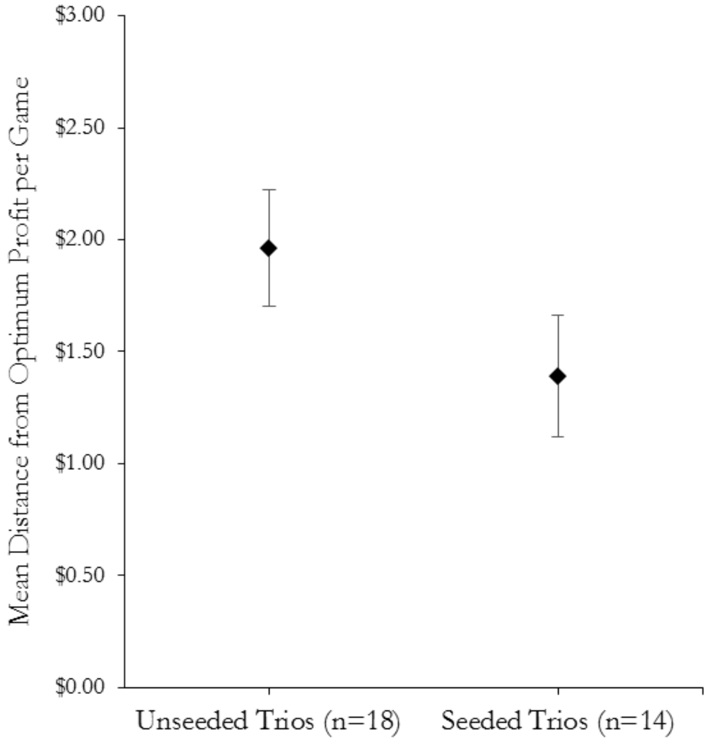

Figure 5: Mean Distance from Optimum Profit per Game among Seeded Trios and Unseeded Trios. Error bars represent standard error.

Diffusion dynamics in our data are also apparent in the observation that the inclusion of the seed's perfect behavior seems to have strongly influenced the imitation behavior of other actors in the network, spurring better average decision-making amongst those players. Across all subtreatments, the Seeded Trios consistently outperformed the Unseeded Trios. This effect is apparent in the diffusion curves for each Subtreatment (Figures 2-4), as well as in the players' average distance from optimum profit in each game (Figure 5). Players in the Unseeded Trios networks averaged $1.96 from optimum per game, whereas those in the Seeded Trios networks averaged just $1.39. A Mann-Whitney significance test on these data confirm a significant difference in performance between players in the Seeded Trios and Unseeded Trios networks (Mann-Whitney U = 893.5; Z = -1.868; Asymptotic Significance (2-tailed) = .062).

2.4.2. The Influence of Network Degree on Mean Distance from Optimum Profit across All Experimental Networks

The presence or absence of perfect information within a peer network, while a marked effect in our data, only partially explains the information diffusion phenomena present in our data. Despite the fact that players within all seeded networks had access to the same ideal information, aggregating results by network degree shows that simply having more peers in a social network also facilitates better economic decision-making. In short, size matters when farm managers are faced with management decisions and must rely upon the information available to them from their own experience and that of their peers.

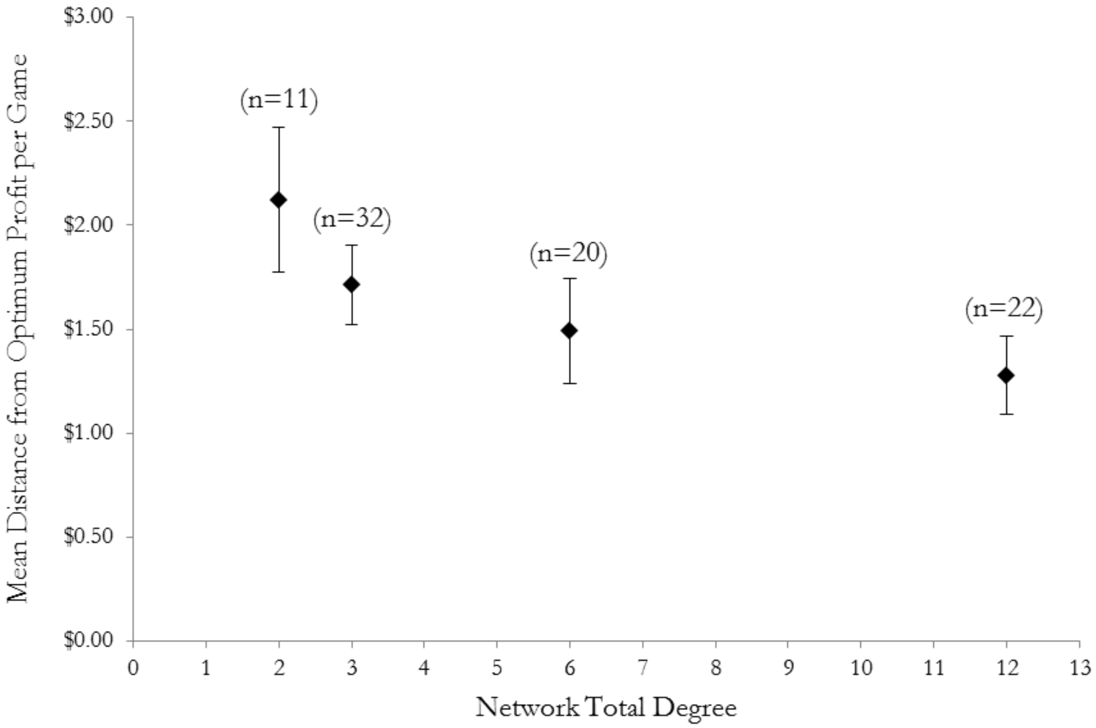

Figure 6: Mean Distance from Optimum Profit per Game by Network Total Degree. Error bars represent standard error.

Examining the mean distance from optimum profit per game for players within networks of varying degree, across all three Subtreatments, provides an overarching metric of network-level performance. The assumption here is that the quality of participants' economic decisions is based at least in part on information diffusion flowing from peer-to-peer imitation. This is a relatively safe assumption to make because, as we have already seen, there is strong evidence of peer-to-peer imitation in the data. Figure 6 shows that, overall, players in networks of degree 2 performed worst, averaging $2.12 less than optimum profit per game, whereas players in networks of degree 12, the maximum level of connectivity in our experiment, performed best, averaging just $1.28 less than optimum per game. Correlating the network degree with distance from optimum profit across all games in our experiment yields a statistically-significant negative correlation (Spearman’s rho Correlation Coefficient = -0.148; Significance (2-tailed) = .018). It would appear that in this experimental context—in which financial outcomes are uncertain, and thus optimizing is not a viable economic strategy—economic agents with more imitable peers in their social networks are more likely to make good economic decisions.

Drawing together the results demonstrating superior performance of the Seeded over the Unseeded Trios with the results demonstrating better performance within networks of higher degree, we may make an interesting observation that lends depth to these findings. Recall that players in the pair networks were connected to only the ideally-performing seed, on whom they could theoretically rely as a model providing perfect information. Upon first glance, it would seem reasonable to assume that, since the only information available to these players was perfect information, players in the pair networks had the highest overall quality information of all network configurations. However, as we have seen, players in the pair networks performed the worst; worse even than the unseeded trios, who had only the trial-and-error behavior of their human peers upon which to base decisions. One possible explanation for this finding is that higher numbers of peers in a social network may increase decision-making confidence in environments where economic decisions are based on imitation rather than optimization. This suggests that increasing peer-to-peer connectivity is valuable in a way that is independent from information quality.

However, another interpretation of these results requires a different look at the concept of information quality. In an environment of uncertainty, even perfect information such as that provided by the seed may only be seen as worthy of imitation when set in contrast to other, less-ideal information. If this were true, then the presence of a few "bad" decision-makers within a network may paradoxically foster better economic outcomes for the network as a whole by highlighting the "good" decision-making of other network members, leading to imitation and enhanced diffusion of those good decisions. This would confirm Rogers' (2010) assertion that effective diffusion takes place in networks with a certain degree of heterophily. Networks of higher degree can be assumed in the context of our experiment to be relatively more heterophilic than smaller networks, within which it may be impossible to guess whether a peer's decisions are truly worthy of imitation due to a participant's inability to monitor the consequences of the opposite course of action. While this effect remains speculative without further research, it may help explain why larger networks, in which a wider range of decision-making could be monitored, generally performed better in our experiment.

2.5. Conclusions

The network-level performance benefits associated with the inclusion of a seed player suggest that the presence of a single farmer within a network whose economic decisions are better than his or her peers may spur others to imitation: "a rising tide lifts all boats." This could be operationalized by establishing model farms within existing farmer peer networks and facilitating information exchange between farmers through mechanisms such as Farmer Field Schools (FFS).

The observation that both homophily and heterophily may be important where facilitation of innovation diffusion is a goal has real-world policy implications in the realm this experiment was designed to model. In a real-world setting, network-level homophily would entail farm operations that are relatively similar with regard to characteristics such as scale, infrastructure, available land, and the marketplace within which they operate. This type of homophily, common among farmers whose peer networks are based on physical location, establishes trust that "if it worked for my neighbor, it will work for me."

Yet our results also suggest that it may be equally important that farmers be familiarized with the operations of their less-successful peers. If larger networks tend to encompass higher levels of heterophily, it will be more likely that a wider spectrum of management choices will be used within these networks. Rather than being a liability, the presence of underperforming peers may actually foster beneficial imitation by building confidence that imitation of successful peers represents a good economic decision. This suggests that, in order to maximize positive information externalities and social learning, farmer network leaders should endeavor to increase the size and diversity of farmer networks. Peer-to-peer engagement opportunities should then occur at a diversity of farms, not just at successful "model farms." The extent to which this conclusion holds warrants future study, as there may be a point when networks become too large and/or too diverse for efficient diffusion to occur.

CHAPTER 3: THE DAIRY FARM TRANSITIONS AGENT BASED MODEL: ANALYZING THE IMPACT OF PEER-TO-PEER LEARNING ON INDICATORS OF ECONOMIC AND ECOLOGICAL SUSTAINABILITY

3.1. Abstract

Recognizing the need to simultaneously address both dairy farm viability and the negative environmental externalities arising from certain elements of dairy production, the Dairy Farm Transitions Agent Based Model (DFTABM) was developed. The model was calibrated using primarily USDA Census of Agriculture data, and predicts factors such as farm profitability, attrition, and soil loss under varying assumptions concerning farmer peer network connectivity and the frequency of peer-to-peer learning. Nine treatments were assessed, which differed according to farmer connectivity, frequency of peer-to-peer learning, and the inclusion of a soil loss reduction tax credit. Overall, it was found that high rates of emulation coupled with high rates of connectivity, especially targeted connectivity among smaller farms, yielded the best balance of farm viability and reduction in soil loss. The addition of a tax credit for reduction in soil loss had no clear correlation with reductions in soil loss figures generated by the model. Policy implications from this study include the finding that direct payment schemes for reduction in environmental harm may not always be a viable solution, and that programs to enhance peer-to-peer learning opportunities, especially among proprietors of smaller farms, may present an effective and relatively affordable means by which to effect long-term change.

3.2. Introduction

3.2.1. Policy Problem Statement

As a state that cleaves strongly to both its agricultural roots and its legacy of environmental stewardship, Vermont is currently faced with a difficult pair of heavily-intertwined policy issues. Farm viability continues to be a problem, especially amongst small and mid-scale dairy producers, which have exited the market at an alarming rate (Parsons, 2010). At the same time, water quality impacts resultant from agricultural runoff have come to the forefront, with the State’s waterways suffering from frequent toxic algae blooms in recent years (State of Vermont, 2014). A number of policy interventions are in their early stages of implementation, primarily revolving around increased regulation and financial incentivization of Best Management Practice adoption (Shumlin, 2014).

Research suggests that for many small and mid-scale dairy producers, a management method called rotational grazing may offer a partial solution to both problems. Farmers who have switched to this system find that farm-level profitability and economic resiliency are generally enhanced, driven largely by lower production costs and less exposure to volatile commodity markets (Kriegl, 2005; Hanson et al. 2009; Gillespie et al., 2009). And, because of the land use change from row-crop to pasture, harmful agricultural runoff may be drastically reduced (Stone, 1996; VDEC, 2006). A study analyzing barriers to the adoption of rotational-grazing found that, whereas prior to adoption the perceived severity of barriers was high, after adoption few if any of these barriers presented an actual concern (Winsten et al., 2011b). It would appear, then, that the biggest barrier to the adoption of rotational grazing may in fact be the uncertainty associated with the adoption of a novel production method.

Social learning has proven to be an effective model for understanding the ways in which the adoption of new agricultural management techniques diffuses through natural social networks (Ryan & Gross, 1943; Foster & Rosenzweig, 1995; Conley & Udry, 2001; Munshi, 2004; Young, 2009; Rebaudo & Dangles, 2013). Given the pressing need to reduce or eliminate the environmental externalities that arise from certain agricultural practices, there has been increasing interest in understanding the processes by which farmers decide to adopt environmentally sustainable Best Management Practices (BMPs), studies which affirm the centrality of social learning for farmers' adoption of BMPs (Baerenklau, 2005; Baumgart-Getz, Prokopy, & Floress, 2012; McCann et al., 2014; Zia, 2014). Observing the successful results of one's peers aids in overcoming barriers to adoption that arise from uncertainty about new agricultural technologies.

In light of the preceding observations, it becomes clear that the diffusion of information from farmer to farmer within existing peer networks may have deep and lasting impacts upon the agricultural landscape. The complexity inherent in Coupled Human and Natural Systems (CHANS) makes an agent-based model an ideal tool to plumb these depths. The DFTABM model and the associated experiments described in this paper examine the relationships between the size, constitution, and information-sharing qualities of farmer peer networks; and desired policy outcomes at both the farm and the watershed level. The efficacy of peer-based policy interventions is compared with performance-based financial incentive programs. Results from these experiments shed light on lingering questions surrounding the extent to which these types of policy programs may foster beneficial innovation, specifically concerning key agricultural practices which are known to enhance farm viability and reduce negative environmental externalities. Understanding peer-to-peer diffusion dynamics, such as the mechanisms by which BMP adoption proliferates among farmers, may provide clues as to how policymakers could leverage existing farmer networks, or establish new ones, to further policy goals.

3.2.2. Optimizing Intervention-Driven Change Using ABMs

Agent-based computer modeling has proven an effective means by which to observe the complex emergent properties associated with the relatively simple actions of a group of independent actors, or agents. Once agents are programmed with a set of decision rules, they are placed into a simulated environment, and often connected to one another in networks (Axelrod & Cohen, 2000; Ostrom, 2005). Because model outputs are derived from the collective action of many agents acting individually, phenomena may emerge which are difficult if not impossible to predict by other means (Ostrom, 2005).

Two distinct goals may be discerned from the existing literature on ABM research. The first is what has come to be known as generative social science, whereby the value of a modeling endeavor is largely to enhance scientific understanding of the mechanisms underlying social phenomena that are observed in the real world. (Epstein, 1999; 2006; Gilbert & Troitzsch, 2005). The second goal is to forecast the behavior of complex systems in order to guide decision-making in the present. Under such experimental conditions, a model must first be precisely calibrated such that model outputs correspond with expected real-world results in a baseline condition, known as the "baseline change" (Ostrom, 2012). Interventions may then be modeled, and results at the whole-system level may be observed (Axelrod & Cohen, 2000). For example, models have been used to predict human population settlement patterns (Epstein, 2006; Campbell, Kim, & Eckerd, 2014; Kim, Campbell, & Eckerd, 2014), transportation project prioritization (Zia & Koliba, 2013), and the utilization of common-pool resources such as water for irrigation (Janssen, 2007).

A subset of ABMs analyzes and predicts the effects of public policy interventions intended to address specific governance aims. In such models, the agents' decision rules are modulated by government programs intended to incentivize certain behaviors, a phenomenon known as "intervention-driven change." There is a growing body of literature in which agent-based models have been used to examine the mechanisms behind public policy implementation (Zia & Koliba, 2013; Janssen & Ostrom, 2006; Maroulis & Wilensky, 2014; Axelrod, 1997; Lempert, 2002; Choi & Robertson, 2014). Agent based modeling is a valuable tool to model governance systems where behavior change is a primary goal, because the agents may be programmed with decision rules reflecting the inherent complexities of actual human actors, such as path dependence, which affects the propensity with which actors may adopt new technologies (Koliba, Meek, & Zia, 2010; Axelrod & Cohen, 2000; Ostrom, 2005).

Agent-based models also lend themselves well to the study of agent behavior within networks. Endogenous agent decision rules, coupled with modeled policy interventions, may impact the extent to which partnerships between agents are formed or sustained. The structures of networks have been shown to impinge heavily upon policy outcomes in a number of policy arenas, and a growing body of literature defines the theoretical underpinnings behind these interactions (Koliba, Meek, & Zia, 2010; O'Toole, 1997; Provan & Milward, 1995; Salamon, 2002). Studies have also begun to put theories of networked governance into practice, for example in the implementation of environmental policy programs (Koontz et al., 2004).

One network characteristic with strong links to network outcomes is the level of similarity between actors. Actors with similar characteristics may form linkages through bonding social capital, which stabilize over time, a process known as homophily (Burt, 1992). Alternatively, actors may form linkages with actors with differing characteristics, thereby increasing bridging capital, a process known as heterophily (Granovetter, 1973, 1983; Burt, 1992). The level of homophily and heterophily within a networked system has been found to correlate with network outcomes (Burt, 2000). Research has also cited the balance between homophily and heterophily as a critical factor in the efficient diffusion of innovation (Rogers, 2010). Finally, research from the theory of behavioral economics confirms the importance of network size and diversity on the facilitation of information diffusion within peer networks (Chapter 2).

An inherent challenge of building a calibrated agent-based model to assess intervention-driven change is the difficulty of acquiring adequate calibration data. This is especially the case for models with high context specificity, which are precisely calibrated to analyze a single area of study (Janssen & Ostrom, 2006). Often, data must be drawn from a large variety of sources such as databases, existing statistical data, and academic literature. To surmount this challenge, a Knowledge Management approach can be valuable in cases where a large amount of disparate data must be drawn together. This approach requires first rigorously evaluating the data that will be required to build out the model, such as baseline parameters, and the formulation of agent decision rules

(North & Macal, 2007). Existing datasets may then be merged with knowledge gleaned from human input, such that the final model represents available tacit and explicit knowledge to the maximum possible extent (Alavi & Leidner, 2001).

3.3. Methods

Using AnyLogic 7.1 computer modeling software, the Dairy Farm Transitions Agent Based Model (DFTABM) was developed to evaluate farm viability and environmental outcomes in Vermont’s dairy industry. Baseline assumptions can be compared to scenarios varying economic forecasts, farmer decision-making characteristics, and/or the implementation of public policies aimed at increasing profitability and decreasing ecological impacts. Financial incentive-based policies may be compared with policies that increase and change the nature of peer to peer connectivity. Model outputs indicate the effect of setup scenarios upon farm management decisions that carry both financial consequences for the farmers, as well as watershed-level ecological ramifications.

The behavior of farmers, codified in the model as DairyFarm agents, is driven by macroeconomic trends including the cost of inputs such as feed and the price of milk sold on the open market, Federal and State agricultural policies, and localized peer-to-peer interaction between farmers. The model setup screen allows the user to alter variables associated with each of these categories in order to assess land-use, farm viability, and ecological outcomes under various scenarios (see Appendix 2). A main view then allows the user to observe land-use and farm-management changes, and track statistical outcomes as the model runs (see Appendix 3).

3.3.1. DairyFarm Agent Initialization

<u>Distribution of Farm Typologies</u>

DairyFarm agents are initialized at model runtime according to observed real-world distributions of dairy farm characteristics in Vermont. The majority of the data used to initialize agents comes from the 2102 US Census of Agriculture (USDA NASS, 2012d).

Table 3: Vermont Dairy Farms by Typology: Distribution and Key Statistics

		Family Farms							
		Small: GCFI < $350,000							
				Farming is Primary Occupation			Large-Scale: GCFI > $1,000,000		
		Retirement	Off-Farm Occupation	Low Sales: < $150,000	Moderate Sales: $150,000 to $349,999	Mid-Size: GCFI $350,000 to $999,999	Large: $1,000,000 to $4,999,999	Very Large: $5,000,000 +	Non-Family Farms
Percent Vermont Dairies		9%	7%	21%	24%	21%	12%	1%	5%
Avg. Gross Income		$13,758	$10,313	$32,290	$228,719	$538,286	$2,122,917	$8,756,830	$308,943
Size of Herd	1-9	64	50	93		1			9
	10-49	19	21	113	59	2			9
	50-99	11	9	20	81	68			15
	100-199			1	17	130	6		12
	200-499					27	75		5
	500+						43	8	7
Avg. Acreage		116	92	140	338	531	1163	3658	315
Percent Organic		4	4	11	26	15	7	0	8

Note: GCFI indicates Gross Cash Farm Income, which includes the farm operator's sales of crops and livestock, fees for delivering commodities under production contracts, government payments, and farm-related income. Off-Farm Occupation indicates that the operators report a primary occupation other than farming. Non-Family Farm indicates that the operator or persons related to the operator do not own a majority of the business. (USDA NASS, 2012d)

The census of agriculture divides farms into eight typologies according to sales figures, land use, and income characteristics. These typologies, along with their distribution in the Vermont dairy farm population, and several measures used in initialization of the model, are listed in Table 3 above.

At model runtime, The Dairy Farm Transitions ABM relies upon statistical distributions, based on distributions given in Table 3, to assign DairyFarm agents to one of the eight typologies identified by the US census of agriculture. Once typologies have been assigned, an initialization function imbues each agent with land use and management characteristics according to the corresponding census data. The farm characteristics generated from the census data for each agent include total acreage, size of milking herd, harvested cropland acreage, cropland pasture acreage, woodland pasture acreage, permanent pasture acreage, hay/haylage acreage, and organic certification status. USDA census data also indicate that, as of 2012, there were 187 dairy farms operating in Franklin County (USDA NASS, 2012c). Correspondingly, the total number of DairyFarm agents the model generates is set by default to 187, although the number of farms in the simulation may be changed at model runtime.

Off-Farm Income

According to the NASS definitions, farms which fall into either the Retirement or Off-Farm Occupation typological categories draw only a portion of their income from farm operations (USDA NASS, 2012d). Many of these farms may operate at a loss, yet stay in business due to external sources of revenue. Accurate modeling of farm viability requires that this outside income be factored into farm-level financial calculations for these farm typologies. To accommodate this dynamic, farms falling into these categories are initialized with a set level of monthly income which covers a proportion of potential losses from farm operations, up to a maximum of between $4000 and $8000 per month for off-farm occupation, or between $100 and $1000 per month for retirement farms.

Agent Localization

Because the actual physical location of each specific dairy farm within Franklin County is not available in any public dataset, DairyFarm agents in the Dairy Transitions ABM do not represent actual farms. However, care was taken to distribute agents spatially within a GIS map of Franklin County according to real-world land use patterns. Land use data were acquired from the Vermont Center for Geographic Information in the form of GIS shapefiles (Vermont Center for Geographic Information, 2015). ESRI ArcMap software was then used to generate a merged shapefile representing all the land inside Franklin County used to grow either corn, soy, hay, or pasture; the primary land uses associated with dairy farming. This merged shapefile was loaded into AnyLogic, and used to define Franklin County's dairy farming region. At model runtime, the agents are stochastically distributed within this farming region.

Peer Network Connectivity

The Dairy Farm Transitions ABM initializes with a distance-based peer network representing connections between neighboring farms. By default, the peer network connection distance is set to four miles—meaning that all farms within a four mile radius of any given farm are linked together—however this assumption can be adjusted by the model user at runtime to evaluate the effect of network size on model outcomes.

Additionally, it has been noted that networks generally exhibit a certain degree of homophily, or similarity between peers, especially when they have existed for some time (Burt, 1992; 2000). In the Dairy Transitions ABM baseline setup, this is accounted for by stipulating that agents are only considered peers if their operations are of a similar size. By default, the model assumes an emulable peer to have a herd size between ½ and 2 times that of a given agent. Whether or not to include this stipulation, along with the ratio of milking herd size required for peer status, may be adjusted by the user at runtime. All DairyFarm agents within the connection distance radius, and meeting the size similarity criterion, are connected by gray lines, and form the pool of DairyFarm agents upon which an agent may base emulation decisions.

3.3.2. Agent Decision-Making

DairyFarm agents' primary motivation within the context of this model is assumed to be maintenance or enhancement of profitability. To this end, agents act according to three primary mechanisms: (a) trial-and-error behavior, (b) adjustment to farm management practices in the event of economic decline, and (c) emulation of other farmers within a peer network. These actions are controlled programmatically using a state-chart incorporating a number of decision nodes (Figure 7). Specifics of these action mechanisms are detailed below.

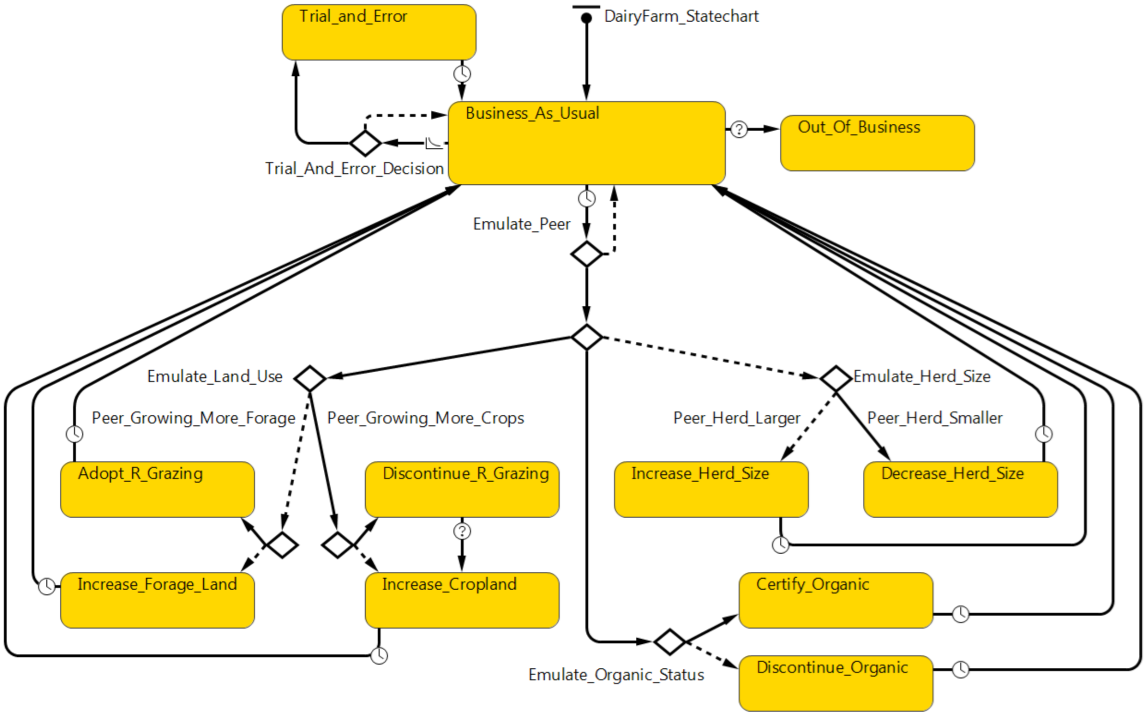

Figure 7: DairyFarm Agent Statechart

Trial-and-Error Behavior

Trial-and-error behavior is a fundamental strategy when economic decisions must be made in the absence of complete information (Alchian, 1950; Rhode & Stegeman, 2001). Because incomplete information is a fundamental property associated with operating in a price-taking commodity market, a number of trial-and-error behaviors have been modeled in the DFTABM. Agents enter the “Trial and Error” state at a rate of once per year, since land-use and other major decisions are generally made prior to the start of each growing season. By default, the model assumes that 50% of farmers may engage in trial-and-error behavior regarding farm management and land use each season. However, this number is alterable by the user at runtime in order to assess varying assumptions pursuant to the frequency with which farmers actually use trial and error as a decision making strategy. Sub-functions within the trial-and-error code are outlined below. These sub-functions are each assessed in turn whenever a DairyFarm agent enters the Trial and Error state.

Increase Herd Size

Data show a general trend toward increasing herd sizes on dairy farms, with the average herd size increasing steadily from 85 in 1992 to 191 as of 2012 (USDA NASS 1997c; 2012c). For this reason, a primary component of agents' trial-and-error behavior is to increase herd size. Provided the agent has sufficient capital on hand, it is assumed that 50% of the times it enters the trial-and-error state, it will increase its herd size by up to 5% of its current herd size, paying a set market rate for each new milker. Two assumptions limit the growth of herd sizes. First, a cap of between 2000 and 3000 milkers is placed on farms operating at the top end of the scale, to account for the fragmented nature of Vermont's geography limiting farm growth in many cases. Second, a rotational grazing farm will not increase its herd size beyond its ability to produce 80% of its feed on-farm.

Purchase Additional Land

Accounting for the rising trend in average acreage on Vermont dairies (USDA NASS, 1997c; 2002c; 2007c; 2012c), it is also assumed that 25% of the times a DairyFarm agent enters the trial-and-error state, it will choose to purchase additional land. Provided it has sufficient operating capital, it will increase its land base by up to 5%. If the farm is primarily growing crops on its land, it will purchase additional cropland, whereas it will purchase additional pastureland if it is a primarily grass-based operation. The price of agricultural land is set by a global parameter.

Rotational Grazing

Rotational grazing is an intensive system of grazing which, if skillfully practiced, can significantly increase the forage yield from a given grazed acreage. While many farmers learn of this practice from its successful use by peers, some also discover it independently, for example through the internet, university extension services, or other resources, and adopt it through trial-and-error. It is assumed that the farms that turn to this intensive grazing practice already have a significant portion of their land in pasture or hay. Additionally, as herd sizes increase beyond about 150-175 milkers, rotational grazing becomes less likely due to logistical challenges. The DFTABM captures this dynamic by assigning a 10% probability that an agent entering the trial-and-error state with at least 80% of its acreage in forage, producing at least 80% of its feed on-farm, and with under 175 milkers, will adopt rotational grazing. The model also stipulates that farms which had been using rotational grazing, but which increased their herd size beyond 200, or decreased the feed produced on farm to below 65%, will no longer use rotational grazing.

Organic Certification

Organic dairy farming has become increasingly popular in recent years, largely due to the potential to earn steadier returns, driven by the lower volatility of organic milk prices. Once again, many farmers choose to certify organic after hearing of the success of a peer, but some make the decision independently through trial-and-error. Due to the pasture rule stipulating that 30% of an organic farm's feed must be from pasture, farms are more likely to independently certify organic if they are already producing a higher amount of their own forage. Upon entering the trial-and-error state, the model assigns a 0.5% annual chance that agents with between 40% and 70% forage acreage will independently choose to certify organic, and a 1% chance for agents with greater than 70% forage acreage. However, agents are only able to adopt organic practices if they have sufficient capital reserves to pay for all of their acreage to be certified, according to a global parameter for per-acre organic certification cost.

Adjustment Due to Financial Pressure

The yearly financial calculation function includes a provision for farms facing significant financial pressures to take emergency corrective measures. If an agent is in significant debt—defined as being in the red by more than the value of its herd—it will sell off some of its assets according to the following assumed heuristics. First, the agent will sell off acreage, receiving the market price for agricultural land in Vermont—another global parameter—for each acre, until it is out of debt. If the farm is primarily crop-based, the agent will sell off pastureland, and vice-versa. If it is still underwater, it will then sell off a portion of its herd, adding the market price for each cow—defined as ½ the global parameter for the price of a milker in its prime—to its capital reserves until it is out of debt. An agent will only sell off 25% of its landbase and 25% of its herd in any given year, however, because otherwise it would have no chance to rebound during the following season.

Emulation Behavior

Making financial decisions in the absence of complete information often takes the form of emulation of other firms operating in a similar financial environment (Alchian, 1950; Rhode & Stegeman, 2001). Qualitative research conducted as part of the Knowledge Management approach used to gather data for this model confirms that peer emulation is a strong driver of decision-making in the context of Vermont’s dairy industry. Out of the six grass-based, rotational grazing farmers interviewed, five had either learned of rotational grazing from a peer, or been encouraged to use it as a result of observing the successes of a peer. These peers were generally neighboring farmers or family members who were also farmers. Among Vermont farmers, at least, it would appear that peer-to-peer learning serves as an important channel by which new farm practices may be learned, and, perhaps even more importantly, by which uncertainties surrounding the likely results of adopting a new practice may be diminished. In addition to anecdotal evidence, behavioral economics research suggests that a primary way farmers make land use and farm management decisions is by emulating the successful decisions of their peers, with the size of peer networks playing a significant role in facilitating the efficient diffusion of novel techniques (Chapter 2). The Dairy Farm Transitions Model simulates these dynamics by including a mechanism for DairyFarm agents to compare their own profitability, land use, and management methods against others in their peer networks.

An event function is executed annually which iterates through connected agents, and determines which is the most profitable. If it is determined that the net annual profit of an agent's most profitable peer is greater than that agent's own net annual profit, emulation behavior will be considered. Under baseline conditions, the model assumes that farmers will consider emulating a successful peer with a frequency of once every two years. The model further assumes that 25% of farmers who consider peer emulation will actually carry through and make adjustments to their own management practices based on the actions of that successful peer. Both the frequency of emulation, and the rate at which agents actually carry through with emulation, can be altered at model runtime to assess alternate assumptions or experimentally examine the effects of varying degrees of peer emulation on model outcomes.

Land use emulation behavior in the Dairy Transitions Model takes the form of either increasing or decreasing the acreage that is devoted to forage versus corn silage production, or adopting or discontinuing rotational grazing. Farm management emulation is operationalized by a DairyFarm agent deciding to increase or decrease its herd size, or certify or discontinue organic production. In order for an agent to determine whether a successful peer's feeding strategy or its herd size is more worthy of emulation, calculations are performed which generate ratios between the percent of an agent's farm that is in forage production versus that of the successful peer, as well as between the agent's herd size versus that of the successful peer. A greater ratio indicates a greater difference in practices between the agent and its peer. The agent will emulate the factor that is deemed to represent the stronger difference between itself and its successful peer.

On-Farm Feed Production Emulation

If it is determined that the successful peer is achieving its differential success primarily through its land use practices, an agent will adjust its own land use practices accordingly. If the successful peer has more of its land in crops, the agent will increase its own crop production, transitioning between 5% and 10% of its arable land that is currently in use as pasture to crops, and paying a set cost per acre for transitional activities such as plowing and fertilizing, defined by a global parameter. If the successful peer has more of its land in forage, the agent will transition between 5% and 10% of its cropland to pasture, once again paying a set cost per acre for transitional tasks such as pasture seeding, also defined by a global parameter.

Rotational Grazing Emulation

If an agent decides to base its emulation on land use, an additional decision node allows that agent to emulate the rotational grazing practices of its successful peer. If the agent is not currently using rotational grazing, and the peer, who is using the method, is found to be at least twice as profitable, emulation of rotational grazing will be considered. In order to carry through with adoption, an agent must fulfill certain criteria: it must have less than 175 milkers, have more than 50% of its acreage in forage, and have a landbase that can support at least 80% of its herd’s nutrition through forage feed. If all these conditions are met, the agent will adopt rotational grazing, transitioning all its harvested cropland acreage to pastureland, and paying a set price per acre, according to a global parameter, to establish rotational grazing infrastructure such as fencing, laneways, and watering systems. Similarly, if an agent is currently using rotational grazing, and a peer who is not is found to be at least twice as profitable, the agent will discontinue use of rotational grazing, and immediately begin to transition a portion of its grazing land back to crops.

Herd Size Emulation

If it is determined that the successful peer is achieving success primarily due to a large difference in herd size, the agent will act to decrease or increase the size of its own herd. If the successful peer has a larger milking herd, to the extent to which the agent has sufficient capital, the agent will increase the size of its own herd by 10% to 30% by purchasing additional milkers. If the successful peer has a smaller herd, the agent will likewise sell off between 10% and 30% of its herd. Agents purchasing milkers pay a set price per head according to a global parameter. Agents selling milkers receive half of that price per head, to account for depreciation associated with an aging herd.

Organic Certification Status Emulation

An agent may also emulate its successful peer by either certifying or discontinuing organic production. If the organic status of the successful peer is opposite that of the emulating agent, and the successful peer is at least twice as profitable as the emulating agent, there is a 5% chance that instead of emulating land use or herd size, the agent will choose to emulate the successful peer's organic status. If the successful peer is certified organic and the agent is not, provided the agent has sufficient operating capital to certify its harvested acreage, the agent will choose to emulate the successful peer by certifying organic. If the successful peer is not certified organic, while the emulating agent is, the agent will discontinue its organic certification status.

3.3.3. Economic Model

Economic Projection Engine

The Dairy Farm Transitions ABM can be set up to run going forward from any date after 1989. While the model date is between 1989 and 2013, the model uses actual historical data for both farm gate milk prices and feed costs (Gould, 2015a; 2015b). Once the model time enters 2014, historical data is no longer available, so the model's economic projection engine takes over to generate realistic milk price and feed cost data for each month based on historical trends, as well as user-input assumptions.

Milk Price Projections

The model uses a compounding interest formula which closely mirrors the historical annual inflation in price of both organic and conventional milk, set by default to 2% annually (Gould, 2015b). In addition to a fixed rate of inflation, it has been observed that milk prices tend to follow cyclic trends. In the case of conventional milk, in particular, these cycles, occurring roughly every three years, have become increasingly large in recent years. Organic milk prices, by contrast, tend to be much steadier (Su & Cook, 2015). For farmers operating on tight margins, these fluctuations can create a "cost price squeeze" which significantly impacts farm viability. The model's price forecasting engine captures these dynamics by establishing a cyclic variation in line with historic trends. In keeping with the stochastic nature of real-world economics, the model also imposes a +/- 2% variation in price on a monthly basis. By default, for conventional milk, the price is assumed to swing by an average of 18% per three-year cycle, whereas for organic milk the swing averages 5% per cycle (Su & Cook, 2015). The user may accept the default assumptions regarding inflation, length of cycle, and cyclic variation, or alter them at model runtime to correspond with economic scenarios she wishes to assess. It is important to note that the milk price projections generated by the DFTABM economic projection engine assume under baseline conditions the continuation of federal milk price subsidies, which have tended to artificially deflate milk prices. Parameters should be adjusted at model runtime if the user wishes to assess scenarios in which these subsidies are discontinued.

Feed Cost Projections

The feed cost projection engine in the model works in a similar way to the milk price projection engine. Once again, a compounding interest formula sets a baseline price according to historic rates of inflation: by default, this value is set to 2% annually. Feed cost has historically varied annually with surpluses or shortages in agricultural production of feed grains. A variability of 5% per year is the default assumption for feed cost (Gould, 2015a). Once again, the user may alter these values at runtime to assess the impacts of alternate economic scenarios on model outcomes. Since organic and conventional feed costs tend to fluctuate simultaneously, the model calculates organic feed in relation to conventional. Similarly to milk price, a +/- 2% monthly stochastic variation is factored into the final feed cost. Feed cost is initially generated in dollars per CWT of milk, which is the industry reporting standard. The model uses assumptions set by a global parameter about the average milk production, in CWT, of a cow per month to generate figures for feed cost per cow per month. These figures are then used to calculate farm profitability for each DairyFarm agent.

Farm-Level Profit and Loss Calculations

DairyFarm agents use a cyclically-executing function to calculate their profits and losses each month. Gross monthly profit is calculated based on the value received for milk produced. Expenses are subtracted, factoring in economies of scale and the influence of management practices on expenses. Finally, net monthly profit is calculated as the difference between gross monthly profit and expenses.

Gross Monthly Profit

Milk production is calculated based on global assumptions about the average quantity of milk produced per cow monthly. Because larger farms have generally been found to produce higher volumes of milk on average, the amount of milk produced per month is defined based on actual observed rates of milk production per cow on various sized farms, multiplied by the number of milkers. To account for inefficiencies in production, such as sick animals or those which are not producing optimally, an additional factor is used to calibrate the “ideal” milk production to the observed actual milk production on Vermont dairies. If the DairyFarm agent is certified organic, it receives the organic milk price for each CWT produced, as generated by the model’s economic projection engine, whereas it receives the conventional price if it is not certified organic. If the user set the model up to assume a premium price for pasture-based milk, that is also factored in to the gross monthly profit calculation.

Monthly Expenses

i. Feed Cost:

Expenses are comprised of feed costs plus other expenses, and are adjusted based on scale and management techniques. Feed costs are calculated by first establishing the percent of food that is produced on-farm. First, global parameters for the stocking rate of both an acre of silage production, and an acre of pasture production, are multiplied by an agent's cropland and forage land, respectively, and summed, yielding the number of animals able to be fed through on-farm production. This is then divided by the number of milkers, yielding the percent of necessary feed that is able to be produced on a given agent's acreage. If the agent is not using rotational grazing, it is assumed to be feeding a total mixed ration, which requires certain elements, such as protein feeds, vitamins, and minerals, to be purchased off-farm. The theoretical percentage able to be produced on farm is reduced by 30% to account for these necessary purchases. The total feed cost per month is then calculated by multiplying the proportion of feed that must be purchased off-farm by the feed cost per cow per month, as determined by the model's economic forecast engine, and finally by the number of milkers that must be fed. Note that the cost output by the economic forecast engine differs for organic versus conventional feed.

ii. Non-Feed Costs:

To simplify the model somewhat, non-feed expenses are not itemized as e.g. machinery, fertilizer, labor, etc., but rather calculated by multiplying the number of cows by a set global parameter representing average non-feed expenses per cow as of 2012. Once again, a compounding interest formula is used to calculate inflation, set at 2% as a baseline. Non-feed expenses are assumed to exhibit a +/- 20% stochasticity each month, since often some months will present relatively few expenses, whereas others will require the purchase of a new piece of machinery or other large capital investment. It has been reported that rotational grazing achieves much of its profitability from its lower level of per-cow expenses; primarily feed, but also including non-feed costs such as infrastructure and capital expenditures (Conneman et al., 2006). Therefore, agents using rotational grazing experience a reduction in non-feed expenses per month, defined by a global parameter set by default to 20%. Likewise, organic farms have been shown to exhibit higher non-feed costs per month (Wisconsin, 2013), and are therefore adjusted in a similar manner by a global parameter, set by default to a 15% increase.

Net Revenue, Income, Operating Capital, and Taxes

Net revenue is calculated monthly by subtracting feed and non-feed expenses from gross sales. The necessary portion of off-farm income in the cases of Retirement and Off-Farm Occupation farm typologies is used where possible to cover any farm losses. As long as operating capital is sufficiently high—defined as the total herd replacement cost—agents withhold up to 85% of net farm earnings as personal income, and invest any reminder back into the farm as operating capital. Year-to-date figures for sales, net revenue, income from farm revenue, and off-farm income are calculated. At the end of each year, these values are used to generate financial numbers for the preceding year. Taxes are also paid annually according to the prevailing Vermont tax rate for agricultural land use of $4.999 per acre (Vermont Department of Taxes, 2015).

Going Out of Business

Each year, a sub-function is executed that determines whether the farm agent is still financially viable. If an agent is in debt by a quantity that exceeds the value of its herd, despite having made all available financial adjustments, that farm goes out of business. It is disconnected from all peers, and subsequently appears on the map as a small gray dot.

3.3.4. Soil Transport Model

The Dairy Farm Transitions ABM includes a simple soil transport model that calculates both per-farm and total soil loss resultant from dairy farming activity within Franklin County. These values are based on the Universal Soil Loss Equation, which indicates that an acre of row crops typically loses approximately 14 tons of soil to runoff annually, whereas an acre of permanent pasture typically loses about 2 tons (VDEC, 2006; Stone, 1996). Soil transport was chosen as an indicator of ecological externalities because where soil runs off, it generally carries nutrients and chemicals with it. Therefore, the level of soil transport into waterways is positively correlated with nutrient loading of waterways, the reduction of which is a key agricultural policy aim in Vermont.

3.3.5. Policy Interventions

Three policy interventions are examined in this model. Two policy interventions are aimed at spurring farmer behavior change by capitalizing on peer networks, and the third is a direct government payment for reductions in soil loss. The peer network connectivity interventions do not offer financial incentives or disincentives to the farmers, but rather examine the way in which simply changing the patterns of interaction between farmers may influence their decision-making behavior and ultimately bring about positive change, both ecologically and financially.

Model Farm

Model farms were commonly established in the 19th century as centers of both agricultural research and education. Their methods were designed to be replicable or emulable, and served as learning hubs for the community, in order to enhance overall agricultural efficiency and productivity (Wade, 2002). The model farm system envisaged here would provide state funding to turn an existing farm achieving high success into a temporary model farm for the community. In exchange for this funding, their doors would be opened, and classes given, so that other farmers could replicate their successes.

If the user indicates the establishment of a county-wide model farm system at runtime, the Dairy Farm Transitions ABM model farm functionality is activated. For the purposes of this ABM, the model farm is simply the farm with the highest annual net revenue of all the farms in the county. If desired by policy aims, the user can stipulate that the model farm may not exceed a certain size, for example if a policy was primarily focused on the viability of small or mid-scale operations. Every five years, a function evaluates all the agents in the county and establishes one farm as the model farm, indicated with an “M” on the map. This farm is then used as a “model” for all the other farms in the county. Its production methods and annual revenue are opened to all other farms. If the model farm functionality is activated, when evaluating other farms to determine whom they should emulate, agents may use the model farm, in addition to those farms in their immediate peer network, to base their emulation decisions.

Farmer Field School

Farmer Field Schools (FFS) are a group-based approach by which to teach best management and other beneficial practices to farmers at a localized level. They rely on bottom-up, local knowledge rather than centrally-designed, “one size fits all” messaging, and often take place at the participants’ own farms. In this way, information may be shared between farmers concerning techniques that work for specific farm typologies, but may be glossed over by hegemonic recommendations (Sustainable Agriculture Information Initiative, 2010). Farmer Field Schools have proven effective in promoting the adoption of BMPs, most notably the technique of Integrated Pest Management (Feder, Murgai, & Quizon, 2004; Rebaudo & Dangles, 2013).

If the user indicates the establishment of a Farmer Field School at model runtime, the ABM’s Farmer Field School functionality is activated. Like the Model Farm, the user may stipulate that only farms under a certain size are allowed to participate in the field school, in order to target key farm demographics. The user may also establish the participation rate in the program. During several months out of each farming season, the ABM indicates that the field school is in session, and participants are temporarily linked together based on their participation in this program. During this time, field school participants may base their emulation decisions on other farmers in the field school program, in addition to those in their regular peer networks. At the end of the farm session, the linkages are culled, and they are regenerated with a new set of participants the following season.

Soil Loss Reduction Credit

The soil loss reduction credit is an incentive-based policy intervention that relies upon direct payments to individual farmers corresponding with land use changes that reduce negative environmental externalities. In this case, the indicator of negative externalities is soil loss, representative of nutrient and sediment transport into waterways. The user may elect to establish a soil loss reduction credit program at model runtime. Soil loss reduction is calculated by first obtaining a baseline soil loss per acre for all Franklin County dairy farms in the model at the model start date. If a farm's soil loss per acre is deemed to be below that value in any given year, the farm is paid annually based on its reduction in soil loss compared to the baseline. The user may specify the level of incentive payment, in U.S. dollars, per ton below baseline, at model runtime. Payments to individual farmers are factored in as a tax credit as part of the model's annual tax payment sub-function.

3.3.6. Model Data and Parameters

Fixed Parameters

A number of global parameters are set which are fixed in the model's code. Where real-world data was available, these parameters were determined using USDA and other dairy farm statistics. Other values were generated based on the best estimates of the modeler, and adjusted during the model calibration process. Table 4 below lists the model's fixed parameters, their values, and their sources where applicable.

Table 4: Fixed Parameters in the Dairy Farm Transitions ABM

Parameter	Value	Source
Average milk production per milker per month, CWT	13.6	McBride & Greene, 2009
Average milk production efficiency (% of optimum)	85%	BE
Average non-feed farm expenses per cow per month	$170	BE
Increase in non-feed expenses for organic farms	15%	Wisconsin, 2013
Reduction in non-feed expenses for grazing farms	20%	Conneman et al., 2006
Stocking rate for silage production, cows per acre	0.5	BE
Stocking rate for pasture forage, cows per acre	0.25	BE
Average price of an acre of agricultural land in Vermont	$3205	USDA NASS, 2012
Average tax rate of an acre of agricultural land in Vermont	$4.999	VT Dept. of Taxes, 2015
Average price of a milking cow in Vermont	$1500	BE
Organic certification costs per acre of corn production	$100	BE
Cost to transition one acre of pasture to corn production	$500	BE
Cost to transition one acre of cropland to pasture	$50	BE
Cost to transition one acre of pasture to rotational grazing	$50	BE
Average row-crop soil loss, tons per acre per year	14	VDEC, 2006; Stone, 1996
Average pasture soil loss, tons per acre per year	2	VDEC, 2006; Stone, 1996

Note: “BE” indicates that the value is a best estimate based on limited data availability.

Runtime-Alterable Parameters

At model runtime, users have control over many model parameters via a setup screen (see Appendix 2). By adjusting these parameters from baseline assumptions, users may analyze the way differing peer network, decision making, and economic forecast assumptions influence future dairy production trends, farm viability, and ecological indicators. Users may also alter parameters associated with the model’s public policy interventions. Table 5 below lists all of the parameters over which the user has control at model runtime. Where applicable, the source of the baseline value is also listed.

Table 5: Runtime Alterable Parameters in the Dairy Farm Transitions ABM

Parameter	Baseline Value	Source
Peer network initialization		
Number of dairy farms in Franklin County	187	USDA NASS, 2012
Peer network connection distance, miles	4	UA
Establish a peer herd size similarity limitation	True	UA
Peer herd size similarity factor	½ to 2	UA
Farmer decision making		
Frequency of emulation, years	2	UA
Probability of emulation	25%	UA
Probability of trial-and-error behavior	75%	UA
Economic forecast engine		
Annual feed cost inflation	2%	Gould, 2015a
Annual feed cost variance	5%	Gould, 2015a
Annual non-feed cost inflation	2%	BE
Annual milk price inflation	2%	Gould, 2015b
Conventional milk price variance per cycle	18%	Su & Cook, 2015
Organic milk price variance per cycle	5%	Su & Cook, 2015
Length of milk price variance cycle	3 years	Su & Cook, 2015
Price premium for grass-based milk	$0	UA
Policy interventions		
Establish model farm	False	UA
Establish model farm size limit	False	UA
Model farm size limit	100	UA
Establish farmer field school	False	UA
Farmer field school participation rate	15%	UA
Establish farmer field school size limit	False	UA
Farmer field school size limit	100	UA

Note: "BE" indicates that the value is a best estimate based on limited data availability. "UA" indicates that the value is an assumption set by the user to analyze differential model outcomes.

3.3.7. Model Calibration

Model calibration is an essential process in enhancing the predictive validity of an agent-based model's forecasts. Calibration of the Dairy Farm Transition ABM was performed both statically, through the agent initialization function, and dynamically, such that in the baseline condition model outcomes would match trends projected forward from historical USDA census of agriculture data. Model calibration work took the form of both crafting small sub-functions in the agent initialization function and adjusting farm-level economic and productivity parameters to bring model behavior in line with historical trends.

Initialization Function Calibration

The model was first calibrated such that at the default model runtime year, 2012, model outputs correspond with the latest census of agriculture data, which was also published in 2012. The census of agriculture assigns farms to one of eight typologies based on net farm income from operations, as well as whether the farm operator receives off-farm income (see Table 3 above). The DairyFarm agent initialization function uses these data to assign agents to one of these typologies based on the frequency each is observed in Vermont's agricultural sector. Associated distributions for number of milkers, overall acreage, land use characteristics such as the amount of acreage that is in crops versus forage production, and management characteristics such as organic certification status, are based on these USDA farm typology data. While simply utilizing these distributions and probabilities "out of the box" yielded a model state at runtime which roughly corresponded with statistical data on characteristics such as milk production, profitability, and expenses, some additional parameter adjustment was required to bring model outputs in further in line with on the ground observations.

Firstly, because the census of agriculture makes mention of the prevalence of rotational grazing only generally, and not with regard to either dairy farms specifically, or to specific farm typologies, a sub-function was added to assign agents which, after preliminary initialization, were deemed to roughly fit the characteristics of rotational grazing farms—namely a small milking herd, and a large reliance on forage, to be formally assigned to fit the more technical aspects of grass-based dairying, namely a forage acreage at least equal to 85% of their total acreage, and milking herd sufficiently small to receive at least 85% of its dry matter intake from the production level associated with their forage acreage. This yields an overall rotational grazing prevalence approximately equal to the observed prevalence of between 12% and 15% (Winsten, Parsons, & Hanson, 2000; Parsons, 2003; Winsten et al, 2011).

Secondly, after preliminary initialization, it was realized that organic certification was underrepresented in the model output, especially as concerns medium-sized and small dairy farms (USDA NASS, 2012c). Therefore, another sub-function was included which assigns an additional 5% probability that farms under 500 milkers will be certified organic.

Thirdly, it was realized that the average total acreage per farm—253 acres, as of 2012—was overrepresented by the model's initialization function prior to calibration (USDA NASS, 2012c). However, the distribution of acreages across farm typologies, as well as the distribution of land uses, were properly generated. In order to account for the distribution, as well as the acreage of land in each use, all initialized acreages are multiplied by a stochastically-generated factor between 25% and 50%. This calibration yields both the proper acreage, as well as the proper land use distribution, at model runtime.

Finally, after preliminary initialization, the proportion of farms with under 200 milkers was found to be underrepresented (USDA NASS, 2012b). Therefore, another sub-function was created to assign farms preliminarily initialized with between 200 and

275 cows in their milking herds to be reduced in number by 75. To maintain and hone the average number of milkers per farm as of 2012, which is 187 (USDA NASS, 2012c), the number of milkers per farm at preliminary initialization was increased by all farms by 25%. This calibration adjustment yields both the proper average number of milkers per herd, as well as the proper distribution of farms with under 200 head, at model runtime.

Dynamic Calibration

Once the model is running, three factors influence farm-level outcomes, and each needed to be calibrated to match model predictions in the baseline condition with historical data trends as the model progresses. These factors are the model's economic forecasting engine, the agents' decision making, and the farm-level economic model that determines production, costs, revenue, and income. To perform these calibrations, the model was set to its standard start date of January 1st, 2012, and programmed to end on January 1st, 2051. Model outcomes over this 50 year period were then used to calibrate the model dynamically.

The model's economic forecasting engine requires little calibration, as it relies purely on historical trend data to make its predictions. Baselines for inflation rates and cyclic variances of milk prices and feed costs were available in the literature (Su & Cook, 2015; Gould, 2015a; 2015b). The baseline assumptions of the model's economic forecasting engine could therefore be confidently programmed based on these data. The user may alter these baseline values if desired based on assumptions he or she may wish to address concerning future economic trends.

Likewise, agent decision-making behavior is also based on certain set information, modulated by user assumptions. For example, we know that farmers use both trial and error, and emulation, as strategies when making farm management decisions (Alchian, 1950; Chapter 2). While these values have been calibrated according to the best estimations of the modeler, it is not feasible based on current knowledge to set a universally accurate and verifiable rate of emulation, for example, since this is not easily measured, and does not appear in the literature to date. A primary aim of the Dairy Farm Transitions ABM is to probe these questions by allowing the user to alter farmer decision-making assumptions at model runtime in order to examine how peer networking and emulation behavior may influence decision-making patterns and model outcomes.

The third factor influencing farm-level outcomes—namely, farm-level economics—was therefore the primary means by which the model was calibrated dynamically to reflect existing trends under baseline conditions. While much of the data on dairy production is available in the literature (see Tables 4 and 5 above), some values had to be generated by fist establishing a best estimation, and then adjusting parameters until the system behaved according to established trends.

For example, while data on the average milk production per milker per month was known for various sized operations, upon plugging in these data, the overall county-wide milk production was somewhat higher than the census data indicate. To calibrate the theoretical to the observed milk production, a milk production efficiency coefficient was added, accounting for factors such as animal illness, mismanagement, and other means by which a farm's production may be less than optimal. By incrementally adjusting this value, and observing the resultant model outcomes, the county-wide milk production, and by extension the overall milk sales figures, was found to correspond with census data at a value of 85% of theoretical optimum production.

The other primary parameter that was dynamically calibrated was the value for average non-feed monthly farm expenses. While certain data do exist to guide this value, they were not found to be specific enough to accurately calibrate an ABM. For example, the census of agriculture includes data on farm expenses, but does not specify expense data for dairy farms alone, which may well have a different level of expenditure. Another datapoint put non-feed expenses per cow per month at around $205 for organic production (Wisconsin, 2013), but equivalent data were not forthcoming for conventional production, which is known to have lower non-feed costs. As a further complicating factor, reported non-feed costs generally include taxes, whereas the Dairy Farm Transitions ABM calculates actual taxes annually based on the agents' acreage. Once again, the model was dynamically calibrated by adjusting the level of non-feed expenses until agents' total annual expenditures were in line with total observed farm expenditures in Vermont, and the rate of dairy farm attrition in the county corresponded with the historical trends (USDA NASS, 1997c; 2002c; 2007c; 2012c).

Calibration Verification Experiments

To assess the efficacy of the calibrations discussed above, a series of experiments was conducted to gauge model outcomes. The key metrics used in the calibration process were (a) the number of operating dairy farms in Franklin County, (b) the percent of dairies certified organic, (c) the average number of milkers on a Vermont dairy, (d) the percent of farms with over 200 milkers, and (e) the annual average value of milk sales for a Vermont dairy. Between each calibration procedure, the model was run ten times consecutively, and outcomes from each trial were averaged. The graphs below show historical data from the 1992, 1997, 2002, 2007, and 2012 USDA censuses of agriculture, followed by outputs from the final calibrated model projecting forward in five-year increments to 2047. In the case of the organic certification percentage, USDA NASS data were not available on organic certification rates of dairy farms specifically, however recent studies have found the rate of organic dairying in Vermont to be 23% as of 2013 (Wisconsin, 2013). The only other data point that was available on the prevalence of organic-certified dairy farms in Vermont was a study indicating that in the early 1990s, there were only two organic dairies in the state (Parsons, 2010). Therefore, while it is known that rates of organic certification on Vermont dairies have increased greatly over the past 25 years, the shape of the adoption curve is unknown. For this reason, the calibration graph for organic production below does not extend backward in time as do the other dynamic calibration results.

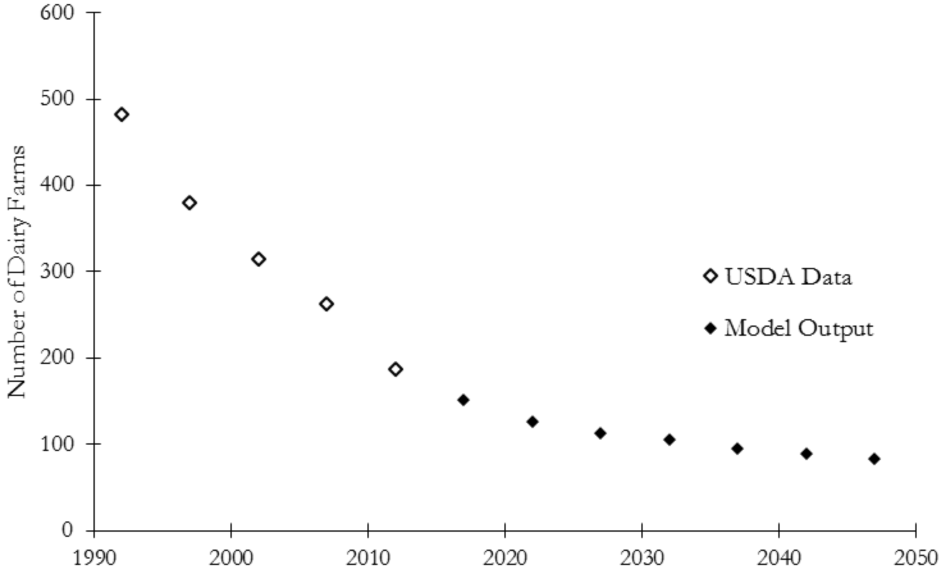

Figure 8: Number of Franklin County Dairy Farms (USDA NASS, 1997c; 2002c; 2007c; 2012c)

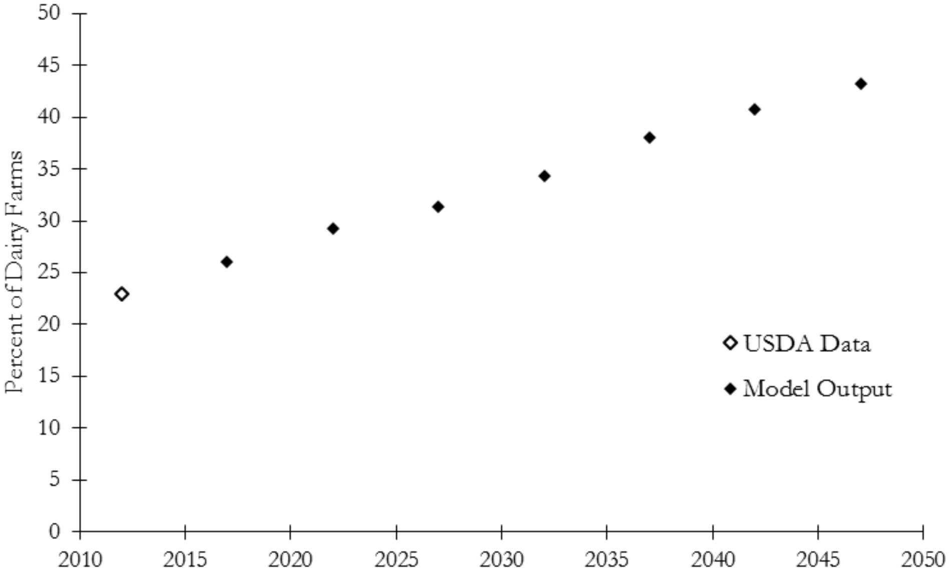

Figure 9: Percent of Vermont Dairy Farms Certified Organic (Wisconsin, 2013)

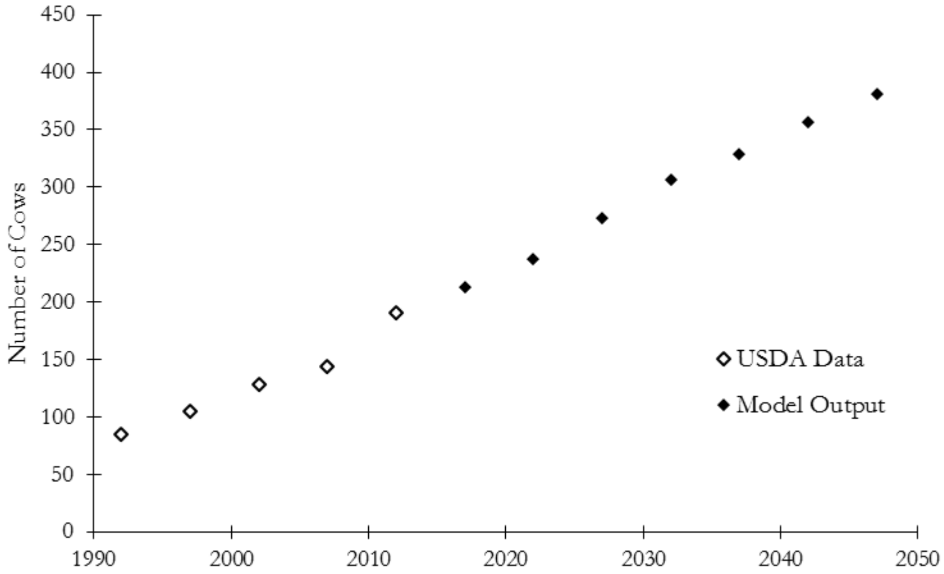

Figure 10: Average Number of Milkers on Franklin County Dairy Farms (USDA NASS, 1997c; 2002c; 2007c; 2012c)

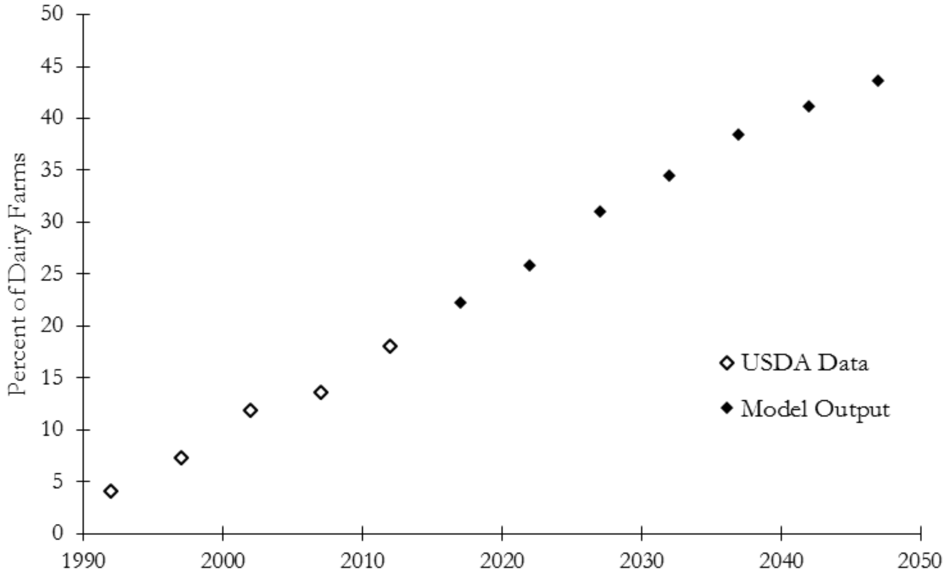

Figure 11: Percent of Vermont Dairy Farms with 200 or More Milkers (USDA NASS, 1992b; 1997b; 2002b; 2007b; 2012b)

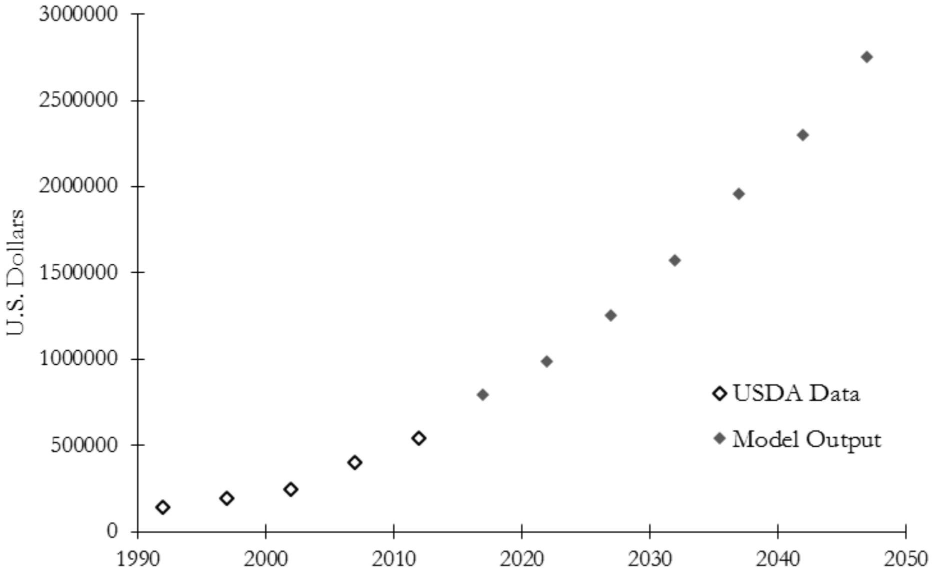

Figure 12: Average Annual Value of Milk Sales, all Vermont Dairy Farms (USDA NASS, 1992a; 1997a; 2002a; 2007a; 2012a)

"The Hollowing Out of the Middle"

An additional trend that was observed during model calibration is what has been called "the hollowing out of the middle", whereby agricultural production is increasingly becoming bifurcated into large-scale production operations, and smaller, "lifestyle" farms (Hicks, 2014). To examine whether this trend is borne out in the predictions of the Dairy Farm Transitions model, the number of DairyFarm agents, grouped by the size of their milking herds, was examined under baseline conditions. Agents were divided into three groups: under 100 milkers; 100 to 599 milkers; and 600 or more milkers. Once again, the calibration verification experiment consisted of averages from ten consecutive model runs under baseline assumptions. Figure 13 shows the model outcome, confirming that, indeed, the model accurately forecasts this trend.

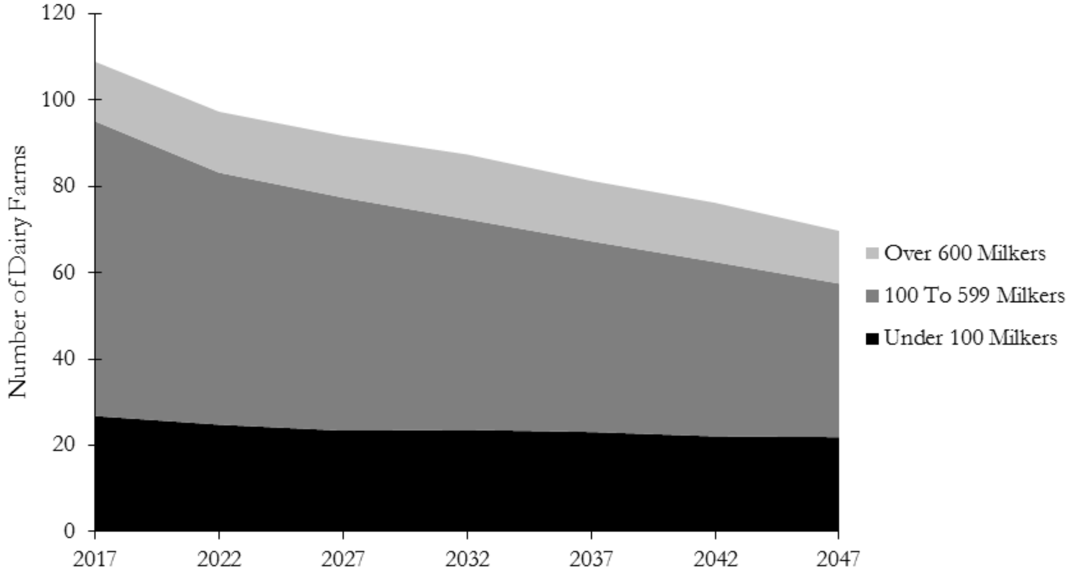

Figure 13: Number of Dairy Farms in Franklin County by Size of Milking Herd: DFTABM Output under Baseline Condition

Resiliency as a Function of Farm Scale and Management Techniques

Another interesting preliminary finding observed during the calibration process concerns the resiliency of the model's DairyFarm agents. Watching the data as the model runs, it quickly becomes clear that whenever a cost-price squeeze is generated by the model's economic forecasting engine, primarily driven by cyclic variations in the farm-gate milk price, the average net revenue that year will plummet, frequently resulting in average net losses at the end of that year. This phenomenon has been frequently noted in the literature, and only seems to be increasing in prevalence and severity (Su & Cook, 2015; Parsons, 2010; Thraen & McNew, 2007). Observing the model's statistical output, one notices that medium and large farms—those with over 200 milkers—are most heavily affected by these cost-price squeeze events. Observing the model map, it is common to see a handful of farms sell off assets and ultimately go out of business within about a year following these events. Generally, it is the mid-sized farms that are most negatively affected. Zooming in to the agent level, it becomes clear that the reason for this is that large scale farms have built up sufficient operating capital to “weather the storm” during the bad years. The mid-scale farms, by contrast, often do not have sufficient resources to stay in business. Small-scale DairyFarm agents do not succumb to cost-price squeeze events at the same rate as mid or large-scale agents, because (a), they are more likely to have off-farm income, and (b) they are more likely to be organic-certified and/or using rotational grazing, both of which have resiliency benefits over conventional dairy production. If the DFTABM is indeed modeling these dynamics accurately, digging into the mechanisms behind cost-price squeeze events and their associated farm attrition may prove a fruitful avenue of future research, as it could target leverage points by which medium-scale farm viability, in particular, may be addressed.

3.4. Experiment Setup

The primary aim of the Dairy Farm Transitions ABM is to analyze the effects of policies which may increase peer-to-peer learning upon both dairy farm viability and environmental conservation. Four indicators were established to evaluate the relationships between a series of nine model setup scenarios and model outcomes. Under each setup condition, results from a series of ten model runs were exported to a spreadsheet, where they were averaged across runs. All indicator values in the analysis below are based on these ten-run averages. For each setup scenario, the model was set to begin in 2012 and end in 2047, recording data every five years to correspond with USDA Census of Agriculture publication dates.

3.4.1. Economic and Ecological Indicators

The indicators chosen to measure the performance of the system are divided into two broad categories. The first two indicators address farm viability, and the final two address agricultural land use and its ecological ramifications, specifically regarding the link between agricultural runoff and nutrient loading of Vermont's waterways (State of Vermont, 2014).

Indicator 1: Number Dairy Farms in Franklin County at Model Termination

Attrition of Vermont's dairy farms has been a major theme in the industry for at least the past half-century (Parsons, 2010). If dairy farm viability is to be a serious policy goal, attrition must be examined and addressed. This analysis uses the number of dairy farms still operating in Franklin County at the conclusion of the experiment, the year 2047, as the primary indicator of farm attrition. Additionally, farms are segmented into three size groups (under 100 milkers; 100 to 599 milkers; and 600 or more milkers) in order to gain a finer-grained understanding of the characteristics of dairy farm attrition under each setup condition.

Indicator 2: Average Annual Net Revenue

The second indicator of farm viability used in this analysis addresses farm profitability. Specifically, the model outputs the average net annual revenue of the dairy farms operating in Franklin County in a given year. Because another major policy goal related to farm viability is the viability of small farms, the numbers are divided into two categories: farms with over 600 milkers, and farms with under 100 milkers. The relationship between these two numbers tells us something about which specific typologies of farms a given set of setup condition affects. Note that, by today's standards, profitability values may appear high. This is because the model accounts for inflation, and inflation affects revenue just as it does input costs.

Indicator 3: Rates of Organic Certification and Rotational Grazing

The third indicator output by the model concerns land use and farm management. Specifically, two management techniques were addressed, due to their known impacts on ecological externalities and farm viability: organic certification and the use of rotational grazing. By examining how these rates are affected by setup conditions, we may explore the connections between peer-to-peer connectivity, incentivization, and adoption of these techniques.

Indicator 4: Soil Loss

The fourth indicator is a direct measure of the effect of setup conditions on ecological outcomes. As discussed above, soil loss was chosen due to its close ties with nutrient loading of waterways. Soil loss as a result of dairy farming activities is calculated both at a county-wide level, and in relation to a number of other factors. This finer-grained approach is necessary because of the inherent positive correlation between farm attrition and reduction in soil loss. At first glance, lower total soil loss may be viewed as inherently positive, but this is not necessarily so if it entails a drastic reduction in the number of farms still in business. Indicators of farm viability must therefore be weighed against indicators of ecological impact with a critical eye. For this reason, in addition to total soil loss at the county level, three other indicators of soil loss are used in this analysis: soil loss per farm; soil loss per acre; and soil loss per CWT of milk produced. By examining this broad spectrum of soil-loss indicators, we may better understand the interrelationships between farm viability, farm management techniques, and agricultural land use; and the effect each setup condition has on these outcomes. To facilitate easy comparison between the evaluated scenarios, soil loss data are reported below as a change from the 2017 baseline value.

3.4.2. Treatment Scenarios

In addition to the baseline control treatment, eight other treatments were analyzed. Broadly speaking, these treatments vary according to three basic categories: the level of peer-to-peer connectivity; the frequency with which agents emulate their peers; and the presence or absence of a soil loss reduction tax credit. All parameters were left at baseline levels in each treatment with the exception of those indicated by the following descriptions.

<u>Level of Peer-to-Peer Connectivity</u>

General Connectivity

The level of generalized peer to peer connectivity is varied by simply altering the peer network connection distance at runtime. While the model operationalizes connectivity based on distance, in reality, spatially-disparate networks may exist. However, at a conceptual level, increasing the model's connectivity distance may be conceived as simply increasing the average number of peers to whom each agent is connected. Two general connectivity scenarios were analyzed here: a baseline connectivity scenario, in which the peer network connection distance is 4 miles; and a high-connectivity scenario, in which the peer network connection distance is increased to 20 miles.

Targeted Connectivity

Targeted connectivity is focused specifically on connecting small farms to one another. Targeted connectivity treatments are operationalized using both the model farm and the farmer field school functionality. Whereas neither of these are enabled in the baseline treatment, in high targeted connectivity treatments, both are enabled. Size limits of 150 milkers are placed on both model farm selection and eligibility to participate in the farmer field school. Under this scenario, all farms under 150 milkers participate annually in the farmer field school. Farms participating in the field school may use one another as potential emulable peers. All farms may use the model farm as an emulable example, provided they meet the baseline herd size similarity requirement.

Level of Peer Emulation

Assumptions concerning the level of peer emulation are operationalized by altering both the emulation frequency, and the emulation probability. To compensate, in high emulation treatments, the level of trial-and-error behavior is reduced. Three emulation scenarios were used in this analysis. In the baseline scenario, 25% of agents choose to emulate a better-performing peer once every two years, and 50% use trial-and-error each year. In the medium emulation treatments, 50% of agents choose to emulate a better-performing peer once every two years, and 25% of agents use trial-and-error each year. In the high emulation treatments, 75% of agents choose to emulate a better-performing peer each year, and 25% of agents use trial and error each year.

Soil Loss Reduction Credit

Whereas in the baseline scenario, the soil loss reduction credit functionality is disabled, in the soil loss reduction credit treatments (indicated as “credit” in the outcome data to follow), a soil loss reduction payment of $25 for each ton of soil a farm keeps out of waterways (calculated in relation to 2012 baseline soil loss per acre) is issued once per year as a tax credit.

Scenarios Evaluated

Elements from the three preceding categories were combined into eight distinct treatments, in addition to a baseline control treatment. Outcomes from these treatments were then evaluated with regard to the indicators discussed above. The treatments evaluated are as follows:

1. Baseline
2. Credit Only
3. Medium Emulation Only
4. High Emulation Only
5. High Emulation + Credit
6. High Emulation + High General Connectivity
7. High Emulation + High General Connectivity + Credit
8. High Emulation + High Targeted Connectivity
9. High Emulation + High Targeted Connectivity + Credit

3.5. Experiment Results

The following graphs show the model's output under each of the treatment conditions described above. Figure 14 pertains to indicator 1, Figure 15 to indicator 2, Figure 16 to indicator 3, and Figures 17-20 to indicator 4. Implications of these results are discussed in the Conclusions section below.

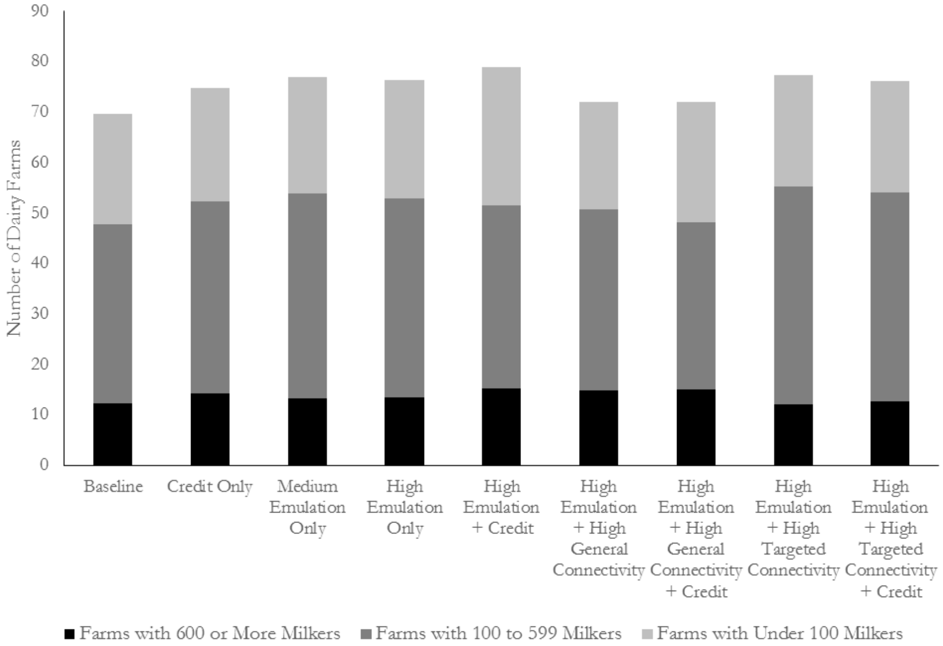

Figure 14: Number of Dairy Farms in Franklin County at 2047 Model Termination

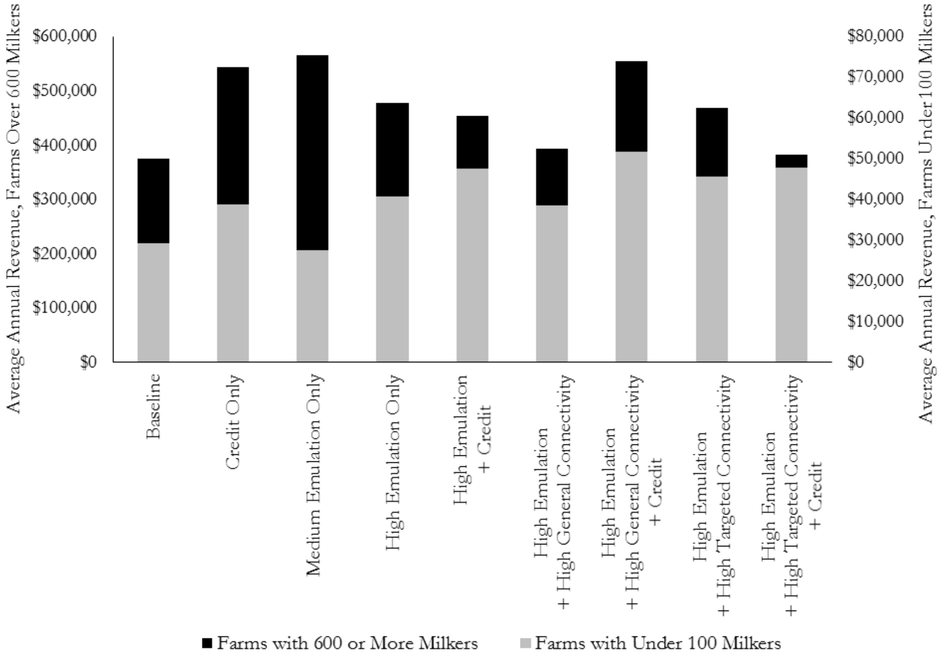

Figure 15: Annual Net Revenue of Farms with 600 or More Milkers and Farms with Under 100 Milkers, Average 2012 through 2047

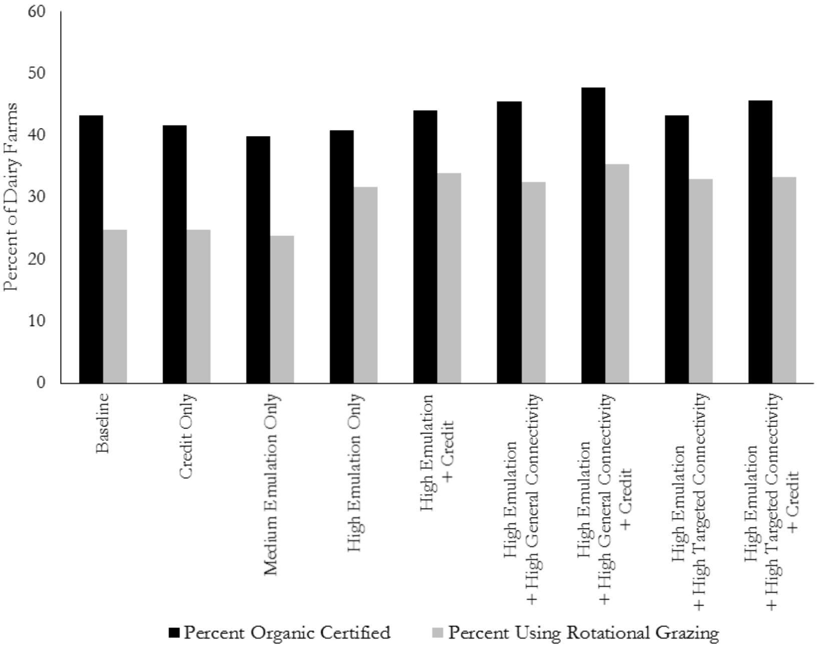

Figure 16: Rates of Organic Certification and Rotational Grazing at 2047 Model Termination

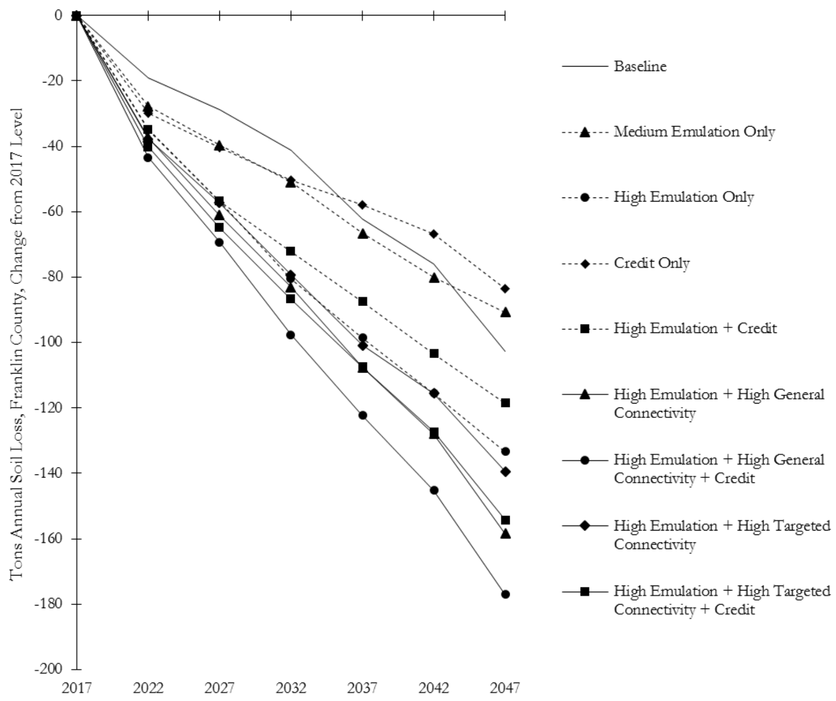

Figure 17: Annual Total Soil Loss, Franklin County, Average 2012 through 2047

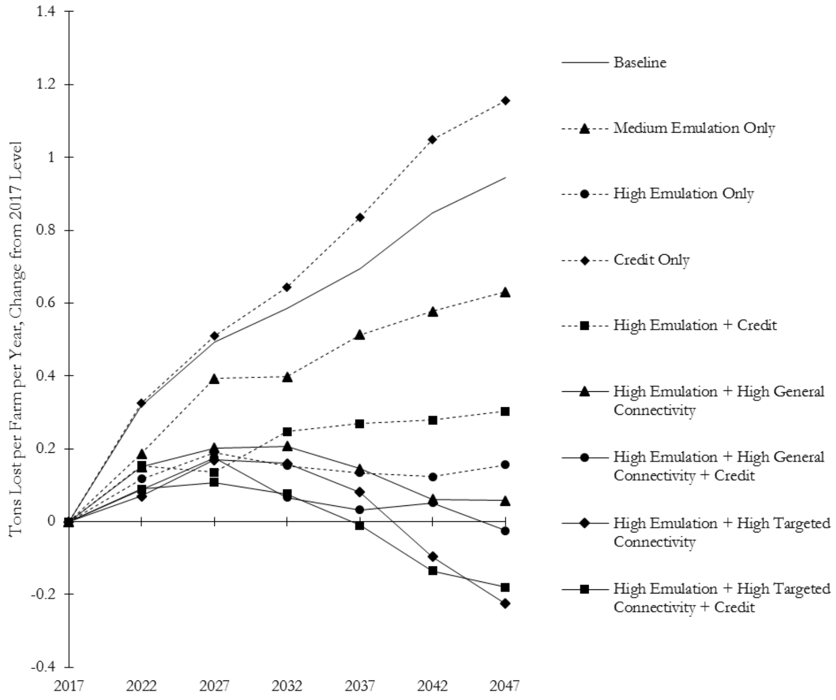

Figure 18: Annual Soil Loss per Farm, Average 2012 through 2047

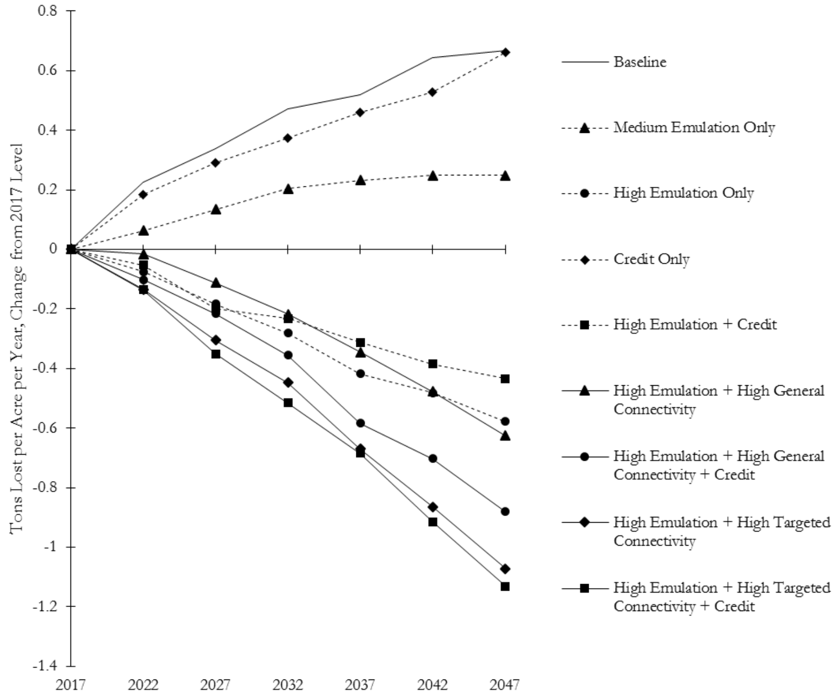

Figure 19: Annual Soil Loss per Acre, Franklin County, Average 2012 through 2047

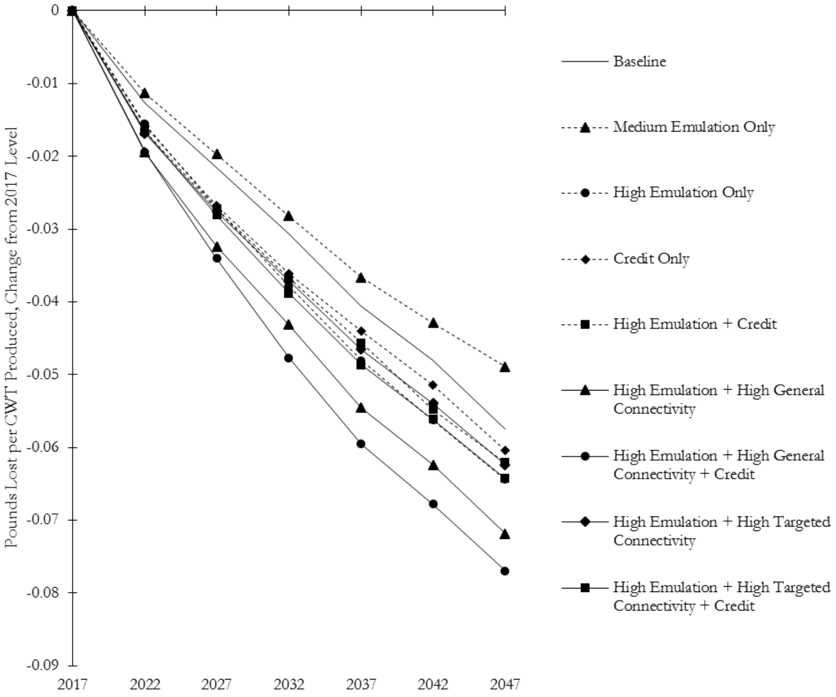

Figure 20: Soil Loss per CWT of Milk Produced, Franklin County, Average 2012 through 2047

3.6. Conclusions

3.6.1. Analysis by Indicator

Indicator 1: Number of Dairy Farms in Franklin County at Model Termination

Under the baseline treatment, dairy farm attrition reached its highest rate, with an average of only 69.7 farms left standing at the end of the model runs (Figure 14). Interestingly, the lowest rate of attrition was achieved under the High Emulation + Credit treatment, in which an average of 78.9 farms were still in business in 2047. This indicates that perhaps a smaller peer network may have certain advantages over networks of higher degree, provided farmers readily capitalize on the experiences of their peers. Indeed, observing agent behavior on the model's main screen map, it is common to see tightly-connected, localized groups of farms learn from one another readily, ultimately adapting their farm management practices until many achieve a sustainable model of profitability. If an agent were getting mixed signals from a larger, and perhaps more heterogeneous peer group, it may succumb to rising economic cost-price squeeze pressures before it is able to adapt.

Whereas the High Emulation + Credit treatment seems to have exacerbated or at least continued the trend of "hollowing out the middle," the treatments with the lowest attrition amongst mid-sized farms were the two High Targeted Connectivity treatments. One possible explanation for this is that the targeted connectivity initially helped small farms to find a sustainable balance leading to steady profitability. This may have been driven by their widespread use of management methods like organic certification and rotational grazing, which can bolster profitability and resiliency on smaller-scale farms.

If these small scale farms found success, they may have incrementally grown into successful mid-scale farms. This analysis suggests that one way to solve the “hollowing out of the middle” problem is to give smaller farms the opportunity to thrive and grow.

Despite the minor differences discussed in the preceding paragraphs, a key takeaway from these dairy farm attrition data is that, no matter what the policy intervention, a good deal of dairy farm attrition is bound to take place. This inconvenient truth is a product of the inherent economic realities of dairy farming, which are only becoming more challenging as margins narrow and, crucially, as fluctuations in the farm-gate milk price lead to periodic cost-price squeezes, as will be discussed in the resiliency section below.

Indicator 2: Average Annual Net Revenue

Whereas rate of attrition is a valuable overall indicator of farm viability, examining farm profitability provides a closer look at what’s going on behind the scenes, revealing some of the nonlinearities and interdependencies at play in such a complex system. Model outputs show that the highest average profitability for large farms was achieved under the Medium Emulation Only treatment (Figure 15). It would appear that, because increasing herd size and purchasing more land are prominent features of the model’s trial-and-error function, for farms that draw their profitability largely from scale, a certain degree of simple “get big or get out” decision-making is beneficial. However, this is by no means a universal mantra: the baseline treatment, which relies even more heavily on trial-and-error, and thus on scaling up, yields the lowest level of profitability for large farms, and the second-lowest for small farms: some adaptation is necessary.

Interestingly, while the High Emulation Only treatment increases per-farm revenue for small farms over the Medium-Emulation Only treatment, it decreases the average revenue for large farms. Thus, it would appear that the relationship between emulation frequency and farm profitability, all else being equal, may peak at a certain point, and that this point is higher (more emulation) for smaller farms, and lower (more simple increase of scale) for larger operations. The precise point of this peak for both large and small farms is an area for future study.

For small farms, the highest level of profitability was achieved under the High Emulation + High General Connectivity + Credit treatment. Overall, as noted above, for small farms, the highest average profitability was consistently achieved in treatments which included high emulation, to the extent that, for small farms, no treatment without the High Emulation scenario outperformed any which did include it. These results suggest that emulating peers to achieve a financially-balanced management style is critical for small farm viability.

As echoed in the preceding section, the effect of high connectivity on profitability is less clear. Increasing the number of connections in a general sense appears in some contexts to actually slightly reduce average profitability. However, increasing connectivity selectively, as is done in the High Targeted Connectivity scenario, does appear to enhance small farm profitability. This result may be due to the effect of too much heterophily, which has been hypothesized to inhibit diffusion of innovation in certain contexts (Rogers, 2010). This may be explained by considering the case of multiple equilibria, in which two peers are profitable to a similar degree, yet each of which draws its profitability from opposing management styles. A peer may become caught in the middle, adjusting first one way, and then the other, and never arriving at one of the equilibria. If a network is smaller and more homogenous, it is more likely that an agent will simply incrementally emulate a single highly-profitable peer, eventually arriving at a similar sustainably-profitable management style.

In general, the Soil Loss Reduction Credit scenario also positively impacted small farms over corresponding treatments which did not include the credit, probably because small farms are more likely to be grass-based, and thus are more likely to receive a payment. The credit had more ambiguous effects on large farms, sometimes increasing profitability, while other times decreasing it. The seeming ambiguity in these data suggests that the establishment of a credit for reducing environmental externalities may exhibit complex interactions with other factors, and ultimately these nonlinearities may make predicting the effects of such a scheme difficult or impossible. For example, it may be the case that payments to farmers to reduce environmental externalities simply enable them to grow larger, ultimately having the opposite of the intended effect. This mechanism is another rich area for further study.

Indicator 3: Rates of Organic Certification and Rotational Grazing

In all treatments, the model predicts a sizable rise in the prevalence of both organically-certified dairy farms and farms using rotational grazing (Figure 16). Tracking the agents as the model runs, it becomes clear that this is largely due to the inherent increase in resilience associated with these methods. In the case of organic production, this resilience is primarily driven by the relatively-lower fluctuations in farm-gate milk prices, which tended to wipe out many conventional operations, especially the mid-scale farms. Thus, despite both higher feed costs, higher non-feed costs, lower milk production, and the price or organic certification, organic farms in the model tended to last. Their peak profitability was not as high as their conventional counterparts, but they were resilient.

Similarly, while they achieved only modest levels of overall profitability, rotational grazing farms often had the highest levels of per-cow profitability, a phenomenon that has often been noted in the literature (Kriegl, 2005; Benson, 2009). These per-cow profits were driven by lower costs, both feed and non-feed. Thus, rotational grazing farms were generally not as susceptible to the “cost” part of the cost-price squeezes, and were more resilient as a result.

The prevalence of organic certification consistently peaked at between 40% and 48%, and did not seem to be strongly affected by the treatments assessed here. However, the High Emulation treatments consistently facilitated higher levels of rotational grazing adoption, with the High Emulation + High General Connectivity + Credit treatment achieving the highest level of adoption, at 35.4%. Since rotational grazing is a technique used primarily by small farms, and we have already seen that High Emulation treatments correlate with small farm viability, these results are not surprising.

Indicator 4: Soil Loss

In general, soil loss outcomes, as calculated by the Universal Soil Loss Equation, exhibited relatively high sensitivity to the treatments assessed. Under the baseline treatment, total soil loss dropped from about 470 tons per year to about 365 tons per year, a decrease of 105 tons annually (Figure 17). This result is not surprising, as it is driven primarily by the aforementioned attrition inherent in Vermont’s dairy industry. While this represents a positive from the standpoint of environmental conservation, as discussed above, this must be weighed against the parallel goal of maintaining a vibrant dairy farm economy in the state. The question therefore becomes: which treatment maximizes dairy farm viability, while simultaneously minimizing the environmental externalities associated with dairy production?

Examining Figure 17 also reveals that the Credit Only and the Medium Emulation Only treatments actually increased predicted total soil loss as of 2047 over the baseline treatment. This is perhaps unsurprising, since both of these treatments also decreased attrition over baseline to some extent (Figure 14), while increasing profitability for large farms in particular (Figure 15). These treatments also performed poorly on a per-farm, per-acre, and per CWT basis. These results suggest that an unintended side-effect of increasing large farm profitability may be to also increase sediment transport, compounding rather than curtailing Vermont’s water quality woes. The probable mechanism here is that increased profitability of large operations facilitates their capacity to increase scale to an even greater degree. Since these farms generally produce large acreages of silage crops, with high associated soil loss, an increase in their average size will naturally tend to increase overall soil loss.

If the treatments that primarily promote the profitability of large farms may actually exacerbate soil loss, what about the treatments that enhance the viability of small and medium-sized farms? Is it possible to both decrease farm attrition, yet also decrease soil loss over baseline? The preceding sections have demonstrated that high rates of emulation are generally financially beneficial for small farms. It was also shown that targeted connectivity has advantages for reducing attrition among mid-scale producers, and for enhancing profitability among small-scale producers. Further, it was suggested that the two may be intertwined, as high profitability on small-scale farms may enable them to grow into mid-scale farms. Examining the soil loss results on a per-cow, per-acre, and per CWT basis, we see that the treatments which generally yield the most reduction in soil loss are those that include the Targeted Connectivity scenario, in addition to the High Emulation scenario (Figures 18-20).

Perhaps the most important of the soil loss data presented here is soil loss per farm (Figure 18). Low per-farm soil loss means more farms can exist on the landscape given a set Total Maximum Daily Load. It is this statistic, more than any other, which joins the parallel goals of minimizing attrition, enhancing profitability, and limiting environmental externalities. The first striking realization is that the six treatments with the best performance all include the High Emulation scenario. Coupled with the farm profitability analysis above, which indicates that the High Emulation scenario also bolsters small-farm profitability, it may be generally concluded that efforts to increase emulation-based decision-making, especially among Vermont’s small and mid-sized dairy operators, may be a valuable means by which to positively influence both dairy farm viability and ecological stewardship.

Examining the curves for the High Emulation + High Targeted Connectivity treatments, which yield the lowest average soil loss per farm at the end of the model runs, one thing becomes immediately apparent: change takes time. In every treatment, the average soil tonnage lost per farm increases to some extent, probably a continuation of the historical growth in average dairy farm size. It is only after agents begin to establish more-sustainable production methods, both economically and ecologically, that the curve begins to bend, ultimately reducing soil losses by over a ton per farm per year over the baseline treatment. Yet, unlike some of the other treatments, this ecological success does not come at a cost to farm viability. The High Emulation + High Targeted Connectivity treatments come in slightly below the middle of the pack for overall soil loss in Franklin County, but this is because they offer some of the lowest levels of attrition of any treatment, especially where small and medium-sized farms—Vermont's most vulnerable farm populations—are concerned.

3.6.2. Limitations of the Model

One of the benefits of computer simulations as research tools is that they may undergo revisions and further development in order to enhance both their functionality and their predictive validity. With this in mind, the current version of the DFTABM may aptly be described as a "beta release." While much care was taken to make the model as accurate as was feasible by a single modeler in a set timeframe, the model and corresponding experiments described in this chapter do have a number of limitations.

Firstly, while real-world data was utilized to a large extent in model parameterization, a significant number of best estimates were required to develop a functional economic forecasting engine and farm-level profit and loss calculation function (see Tables 4 and 5). In future iterations of the DFTABM, the accuracy of these estimates should be further verified and enhanced through additional consultation with dairy industry experts. By viewing the predictions of the current version of the model, such experts may offer suggestions upon which to base revisions to these functions.

A second, similar limitation concerns assumptions about farm management decision-making, as encoded in the DairyFarm agent statechart. While a certain amount of direct farmer input was solicited and utilized to encode agent decision heuristics (see Chapter 1, section 1.4.2), in the current version of the model, heuristics were also inferred from macro-level trends in the industry, and sanity-checked based solely on the experiences and assumptions of the modeler. For example, while the general propensity for farms to increase in average size is a robust data-driven observation, the precise actions farmers may take to effect those results—for example, the average number of milkers a farm would reasonably add in any given year—were largely based on the necessity to calibrate the model to fit macro-level data trends. Similar agent decision heuristic assumptions include the degree to which a farmer may alter his land-use in any given year, and the frequency with which farmers may alter their production methods based on trial-and-error versus peer emulation. To enhance the precision of such agent-level heuristics, farmers would need to be consulted in greater depth, for example through a survey instrument, or by conducting additional interviews during which the DFTABM may be further ground-truthed.

Thirdly, the current version of the model includes only a rudimentary soil transport model. In reality, many more factors go into determining levels of runoff from any given farm site. These factors include soil type; the grade of fields; proximity to waterways; and the use of other BMPs not currently simulated by the DFTABM such as buffer strips, field rotation, manure injection, or cover-cropping. Additionally, an explicit model of phosphorus transport, which accounts for both sediment-bound P and soluble P runoff, would add a great deal of value to a model which is intended in part to address phosphorus loading of waterways. The "phosphorus index" is a farm planning tool which may aid implementation of a phosphorus transport sub-model within the DFTABM. Implementation should be conducted in close coordination with experts in soil science, and ideally calibrated to include the impacts of the BMPs discussed above.

Fourthly—in order to allow for comparisons between existing agri-environmental policies, policies currently being proposed by industry experts, and experimental peer-based policies—additional experimental treatments should be run. For example, some dairy farm economists advocate eliminating existing milk subsidies in order to correct macroeconomic imbalances in the industry, leading to higher farm-gate milk prices and ideally increasing farm profitability. Scenarios could also be evaluated which reflect current agri-environmental policy strategies such as increased use of cost-sharing programs and stricter enforcement of Vermont's Accepted Agricultural Practice (AAP) regulations (see Chapter 1, section 1.3.5).

A fifth limitation concerns the structure of farmer networks generated by the model. In its current iteration, the model assumes a simple distance-based peer network among farmers, modulated by a consideration of farm size similarity. However, in reality, farmer peer networks are likely based on other factors such as ideological similarity, similarity of production methods, and kinship, in addition to distance and farm size. The inclusion of more complex network connectivity algorithms would likely lead to more homophilic baseline peer networks, predicated upon the voluntary selection of peer connections observed in the real world. In order to ascertain data pursuant to more accurate farmer peer network models, additional survey research would likely have to be conducted.

Finally, the model experiments described here represent only one kind of experiment that can be run using an agent-based model, and the simplest kind, at that. While the model was run multiple times for each treatment, and the results averaged across runs, a more formal process of sensitivity analysis would ensure that the model results are robust and that no single model parameter causes undue uncertainty in the experimental results. Secondly, parameter variation experiments should be conducted in order to assess the impact of altering individual parameters in narrow increments across a wider range. Parameter variation would allow for an experiment which, for example, determined more precisely the level of network homophily which produces the best peer learning dynamics. Such an experiment would likely prove valuable to both network theorists and practitioners. Due to limitations of the software used to run the experiments presented in this paper, neither formal sensitivity analysis nor parameter variation experimentation were possible, necessitating the use of the somewhat more rudimentary experimental methods described above.

3.6.3. Final Remarks

Overall, although the results presented here are complex, and there are still many lessons to be learned by creating new versions of the software, further calibrating the model, and analyzing new scenarios, a few overarching themes emerge. First of all, it has been demonstrated that the performance-based incentives like the Soil Loss Reduction Credit may have ambiguous effects due to the difficult-to-predict nonlinearities that emerge. For example, inclusion of the credit on top of high connectivity and emulation scenarios slightly increased per-farm soil loss, while slightly decreasing per-acre soil loss. It also generally improved small-farm profitability, but may have negatively impacted large-farm profitability. And perhaps most crucially, implementing the credit program in the absence of other interventions actually increased total soil loss over baseline conditions. Given that the cost of the Soil Loss Reduction Credit program in these model runs was often in excess of $1.5 million per year, in this context, at least, it would appear that such direct performance-based subsidy programs probably do not represent the best use of state funding.

Secondly, this study concludes that enhancement of peer-to-peer learning among smaller farmers, and encouragement of emulation between peer farmers, may represent a valuable leverage point to bend the curves of both dairy farm attrition and mitigation of agricultural runoff in the right direction. Emergent self-organization resulting from the peer-to-peer learning of DairyFarm agents in the DFTABM can be clearly seen on the map as the model runs. Much like in the real world, multiple equilibria appear to exist under which farms can achieve sustainable profitability. In the DFTABM, this often takes the form of (a) scaling up, (b) maintaining a mid/large scale, but certifying organic, or (c) remaining small and adopting rotational grazing. In general, after the simulation runs for about 20 years, the majority of agents that have not succumbed to economic pressures fall into one of these three “equilibrium” categories. Additional self-organization in the model manifests itself through the structure of the embedded peer network. Since the default network typology in the DFTABM is distance-based, often, pockets of spatially-neighboring farms will arise which all trend toward one of the three equilibria listed above, each learning from the others until all have achieved a sustainable equilibrium, a case of “a rising tide floats all boats.” This effect is especially apparent when economic assumptions are set such that cost-price squeeze events are especially severe; agents must quickly adapt to their environment if they are to survive. Qualitative evidence suggests that peer learning plays a large role in many farmers’ decisions to adopt grass-based dairy farming (see section 3.3.2). Research also shows that peer-based solutions like grazing networks, model farm programs, and farmer field schools can stimulate the diffusion of beneficial innovations (Wade, 2002; Feder, Murgai, & Quizon, 2004; Rebaudo & Dangles, 2013). The DFTABM begins to build up the theoretical foundations underlying these qualitative observations, lending evidence to support the validity of peer-based policies as an avenue for positive change.

By harnessing and leveraging the nexuses where farmer self-interest intersects state ecological interests, and then working to spread knowledge of those solutions—either through existing networks, or by working to build new networks—both attrition and ecological externalities may be reduced. Of prime importance is that, unlike incentive and regulatory-based policies, there are no direct payments to participants, and no cost of enforcement associated with peer-based programs, yet they may be just as effective. The DFTABM demonstrates the truism that, all else being equal, agricultural runoff will be reduced if farms simply go out of business, as many of them might if harsh fee-based regulatory policies are enacted. However, the consequences of that result will likely have implications for rural communities and the tourist dollars that are generated by a flourishing working landscape. It is also important to consider that if farmers sell off land, and that land is eventually developed, water quality may ultimately take an even bigger hit. On the other hand, encouraging a deliberate process of adaptation may allow Vermont to “have its cake and eat it too,” spurring a proliferation of sustainably-profitable dairy farms while also meeting water quality goals.

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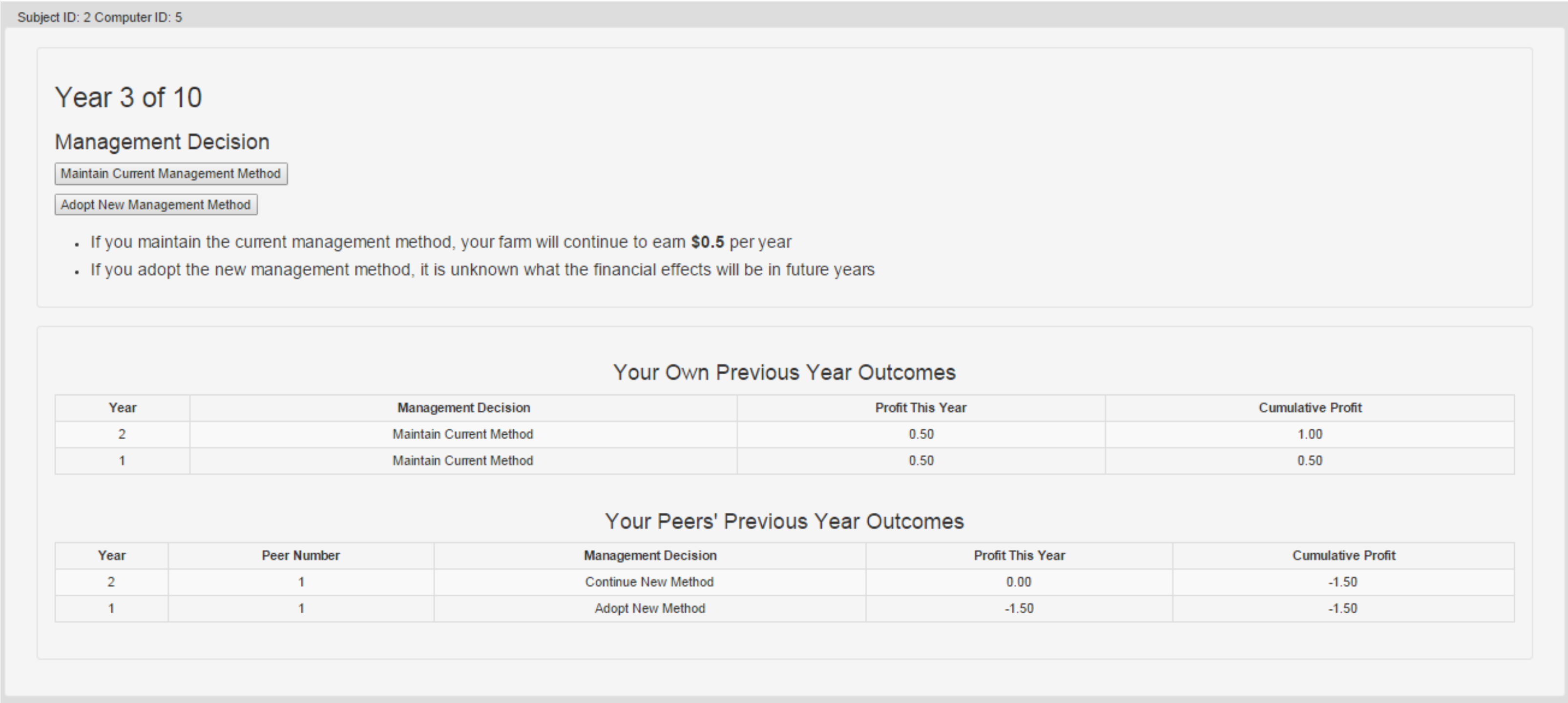
APPENDIX 1: BEHAVIORAL ECONOMICS GAME SCREENSHOT



Subject ID: 2 Computer ID: 5

Year 3 of 10

Management Decision

- If you maintain the current management method, your farm will continue to earn **$0.5** per year
- If you adopt the new management method, it is unknown what the financial effects will be in future years

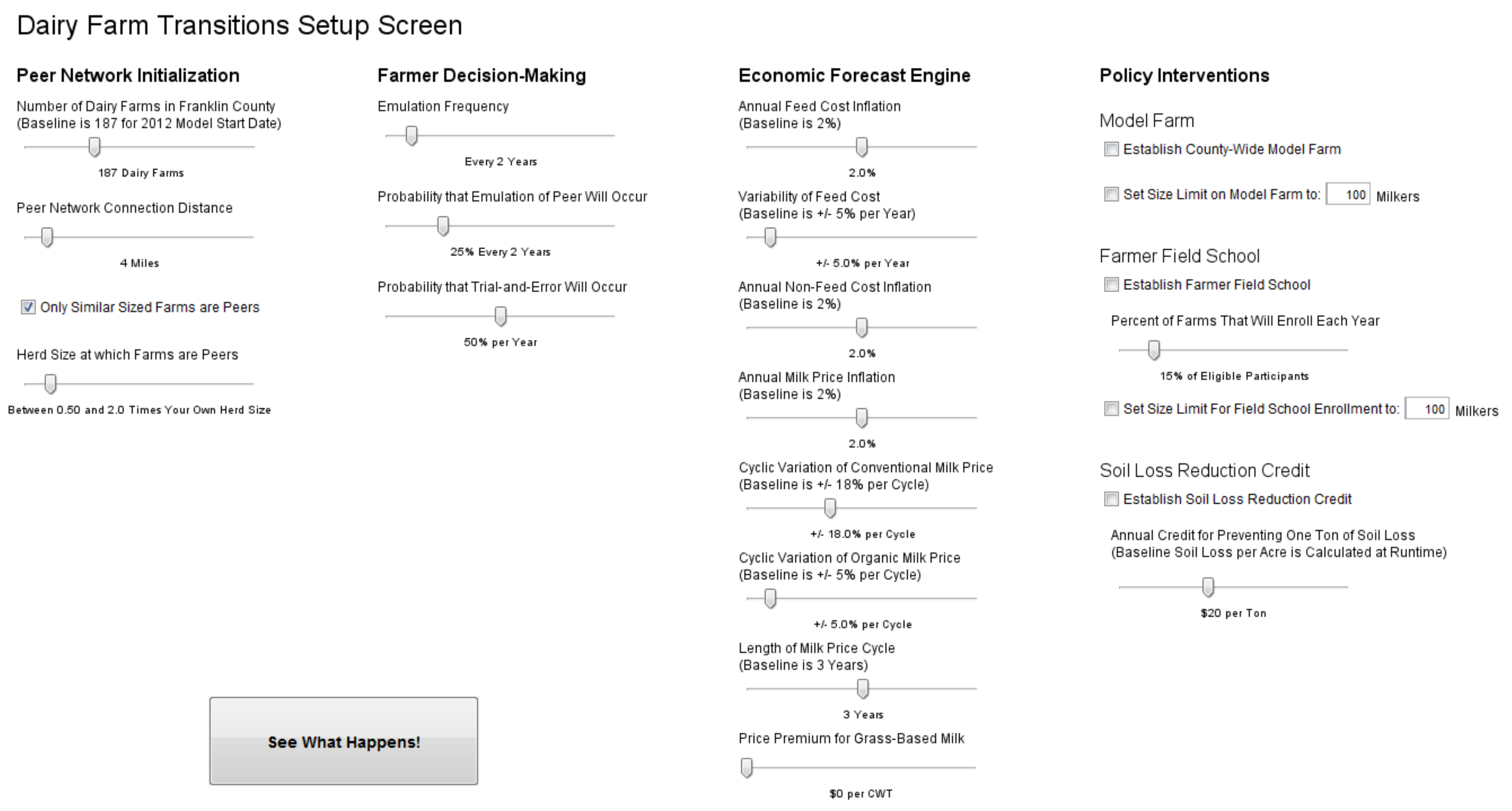
Your Own Previous Year Outcomes

Year	Management Decision	Profit This Year	Cumulative Profit
2	Maintain Current Method	0.50	1.00
1	Maintain Current Method	0.50	0.50

Your Peers' Previous Year Outcomes

Year	Peer Number	Management Decision	Profit This Year	Cumulative Profit
2	1	Continue New Method	0.00	-1.50
1	1	Adopt New Method	-1.50	-1.50

APPENDIX 2: MODEL SETUP SCREEN



Dairy Farm Transitions Setup Screen

Peer Network Initialization

Number of Dairy Farms in Franklin County (Baseline is 187 for 2012 Model Start Date)
187 Dairy Farms

Peer Network Connection Distance
4 Miles

☑ Only Similar Sized Farms are Peers

Herd Size at which Farms are Peers
Between 0.50 and 2.0 Times Your Own Herd Size

Farmer Decision-Making

Emulation Frequency
Every 2 Years

Probability that Emulation of Peer Will Occur
25% Every 2 Years

Probability that Trial-and-Error Will Occur
50% per Year

Economic Forecast Engine

Annual Feed Cost Inflation (Baseline is 2%)
2.0%

Variability of Feed Cost (Baseline is +/- 5% per Year)
+/- 5.0% per Year

Annual Non-Feed Cost Inflation (Baseline is 2%)
2.0%

Annual Milk Price Inflation (Baseline is 2%)
2.0%

Cyclic Variation of Conventional Milk Price (Baseline is +/- 18% per Cycle)
+/- 18.0% per Cycle

Cyclic Variation of Organic Milk Price (Baseline is +/- 5% per Cycle)
+/- 5.0% per Cycle

Length of Milk Price Cycle (Baseline is 3 Years)
3 Years

Price Premium for Grass-Based Milk
$0 per CWT

Policy Interventions

Model Farm

☐ Establish County-Wide Model Farm

☐ Set Size Limit on Model Farm to: 100 Milkers

Farmer Field School

☐ Establish Farmer Field School

Percent of Farms That Will Enroll Each Year
15% of Eligible Participants

☐ Set Size Limit For Field School Enrollment to: 100 Milkers

Soil Loss Reduction Credit

☐ Establish Soil Loss Reduction Credit

Annual Credit for Preventing One Ton of Soil Loss (Baseline Soil Loss per Acre is Calculated at Runtime)
$20 per Ton

APPENDIX 3: MODEL MAIN VIEW