Title: Modeling the effect of social networks on adoption of multifunctional agriculture

Abstract: Rotational grazing (RG) has attracted much attention as a cornerstone of multifunctional agriculture (MFA) in animal systems, potentially capable of producing a range of goods and services of value to diverse stakeholders in agricultural landscapes and rural communities, as well as broader societal benefits. Despite these benefits, global adoption of MFA has been uneven, with some places seeing active participation, while others have seen limited growth. Recent conceptual models of MFA emphasize the potential for bottom-up processes and linkages among social and environmental systems to promote multifunctionality. Social networks are critical to these explanations but how and why these networks matter is unclear. We investigated fifty-three farms in three states in the United States (New York, Wisconsin, Pennsylvania) and developed a stylized model of social networks and systemic change in the dairy farming system. We found that social networks are important to RG adoption but their impact is contingent on social and spatial factors. Effects of networks on farmer decision making differ according to whether they comprise weak-tie relationships, which bridge across disparate people and organizations, or strong-tie relationships, which are shared by groups in which members are well known to one another. RG adoption is also dependent on features of the social landscape including the number of dairy households, the probability of neighboring farmers sharing strong ties, and the role of space in how networks are formed. The model replicates features of real-world adoption of RG practices in the Eastern US and illustrates pathways toward greater multifunctionality in the dairy landscape. Such models are likely to be of heuristic value in network-focused strategies for agricultural development.

Keywords: multifunctional agriculture; land change; rotational grazing; social networks; agent based model

1 Introduction

Multifunctional agriculture (MFA) promises benefits over many other forms of agriculture but its potential is unrealized in many places (Jordan and Warner, 2010). Agriculture is considered multifunctional when it produces standard commodities such as food or biomass as well as social and ecological outputs. These range from economic contributions such as ecotourism in agricultural landscapes to provision of ecological services including denitrification and protection of human systems from climate change impacts (Flora, 2001; Renting et al., 2009). Despite these benefits, MFA adoption has been very uneven, with some locales like New Zealand and several European countries seeing active participation and growth, while others including the United States have not (Jordan and Warner, 2010).

Why is MFA distribution uneven? It does well under top-down policies that explicitly support it as a form of production satisfying broader social and environmental goals (Potter and Burney, 2002; Uthes et al., 2011). Less clear is how MFA grows absent such support. As detailed below, some recent explanations emphasize ‘bottom-up’ processes and self-reinforcing feedbacks of systems at a variety of scales. These feedbacks rely on linkages among social and environmental systems that connect farmers, farmers to markets, organizations, and environments that benefit from MFA and subsequently support it (Jordan and Warner, 2010; Selman and Knight, 2006).

Social networks that help create linkages among social and environmental systems are critical to these explanations of MFA growth, but there are unanswered questions about how and why these networks matter. In this paper, we draw on an empirical case study to develop a stylized model of social networks and systemic change for a form of MFA called rotational grazing dairy farming (RG). We are particularly interested in differentiating between the effects on farmer decision making of weak-tie social relationships, which bridge across disparate people and organizations, and strong-tie relationships, which are shared by groups with closely integrated members. We also examine the effect of spatial distance on network formation and activation on RG practices within a broader context of confinement practices in dairy farming (CP). We draw on existing research and our own empirical work to develop an agent based model (ABM) that explores these networks and their spatiotemporality. This model of dairy farmers in the United States examines how social networks affect adoption of new forms of agriculture, and in turn how social and spatial factors influence these networks. The model is kept fairly abstract to examine general dynamics of these networks and the agricultural system.

This work makes several contributions to modeling and analysis of the role of social networks in land use change. The study of social networks in landscape dynamics and in agricultural extension is both important and relatively neglected (Beilin et al., 2013; Entwisle et al., 2008; Hellin, 2012), which has led to calls for research on the role of

social networks in complex resource systems such as MFA (Agrawal et al., 2013; Bodin and Crona, 2009). This paper answers these calls by specifying possible impacts of different kinds and configurations of networks. This work also addresses the need to understand MFA dynamics at the farm scale (Renting et al., 2009), especially because the effectiveness of policy interventions must be measured and understood at the farm scale (Uthes et al., 2010). Finally, this work meets the specific need to create ABM to understand MFA (Van Berkel and Verburg, 2012) and addresses the more general paucity of tools to understand and design multifunctional landscapes (O’Farrell and Anderson, 2010; Rossing et al., 2007; Zander et al., 2007).

The remainder of this section describes multifunctional agriculture in the United States and the potential roles that social networks could play in the greater adoption of one kind of MFA, dairy production based on rotational grazing (RG). Section 2 describes methods centered on a stylized yet empirically based model of network dynamics and their role in the growth of RG in the northern United States. Section 3 offers results and discussion, focusing in particular on the impact on RG of network processes that were reported by farmers about their transition to RG production. Section 4 concludes with a recap of results and examines future research and policy directions.

1.1 Social Networks and Multifunctional Agriculture in the US

MFA in the United States is less established and studied than elsewhere (Jordan and Warner, 2010). The top-down policies that support MFA in other contexts are largely absent and are likely to remain so given a policy focus on standard commodity production (Uthes et al., 2011). Other countries design policies to encourage MFA for broader social and environmental reasons, ranging from preservation of rural livelihoods to encouraging biodiversity (Baylis et al., 2008; Cocklin et al., 2006; Potter and Burney, 2002). In contrast, US agricultural programs are largely incidental to MFA. They focus instead on specific environmental issues such as minimizing soil erosion by taking land out of production, and economic concerns such as supporting commodity agriculture. There is concomitantly less known about the biophysical and social nature of MFA in the US (Boody et al., 2005; Polasky et al., 2011).

How might MFA arise in the absence of top-down policies? One promising route is for farmers and other stakeholders to endogenously develop networks that create self-reinforcing flows of information and resources about multifunctionality (Jordan and Warner, 2010; Selman and Knight, 2006). This perspective posits an important role for social networks that are composed of nodes (people or other actors) that are joined by ties (relationships that convey information or resources). Networks can serve as conduits for information and resources, exert social influence, and shape actions (Knoke et al., 2008; Wasserman and Faust, 1994). Social networks link farmers to a broader array of actors and human-environment systems (Ortiz-Miranda et al., 2010; Sonnino and Marsden, 2006; Steyaert et al., 2007). These systems can include farmers and their neighbors trading production strategies (Conley and Udry, 2001), farmers and consumers forging links with cultural, social, and ecological meaning such as increased landscape amenity or healthful food (Van Huylenbroeck et al., 2007), or environmental organizations and scientists sharing information about benefits of multifunctionality (Ploeg, 2003).

Research on the social context of natural resources management and agriculture points to critical distinctions among kinds of relationships in networks (Moore and Westley, 2011). Such network ties are of three types: bonding or strong ties, bridging or weak ties, and linking or vertical ties (Woolcock and Narayan, 2000). Strong ties are relationships within largely homogeneous groups such as families that provide benefits to members. Weak ties bridge nodes among heterogeneous groups across sociocultural or geographical gaps, creating flexible networks that can transmit new ideas. Vertical ties are a variant of weak ties that serve as conduits among nodes at one level with nodes at another level of organization, such as between farmers and state agencies.

Network effectiveness is contingent on its structure and dynamics. A combination of weak and strong ties may be necessary for propagating new practices like MFA, judging by the work on related forms of production like agroforestry and sustainable agriculture. Weak ties in particular may help information generation and alliance building (Nelson et al., 2014; Olsson et al., 2006), creating knowledge across sectors (Steyaert et al., 2007),

and developing ties among disparate organizations (Ortiz-Miranda et al., 2010; Sonnino and Marsden, 2006). Networks can form and dissolve as a function of physical space, social distance, and happenstance in ways that affect their ability to convey information and resources (Carolan, 2005; Nelson et al., 2014; Olsson et al., 2006). The structure of networks can affect how they function in natural resource situations (Bodin and Crona, 2009), including how well the effects of networks at one spatial scale or level of organization are manifested at other scales, or across different sectors of social systems (Moore and Westley, 2011).

1.2 Rotational Grazing and Multifunctional Agriculture

Rotational grazing is an excellent system in which to study the network dynamics of MFA. The majority of dairy farms exemplify standard commodity agriculture in their use of confinement practices (CP) while a minority use rotational grazing (RG). While both CP and RG dairy farms use a range of practices and methods (Lyon et al., 2011), in CP farms, cows spend much of their time in barns and eat processed feed. CP has what is commonly termed a standard productivist focus on maximizing production and efficiency (see for in depth treatment Wilson, 2008). In contrast, RG dairy farms move the grazing herd through a series of paddocks in which the livestock are held for one to seven days (Taylor and Foltz, 2006). RG centers on ‘good grass farming,’ which translates into minimizing costs while promoting a sustainable environment for healthy animals that create higher profits than conventional production methods (Gloy et al., 2002; Lyon et al., 2011). Grazing reduces input costs through having cows eat grass in pastures instead of prepared feed and via lower costs for manure disposal and veterinary care (Undersander et al., 2002). RG has biophysical benefits including lower soil-erosion rates than row cropping (Gantzer et al., 1990) and improved wildlife habitat (Vondracek et al., 2005). Additional motivations include perceived lifestyle and community benefits, such as RG offering greater labor flexibility and more readily maintaining family farms (Murphy, 1998; Parsons et al., 1998).

Rotational grazing is also an interesting system to study because despite offering advantages for farmers and society, it has not yet expanded beyond roughly 25% of dairy

farms in a few areas in the northern US and is far less in most places. In Wisconsin, the number of RG farms grew rapidly during the 1990's, from approximately 7% of dairy farms in 1993 to its current plateau of 26% in 2005 (Taylor and Foltz, 2006) and after (Kloppenburger et al., 2012). In Northeast US, the rate of RG plateaus in the range of 8-22% depending on sub region (Winsten et al., 2010). In addition to being limited to a small proportion of dairy farms, most of the grazing farms we studied were also spatially limited, forming small 'islands' of grassland embedded in a larger matrix of various land uses.

We focused on household farms as the primary entry point into examining MFA. Household farmers are defined as those who rely primarily on the immediate family for labor and are not heavily capitalized, reflecting the fact that dairy has seen steady consolidation into small numbers of large industrial operations and decreasing numbers of household farms (Winsten et al., 2010). These farms are important to study because they blend the market orientation of commercial farms with social elements such as values that are linked to MFA practices and the life course, or the sequence of socially and culturally defined events and structures that define an individual (Taylor and Foltz, 2006). At the same time, they are most likely to experiment with labor-intensive practices, such as rotational grazing, outside of the mainstream focus on capital-intensive commercial production.

2 Methods

We develop an agent based model of social network dynamics in the growth of RG in the northern United States. There are other excellent approaches for modeling MFA, including econometrics, farm-scale simulations, and integrated socioeconomic simulations (Jongeneel et al., 2008; Renting et al., 2009). These methods offer advantages including long histories and integration with specific bodies of research, such as derivation of econometrics from economics or basing farm-scale simulations on in depth agricultural research. ABM have less of a track record and can therefore be harder to specify, validate, and communicate to other researchers given the lack of commonly accepted approaches (Parker et al., 2003). Nonetheless, there is great interest in using

ABM to model MFA and household-scale land change more broadly given its ability to represent individual decision making, capture feedbacks among human and environmental systems, model social networks, and integrate across many features of these systems (Manson and Evans, 2007; Manson, 2006, 2005; Renting et al., 2009; Van Berkel and Verburg, 2012).

The model is part of a class of ABM that represents households with hybrid decision making models, in that they represent realistic economic behaviors such as profit seeking but integrate environmental considerations and broader social and cultural interactions (Brown et al., 2008; Manson and Evans, 2007; Valbuena et al., 2010; Walsh et al., 2013). Related work on ABM of agricultural shifts in household production examines diffusion of agricultural innovations (Berger, 2001), diffusion of greenhouse agriculture (Schreinemachers and Berger, 2006), effects of markets on diffusion of innovations in land use (Polhill et al., 2008), switching agricultural production (Evans et al., 2011), and the role of formal organizations and informal networks in common-pool situations (Agrawal et al., 2013). We describe the model using the Overview, Design concepts and Details (ODD) protocol (Grimm et al., 2010). Section 2.1 describes the study site and data collection while sections 2.2 through 2.8 constitute the ODD description.

2.1 Study sites and data collection

We developed our model as part of a larger project on multifunctional agriculture in the United States (Nelson et al., 2014). We examined the social networks of small dairy farmers in areas of Wisconsin, Pennsylvania and New York that have both conventional and rotational grazing dairying (Figure 1). We interviewed 53 farmers and another 35 key informants identified by farmers as playing important roles in the broader social networks of the dairy landscape. We then used a blend of quantitative and qualitative methods to translate these interviews into a multi-faceted dataset on farmers and the broader social system of which they are part. These data in turn form the foundation for a simple model of adoption by farmers of rotational grazing as a function of their social networks.

Figure 1. Study locations. Study sites in Wisconsin, Pennsylvania, and New York, United States

Household interviews. From a list of 684 farms from federal dairy producer lists, we used postcards and phone calls to select 53 households practicing a range of management styles within an upper limit of 300 milk cows and a lower limit of 30 to eliminate commercial and “hobby” farms respectively. This sample size supported a semi-structured extensive interview with the primary decision-makers of each of the 53 farms designed to create rich, qualitative data. Interviews averaged about 3.5 hours but ranged between 2 and 5 hours. Interviews delved into farm history, personal motivations, farm management innovations, land management practices, and animal well-being. On CP farms, herd nutrition was a mix of hay or corn silage, grains, and total mixed rations. RG farms ranged from low-intensity grazing, where milk cows were largely kept on pasture during the grazing season, to high-intensity farms where the farmer spoke about actively managing pastures and rotated the herd to new grass at least once a day. We also covered social networks, determining the organizations, businesses, and individuals most important to the interviewee in supporting the farm. For households that had switched production to rotational grazing, we discussed what social entities were important to

making this transition (e.g., banks, cooperatives) and the role of social networks, including the nature of the relationship (e.g., family, neighbor, extension specialists), type of exchange (e.g., information, money, labor, service, material), and additional details such as the frequency of interaction. Note that we focused on egocentric networks, or those of specific individuals, as opposed to sociocentric networks, which comprise every single actor in a network (Wasserman and Faust, 1994).

Social network interviews. In addition to interviewing farmers, we conducted interviews with 35 individuals in the broader social landscape that farmers personally saw as important to their dairy management and with ‘key informants’ who farmers felt who would understand dairy operations in the study site. Interviews ranged between 30 and 90 minutes to establish a broad view of the social landscape and social networks important to supporting dairy. In selecting interviewees, we balanced the need to talk to people across the dairy support landscape with the desire to interview people most often mentioned by farmers. Informants included veterinarians, nutritionists, extension specialists, dairy companies, bankers and farm loan officers, employees of farmer cooperatives, and employees of federal and state conservation agencies including the federal Natural Resource Conservation Service and local Soil and Water Conservation Districts.

Transcription and coding. We transcribed the interviews with the farmers and social-landscape informants and analyzed the resultant text for social network themes by coding with the NVivo 8 qualitative analysis software package. The transcription and coding of farmer and social-informant interviews centered on core social network measures: the type of node and the kind of the relationship (e.g., family member, veterinarian, bank officer); the nature of the relationship or exchange (e.g., information, money), the directionality of the exchange (uni-directional vs. bi-directional); and the quality of the tie (weak vs. strong). Granovetter (1973) characterizes tie strength as “the amount of time, emotional intensity, the intimacy (mutual confiding), and reciprocal services which characterize the tie” (p. 1361). He further argues that operationalizing a tie as either weak or strong involves combining these factors and we therefore used these criteria to assess

whether a given tie was strong or weak. Strong-tie relationships were generally redundant, highly dense, frequently used, involved reciprocal exchange, and evoked a sense of intimacy or “we” in the interviewee. Examples include relationships in families or church groups. We coded a relationship as a weak tie if it tended towards being non-emotional or non-intimate, involved infrequent interaction, involved asymmetric reciprocal exchange, and if it implied an attitude or characterization of ‘them’ instead of ‘we.’ Weak-tie relationships were often between the farmer and representatives of an organization, business, or government agency that served as a ‘bridge’ that connected the farmer to a new resources such as a new network or new information. Assessing the combination of frequency, intimacy, exchange, and emotional intensity to operationalize tie-type is a long-standing approach across disciplines (Hansen, 1999; McPherson et al., 1992).

Linking interviews to the model. In terms of model calibration and validation, we applied a mix of quantitative and qualitative assessments of farmer experience, which is a common strategy for models like ours drawing on empirical data to create a stylized account of reality (Janssen and Ostrom, 2006). In addition to using farmer characteristics like income from survey questions, we also derive broader ranges of values from the qualitative analysis to explore general trends and relationships among model components. This approach bridges two modes for empirical specification of agent based models, survey research and participant observation (Robinson et al., 2007). We used a survey to start the semi-structured extensive interviews but went well beyond just administering closed-form questions. As a result, responses to questions such as “what was your income last year” are readily translated into model values, while open-ended answers concerning issues such as meaning making and social networks were transcribed, coded, and interpreted qualitatively in a manner that produces results similar to (if less deep given the shorter interaction time) those generated by participant observation. As such, this extensive interview approach shares advantages and drawbacks with participant observation, in that it gives nuanced perspective into household decision making at the cost of large sample sizes and simple numeric scales, just as participant observation gives insights into agent “motivations and perception of the world, and about the range of

heterogeneity among these individuals, but is not likely to provide precision about the relative numbers having different characteristics.” (Robinson et al., 2007: 36). Finally, we refer to the survey and field work throughout this paper, but focus on model results as such in the results section.

2.2 Purpose

The model represents how networks influence farmer transition to RG production. The qualitative interview coding and analysis highlighted social dynamics that we distill into an agent based model with archetypal networks (family and friends, extension agency, grazing networks) that exemplify a certain kind of tie (strong, vertical, weak). Each archetypal network is capable of supporting three types of relationship (signaling possibilities, defraying switching costs, aiding consolidation) but is primarily associated with one (Table 1). Farmers see the possibility of RG primarily via strong-tie networks like family, rely on vertical-tie networks for meeting switching costs, then look to weak-tie networks to help consolidate RG practices (for a deeper explanation see Nelson et al. 2014). The model instantiates these archetypal networks and examines how their formation and relationships affect the adoption of RG.

Table 1. Network tie types, archetypes, and relationships

	Tie type		
	<i>Strong</i>	<i>Vertical</i>	<i>Weak</i>
<i>Archetypal network</i>	Family and friends	Extension agency	Grazing network
<i>Primary relationship</i>	Signaling possibility	Defraying switch	Aiding consolidation
<i>Secondary relationships</i>	Defraying switch	Signaling possibility	Signaling possibility
	Aiding consolidation	Aiding consolidation	Defraying switch

Three kinds of relationship convey information and resources that address the needs of a farmer in adopting RG practices at a specific phase of the adoption process. The first relationship is ***signaling possibilities***, where networks are essential for demonstrating the possibilities offered by RG. Although farmers are aware of RG practices in general and can find information themselves, they rely on networks for the initial impetus, where discussion and observation help convince them of the possibility of converting from CP to RG practices. The second is ***defraying switching costs***, in that once a farmer is alert to the possibilities of RG, the next step is overcoming start-up issues, such as installing

fencing for movable paddocks and developing water systems, and outside resources aid the transition. The third relationship is *aiding consolidation*, in that the first several years of a new RG operation are difficult because farmers must learn new methods and aptitudes, in essence becoming more efficient. Successful movement to RG practices is easier for farmers who engage in joint problem-solving through networks.

Each archetypal network exemplifies a particular kind of tie (strong, vertical, weak) and supports one primary type of relationships and two secondary ones. The first kind is *strong-tie networks of family and friends*. The primary relationship of this network is signaling possibilities, where someone who is both trusted and proficient in RG is available to demonstrate that RG is a successful mode of production. Secondary relationships include helping a farmer to defray switching costs and consolidating production via shared labor, information, and problem solving. The second kind of networks are *vertical ties between farmers and extension agencies*, in that these agencies issue subsidies to overcome the costs of switching production associated with specialized systems for fencing and watering. Secondly, extension agents support both signaling possibility and aiding consolidation by channeling information and resources and helping forge connections among potential graziers. The third archetypal network is *weak-tie grazing networks*. We found that RG farmers who were successful, as opposed to just staying in business, often relied on grazing networks, farmer-to-farmer organizations that act as clearing houses for information and for making personal contacts. The primary relationship for grazing networks is aiding consolidation, where the networks propagate information about RG, including feedback on animal health, pasture quality, and new breeds and calving patterns. These networks also help farmers develop personal and social meaning around issues central to RG, such as a focus on healthy environment, pasture, cows, and food. Grazing networks can also play a secondary role in signaling possibilities of grazing and can occasionally provide aid for switching to RG via shared labor and equipment.

2.3 Entities, state variables, and scales

2.3.1 Spatiotemporal units

The model is written in NetLogo (Wilensky, 1999) and represents the landscape as a uniform grid of square cells that hosts farmers and extension agents. In order to simplify model dynamics and reduce artifacts introduced by the particularities of any specific site, the landscape is a generic 60 km by 60 km grid of 25 ha cells (500m a side), which falls below the size of land management units. Time is measured in NetLogo steps (or ‘ticks’) where each step corresponds to one year in reality. Each model run iterates over fifteen model years because that encapsulated the ten-year period that weak ties last. Source code is available via the NetLogo Modeling Commons (http://modelingcommons.org/browse/one_model/4098).

2.3.2 Agents

Farmers. Farmers are of two types, defined by their use of either confinement practices (CP) or rotational grazing (RG). In order to focus on network dynamics, we model only the simplest features of farmers and their decision making, as described by the state variables in Table 2 and the production processes in section 2.4.

Table 2. Farmer state variables

Variable	Description	Value
Identifier	Unique identifier	Varies; assigned randomly at creation
Size	Display symbol size	Twice <i>spatial resolution</i>
Shape	Display symbol shape	RG: Circle CP: Square
Color	Display symbol color	RG: White; grey if switched from CP CP: White
Type	Type of farmer by production	RG or CP
Time in type	Years in current type	Increases one year/tick
Location	Spatial coordinates (x/y)	Assigned randomly at creation
Network degree	Degree of separation from center	0 or higher
Efficiency	Efficiency applied to payoff	Uniform distribution [0.6, 1.0]
Base income	Median income by type (\$/a)	RG: 34 000; CP: 25 800
Income range	Income range (\$/a)	RG: [9800, 70 900]; CP: [0, 42 800]
Neighbor ties	List of neighbor ties	Assigned during network formation
Strong ties	List of strong ties	Assigned during network formation
Weak ties	List of weak ties	Assigned during network formation
Vertical ties	List of vertical ties	Assigned during network formation
Signaling threshold	RG possibility activation threshold	Assigned during scenarios
Central node	Is farmer grazing network center?	False except for one farmer

Extension agent. An extension agent, introduced in section 2.2, helps farmers make the transition from CP to RG. Table 3 describes its state variables and section 2.4 details how it influences farmer decision making.

Table 3. Extension agent state variables

Variable	Description	Value
Identifier	Unique identifier	Varies; assigned randomly at creation
Size	Display symbol size	Twice <i>spatial resolution</i>
Shape	Display symbol shape	Nested circles
Color	Display symbol color	Black and white
Location	Spatial coordinates (x/y)	Assigned randomly at creation
Subsidy	Subsidy for switching to RG (\$)	Varies; default of 30 000
Funding	Subsidy funding remaining (\$)	Varies; default of 400 000

2.3.3 Environment

The environment refers to model features that are outside of agents or collectives (Grimm 2010), which includes global variables pertaining to the model world such as spatial resolution and number of households (Table 4).

Table 4. Environment variables

Variable	Description	Value
Switching cost (\$)	Cost of switching to RG	Varies
Number of RG farmers	Number of RG households	25 – 800
Number of CP farmers	Number of CP households	25 – 800
Spatial resolution (m)	Resolution of individual grid cells	500
Horizontal extent (cells)	East-west extent of study area	120
Vertical extent (cells)	North-south extent of study area	120

2.3.4 Collectives

Networks are collectives defined by links among farmers and extension agents that signal possibility, defray switching costs, and aid consolidation. Network formation is governed by parameters drawn from numeric responses and estimates from qualitative coding and analysis (Table 5).

Table 5. Network formation parameters by type of tie

Network formation	Type of tie		
	<i>Strong</i>	<i>Vertical</i>	<i>Weak</i>
<i>Exemplar</i>	<i>Family and friends</i>	<i>Extension agency</i>	<i>Grazing network</i>
Number of ties	0 – 5	0 – 1	0 – no limit
Duration (years)	15	15	10
Neighbor entrainment (km)	0.0 – 30.0	Not applicable	0.0 – 30.0
Institutional entrainment (km)	Not applicable	0.0 – 50.0	Not applicable
Tie formation probability	0.0 – 1.0	1 if funds available	0.0 – 1.0
Degrees of separation	0 – 1	0 – 1	0 – 2

Number. Each actor has a number of ties. People tend to have fewer strong ties, since they tend to be family bonds or longer-term friendships, and more weak ties.

Duration. Ties have a duration, or how long they last, that is determined by farmer experience. Strong are ties for life for family members while strong friendships are assumed to be good for the duration of the simulation. In contrast, weak ties have a limit of up to ten years, based on farmer histories.

Entrainment distance. Networks have an entrainment distance, or a spatial limit beyond which network ties are not formed because it is not practical to exchange resources such as labor, or because they lack the immediacy and trust of face-to-face communication. The entrainment distance for weak ties and strong ties is defined by a neighborhood, where any farmer within the *neighbor entrainment distance* of a given household is considered a neighbor and therefore a potential partner for a strong tie or weak tie. An upper limit of thirty kilometers for neighbor entrainment is an estimate based on the average distance to the county border for any location within the study site and roughly the longest distance that our respondents would normally drive in the course of their day. *Institutional entrainment distance* is one within which extension agents establish ties with households but is necessarily more abstract (and broader, up to 50 km) than neighbor entrainment because extension agents are generally responsible for a given territory (Table 7).

Tie formation probability. The likelihood that a given household forms a tie is governed by a tie_formation probability. A strong-tie probability of 0.05, for example, means that each of a household's neighbors has a one-in-twenty chance of forming a strong tie with the household. Institution agents, in contrast, form a vertical tie with any household within spatial entrainment distance.

Degrees of separation. Networks have degrees of separation, where a single degree corresponds to direct ties, while multiple degrees allow relationships to pass through intermediary nodes. Strong and vertical ties are direct. Most weak ties are direct although grazing networks can have two degrees of separation by virtue of having 'friends of friends' of the network's central node, which corresponds to real network structure (Nelson et al., 2014; Paine et al., 2000).

2.4 Process overview and scheduling

Grimm and others (2010) recommend pseudo-code to describe model processes. We use code blocks in conjunction with textual explanation. A model run is shown by Block 1. The model initializes by establishing the spatial grid and placing upon it extension agents, farmers, and networks. Initial model settings vary according to a simulation strategy and experimental structure described in section 2.6. One randomly chosen RG farmer serves as the central node of the grazing network (see Block 5). The model then runs for fifteen model years over three steps: 1) farmers update their ties; 2) CP farmers assess whether to switch; and 3) farmers calculate their production pay offs (Code Blocks 2, 3, and 4 respectively). Finally, the model exports results to a spreadsheet, takes a screen snapshot, and saves the final state of the model world to a file.

Code Block 1: Model run	Code block
Initialize Model	5
Run Model for 15 iterations (each iteration is one model year)	
Step 1: all farmers update their ties	2
Step 2: CP farmers assess whether to switch	3
Step 3: all farmers calculate their production pay offs	4
Export Results	

In step one of the main model run, farmers canvas weak and strong ties to determine if they link to a RG farmer and update signaling and switching relationships accordingly (bearing in mind that a tie between two nodes must be either strong or weak). Farmers also determine whether they are within two degrees of the grazing network central node, in which case they increase support available for RG consolidation. Weak ties become ineffective after a set duration (Table 5).

Code Block 2: Model Run Step 1 – farmers update their ties
For all farmers if strong-tie links to RG farmer then <i>tie.possiblity</i> = 1.0, <i>tie.switch</i> = 0.2, <i>tie.efficiency</i> = 0.2 else if weak-tie links to RG farmer then <i>tie.possiblity</i> = 0.2, <i>tie.switch</i> = 0.1, <i>tie.efficiency</i> = 0.1 if grazing network central node is within <i>degrees of separation</i> then <i>tie.switch</i> = 0.2, <i>tie.efficiency</i> = 0.2 increment <i>tie.duration</i> by 1 for all weak ties, if <i>tie.duration</i> > <i>network.weak tie duration</i> then <i>tie.possiblity</i> = 0, <i>tie.switch</i> = 0, <i>tie.efficiency</i> = 0

In step two, CP farmers sum signaling possibility over ties and, if sufficient, canvas their relationships for help in defraying switching costs. Interviewed farmers indicated that strong-tie networks were more effective at signaling possibility than weak and vertical ties, in that a single trusted strong tie could spur the switch to RG while farmers needed about five weak ties before considering a switch. In model terms, the signaling relationship of a strong tie is 1.0 while a weak tie or vertical tie is 0.2 (Table 6). The activation threshold for the sum of signals varies over simulations. If the signaling threshold is a low value, like 0.15, then a single weak-tie RG could be enough to indicate that RG is possible, where a default value of 1.0 equates to a single strong tie providing

the impetus to consider switching, while a high value such as 1.5 would require a large number of weak ties or a mix of strong and weak ties.

Table 6. Network relationships by tie-type

Relationship	Type of tie		
	Strong	Vertical	Weak
Signaling possibility	1	0.2	0.2
Defraying switching costs	0.2	1	0.1
Aiding consolidation	0.2	0.2	0.2 if to grazing network
			0.1
			0.2 if to grazing network

A sufficiently strong aggregate signal about the possibility of switching to RG encourages the farmer to assess whether there are sufficient resources to switch. Switching costs can be met by a combination of farmer wealth and network resources. Up to half of the total switching cost can be provided via in-kind support derived from relationships across weak ties and strong ties, the remainder being monetary needs for physical plant such as fencing or water systems that cannot be substituted for by labor and must be paid by the farmer or offset by an extension subsidy. A farmer takes the subsidy if available and reduces the subsidy funding pool accordingly regardless of the level of in-kind and existing wealth. A farmer that switches changes type to RG, resets its efficiency, and deducts the switching cost from wealth. If switching cost is greater than wealth then the remainder is assumed to be in-kind.

Code Block 3: Model Run Step 2 – CP farmers assess whether to switch

```

For all CP farmers
  if sum of tie.signaling possibility across all farmer.ties > signaling threshold then
    switching in-kind = sum of tie.switch across all strong and weak ties
    if switching in-kind > 0.5 then switching in-kind = 0.5
    switching in-kind = switching in-kind * switching cost
    switching funding = sum of tie.switch across vertical ties* extension.subsidy

    if farmer.wealth + switching in-kind + switching funding > switching cost
      if vertical tie exists then
        add subsidy to farmer.wealth
        ask extension agent to subtract subsidy from extension.funding
      change farmer.type to RG
      reset farmer.efficiency
      reduce farmer.wealth by switching cost

```

In step three, farmers calculate financial payoffs from production. The payoff is the product of farmer efficiency and a normal stochastic function of the base income for their type bounded by an income range derived from the survey. This function is a simple representation of the vagaries of the market and how household farmers are price takers, or cannot influence price with their own production. Farmers increase their efficiency over time via summing over weak and strong ties to other farmers of the same type. In essence, they get better through interaction with other farmers and this interaction is central to the third stage of adoption, aiding in consolidation. This network effect is particularly important to new RG farmers.

Code Block 4: Model Run Step 3 –farmers calculate production pay offs
--

<p>For all farmers add to <i>farmer.efficiency</i> the sum <i>tie.efficiency</i> across all ties with farmers of same <i>farmer.type</i> $farmer.income = \text{bound}(farmer.efficiency \text{ to range of } [0,1]) * \text{normal distribution}(base \text{ income})$ bound income to <i>income range</i> add <i>farmer.income</i> to <i>farmer.wealth</i></p>

2.5 Design concepts

There are eleven ODD design concepts that capture broader characteristics of a model (Grimm 2010):

1. Basic principles. Social networks defined by weak and strong ties affect switching among modes of agricultural production.
2. Emergence is exhibited in farmer network formation, stemming from both the random nature of initial node locations and the probabilistic nature of tie creation, which can lead to situations ranging from almost no networks being formed to many forming spontaneously. The final network structure and spatial locations of switching farmers arises over the course of the simulation and the odds that any given farmer converts to RG is heavily contingent on broader dynamics of network formation, as examined in the results and discussion.
3. Adaptation. Agents react to changes in network structure and payoff stochasticity and have the ability to modify production type.

4. Objectives. Farmers seek to receive income from production, while extension agents seek to aid farmers in switching to RG. Farmers will switch to RG if their networks are sufficiently supportive.
5. Learning. Agents do not learn.
6. Prediction. Agents do not predict.
7. Sensing. Agents sense the locations of other agents, kinds of neighbors, and relationships over links.
8. Interaction. Agents interact via networks ties and do not inhabit the same location.
9. Stochasticity. The model randomly locates agents, probabilistically assigns basic agent characteristics (wealth, income, type), and network construction is heavily stochastic because it relies on several probabilistic elements and random spatial location of agents.
10. Collectives. Networks are weak collectives in that they are linked and farmer agents influence each other, but do not plan or have collective intentions.
11. Observation. The model generates outputs including network configurations, final landscape, and tabular data of all state variables.

2.6 Initialization

Model initialization first assigns global variables and establishes the spatial grid. It places on this grid a mix of RG and CP farmers, choosing one random RG farmer to be the central node of the grazing network. Farmers form neighbor ties with all farmers within neighbor entrainment distance, making these farmers their neighbors, and then from these form strong ties and weak ties with subsets. Extension agencies form vertical ties to all farmers within institutional entrainment distance.

Code Block 5: Initialize Model

```

Create spatial grid of horizontal extent and vertical extent with cells of spatial resolution

Create number of RG farmers and number of CP farmers, and for each
  Assign random location
  Assign initial values of state variables per Table 2

For one randomly chosen RG agent, farmer.central node = true

All farmers
  Establish neighbor ties with each farmer within network.neighbor entrainment distance
    if random U(0,1) < network.strong tie formation probability
      Establish strong tie with neighbor (i.e., add to farmer.strong ties)
    else if random U(0,1) < network.weak tie formation probability
      Establish weak tie with neighbor (i.e., add to farmer.weak ties)

Create an extension agent
  Assign random location
  Assign initial values of state variables per Table 3
  Establish vertical tie with each farmer within network.institutional entrainment distance
  tie.possibility = 0.2, tie.switch = 1.0, tie.efficiency = 0.2

```

The logic of a mixed qualitative-quantitative approach to model calibration holds for model validation for a stylized ABM (Manson, 2007; Messina et al., 2008). We assessed the coherence of the model outcomes against published accounts where available (e.g., RG rates) and conducted a sensitivity analysis of inputs versus outcomes over a stratified factorial model design (after Saltelli et al., 2000). Table 7 details the default values, ranges, and steps for scenario parameters and sensitivity analysis.

Table 7. Simulation settings

Owner	Parameter	Default	Range	Step
Environment	Households	100	25 – 800	25
Environment	Mix of RG to CP	0.1	0.1 – 0.9	0.1
Network	Neighbor entrainment distance (km)	5	2 – 30	2
Network	Institutional entrainment distance (km)	20	2 – 30	2
Network	Strong-tie formation probability	0.1	0.05 – 0.95	0.05
Network	Weak-tie formation probability	0.5	0.05 – 0.95	0.05

In addition to sensitivity analysis, we examined sets of scenarios (Table 8) based on ranging over two or three parameters while holding the others at their default values (Table 7). We performed 100 replications per combination of scenario parameters to ensure trend stationarity.

Table 8. Scenario sets

Set	Parameter	Runs
1	Initial mix (0.05 – 0.95) + Households (25 – 800)	60 800
2	Strong-tie formation probability (0.05 – 0.95) + Households (25 – 800)	60 800
3	Neighbor entrainment distance (2 – 30) + Households (25 – 800)	48 000
4	Institutional entrainment distance (2 – 50) + Households (25 – 800)	80 000
5	Weak-tie formation probability (0.05 – 0.95) + Households (25 – 800)	60 800

2.7 Input data

Input data are described in tables for agents (Tables 2 and 3), the environment (Table 4), network formation (Table 5), network relationships (Table 6) and scenario generation (Table 7). Variables are based on the farmer interviews described in Section 2.1.

2.8 Submodels

There are no submodels.

3 Results

We used the model to explore the impact of a sequence of network processes on RG adoption. As described above, farmers were introduced to RG via strong-tie networks like family, relied on vertical-tie networks for subsidizing switching costs, then on weak ties to help consolidate. The goal was to explore how network attributes and related interactions might affect the prevalent dynamics in our study region, namely an initial phase of rapid adoption followed by a static plateau. Our primary finding is that widespread adoption of RG practices was contingent on network attributes that reflect spatial and social considerations, which is in line with similar work (Agrawal et al., 2013; Bodin and Crona, 2009; Evans et al., 2011). In the model, the number of CP households adopting RG practices is heavily dependent on number of dairy households initially in the landscape, initial mix (RG vs. CP) of households, probability of neighboring farmers sharing a strong tie, and neighbor entrainment distance. Under realistic conditions, the model replicated the general nature of real-world RG adoption in the Eastern US. The number of RG farms plateaued at less than a quarter of dairy operations, and the spatial extent of RG was limited to pockets in the landscape. Only under certain conditions did

modeled RG become common, pointing towards some pathways for greater RG in the dairy landscape.

Scenario set 1 illustrates the primary importance of the number and mix of dairy farms in the landscape. We experimented with household numbers ranging from 25 to 800 and the initial proportion of RG to CP households ranging from 0.05 through 0.95. Given that the study site that is 60 km by 60 km, a realistic number is about 50 to 100 dairy households and 10% of these being initially RG. Figure 2 illustrates some sample outcomes for a range of household populations and initial mix that illustrate how realistically low numbers of households inhibit network development and therefore interactions among households, forestalling signaling of possibilities for RG and subsequent adoption.

Figure 2. Conversion, numbers of households, and household mix. Effects of number of households and initial mix of RG to CP on proportion of CP who convert.

Figure 3 is a graphical view on how the household population affects network density, grazing network size, and shifts to rotational grazing. Note that in order to aid interpretation, the location of the central grazing node in these images was centrally fixed. The actual simulation runs use a randomly located node.

Figure 3. Conversion and household population. Effect of differing numbers of households on network density, grazing network size, and shifts to rotational grazing.

Scenario set 2 examines the impacts on RG adoption of the likelihood of forming strong-tie networks of family and friends that signal the possibility of RG. We tested the probability of strong-tie relationships occurring with neighbors from a rare 0.05 through

to an almost certain 0.95 (Figure 4). We conducted tests over a broad range of initial household numbers given the importance of the household population to model outcomes. Realistic strong-tie probabilities are 0.05 to 0.2, or in other words, a one-in-twenty to one-in-five chance that a neighbor is family or a close friend. Conversion at these rates is quite low unless the number of households climbs above 150 to 200. These results support the broader supposition that strong ties in particular are important, either because they inhibit transitions to new multifunctional practices by reinforcing the status quo, or because they do not offer counter examples to conventional practices (Bodin and Crona, 2009; Sandström and Carlsson, 2008).

Figure 4. Conversion and strong ties. Proportion of households converting to RG as a function of strong-tie probability accounting for number of households.

Scenario set 3 examines the effect of neighbor entrainment distances from 2km to 30km over the range of household populations. Any distance below 8 km has a profound impact on the likelihood of RG conversion (Figure 5). A distance of 2 km translates into no more than a tenth of households shifting production to RG even with an unrealistically high 800 households. For a more realistic range of 50 to 100 households, the numbers range from 0.011 to 0.023 respectively for 2 km and only 0.053 to 0.15 for 4 km, in keeping with the general plateauing of RG in the 10% to 25% range described above. Only when the range gets beyond 8 km do adoption rates take off, whereas a realistic default value is half of that (Table 7).

Figure 5. Conversion and neighbor distance.
Proportion of households converting to RG as a function of neighbor spatial entrainment accounting for number of households.

Scenario set 4 tests the impact of varying institutional entrainment distances. Figure 6 shows a scenario with varying institutional distances using a very high switching cost of \$450 000 (to emphasize the level of switching costs necessary to have an impact) and distance starts to matter only with household populations greater than 250. The limited impact of institutions at low household numbers is likely due to the simplicity of the model, because institutions interact with the pool of farmers who have already decided to make the leap due to the signaling effect of strong ties. Related to this, simple distance and the notion of entrainment may simply not be the best way to model the influence of institutions given that agents of the state, such as extension specialists, most often have jurisdictions defined as a set area. They are more likely to have interactions near the location from which they are based as a matter of course, but this effect may be small assuming they range over their jurisdiction. In addition, we are primarily modeling switching from already established farmers and not examining the entry of new farmers into the system who would require larger startup sums.

Figure 6. Institutional entrainment distance.
Proportion of households shifting as a function of institutional entrainment distance over household population.

Simulation set 5 examined the role of weak ties in grazing networks. In our field work, we found that successful farmers often disproportionately relied on grazing networks as they expanded their operation for joint problem-solving and exchange of information. In model terms, households in a grazing network had a greater number of weak ties. Similar, but less pronounced differences exist for the number of neighbors in general, which provide the pool of possible anchor nodes for weak ties (both immediately and at a remove, through degrees of separation) (Figure 7). This large difference in weak tie availability translates into similarly large differences in support that any given switching household could experience. Many households making the switch could not draw on a grazing network during the consolidation phase, in contrast to those agents that had a large number of weak-tie relationships via the grazing network.

Figure 7. Relationship type and households. Mean and maximum number of relationship for neighbors and weak ties for households switching to RG.

A spatial driver of this difference in weak-tie support is grazing network location, as seen across model runs where the location of the central node of the grazing network relative to other households has a disparate impact on the final size of the grazing network (Figure 8). In Figures 8a and 8b, model runs each show where the grazing network central node is very spatially isolated and has no neighbors (8a) or only a few (8b), which serves to insulate the central node and its grazing network from most farmers. Only in 8c does the node fall within a collection of both RG and CP farmers, which allows it to extend the grazing network spatially, although it still has a majority of CP neighbors who do not convert to RG. The key lesson is that both the number of households and their location matter. Having more households (which are placed randomly) makes it more likely that the central node will have neighbors, but ultimately, the initial locations of the central node and households can trump raw quantity.

Figure 8. Grazing network location. Effect of grazing network central node location, where it is spatially very isolated in set (a) and somewhat isolated in (b) compared to (c), which limits its reach and influence with RG farms.

4 Discussion

The motivating question for this work is how can MFA, as exemplified by RG, grow in the absence of large scale, top-down support? One promising answer to this question lies

in the potential for networks of farmers and other actors in the social system to host and generate ‘bottom-up’ processes that create self-sustaining growth of RG. Our work illustrates ways in which these social networks may be important to forming pathways toward MFA but their effectiveness is contingent on social and spatial factors, particularly in the mix of strong and weak ties. We found empirical evidence for a specific profile of successful adoption that highlights the importance of a mix of these strong, vertical, and weak ties. Encoding this profile into an ABM illustrates how the real-world nature of RG may result in part from a mix of general processes and specific vagaries. RG adoption in the model is dependent on the social landscape defined by the number of dairy households, the initial mix of farmers, the probability of neighboring farmers sharing strong ties, and the distance at which relationships are formed. During each stage of adoption, the likelihood of a tie being formed has a spatiotemporal element in that suitable nodes need to be spatially proximate (e.g., grazing networks for consolidation, family for signaling) and timed well (e.g., neighbors practicing MFA when farmers are considering the possibilities of MFA in the first phase).

In terms of policy implications, realistically low values of adoption stem from realistically low values of households, initial mix, strong-tie probability and neighbor entrainment distance. Barring the unlikely creation of large-scale programs that introduce and support large numbers of small farms (particularly RG operations) in the landscape, the way forward may lie with small but targeted initiatives aimed at strengthening social ties and their attendant information and resource flows. For example, one plausible strategy is to focus on converting vertical ties into strong ties by focusing extension efforts on enhancing the operation of strong-tie interactions, in which a trusted person offers active encouragement in the transition to RG. This form of help was important to some of the farmers with whom we spoke (Nelson et al. 2014) and there is evidence for rotational grazing more broadly where farmers credit a long-term relationship with an extension agent or similar state actor in helping them make the transition (Hassanein and Kloppenburg, 1995; Nerbonne and Lentz, 2003; Paine et al., 2000; Parsons et al., 1998). Another potential way to increase the effectiveness of ties is boost the development and reach of weak-tie grazing networks by partnering with extension agencies and university

researchers who can support the formation of peer-learning networks, even if they cannot substantially contribute to these networks on a day-to-day basis (Hassanein and Kloppenburg, 1995; Paine et al., 2000).

More broadly, our work is informative to network-focused strategies for addressing agricultural development. Such strategies, in which development goals are conceptualized as emergent properties of networks, are beginning to appear widely in agricultural extension work (Ison et al., 2012; Schneider et al., 2012) that is addressing transformation in agriculture. Examples of such emergent properties include resilience in Tasmanian sheep production (Hunt et al., 2011), diffusion of farmer innovation in winter greenhouse horticulture in China (Wu and Zhang, 2013), and coordinated innovation in tillage systems in Switzerland (Schneider et al. 2012). In these cases, extension and development workers searched for effective network configurations and considered how multi-stakeholder efforts could support and extend these configurations. In the US, relatively little attention has been given to network-focused strategies for agricultural development, despite awareness of the need to enhance capacity for transformational change in US agriculture (Reganold et al., 2011). Only recently are institutions that focus on network strategies for development appearing in US agriculture (Jordan et al., 2013). Modeling of complex multi-faceted networks, such as the grazing networks explored in our work, can be of much heuristic value for these institutions as they develop in US agriculture.

There are a number of promising future directions in this work. First is experimentation with a broader set of parameters for network formation and activation, such as varying the probability that any given farmer can become a seed node in more than one grazing network. Related to this experimentation is finding real-world settings where RG adoption is high under preconditions for adoption in the model, such as a large number of existing dairy operations or social settings like cultural communities where strong ties among neighbors are more likely. Second is adding greater detail on land use dynamics, biophysical feedbacks, and production choices given the simple dynamics employed here, which would also involve greater sensitivity analysis of these elements as they are

modeled. Of course, these changes would have to be balanced against the desire to keep the model fairly general and abstract, which allows it to give insight into a broad class of network dynamics. Third, as the model becomes more complicated, there is an attendant need for more sophisticated sensitivity testing, including the potential for spatiotemporal testing (Ligmann-Zielinska and Sun, 2010) and using more complex visualization methods like heat mapping of sensitivity results. Fourth, there is much potential for modeling a greater number and diversity of networks and more explicit consideration of the kind of relationships involved. We found some evidence, for example, that strong-tie networks are essential to long-term operation of the farm, beyond the final stage modeled here for weak-tie grazing networks. Related to this, the policy situation is always changing, with conservation programs and other potentially pasture-friendly initiatives being proposed and adopted in various jurisdictions, and modeling these programs is an important avenue for future research given their importance to some farmers. Importantly, our models will allow heuristic exploration of how such policy initiatives will interact with network processes and emergent properties. Finally, we focused on spatial ordering in networks and little on social topology beyond the nature of the weak-tie grazing network. Future work can tie into the long standing interest in network structure that extends to work in agriculture and natural resources (Bodin and Crona, 2009; Isaac et al., 2007; Kroma, 2006) and examining how network topologies could be optimized with respect to subsidy provision or other policy impacts.

Acknowledgements

This work is supported in part by the National Science Foundation grant BE/CNH: Understanding the Importance of Weak-Tie Networks in Complex Human-Environment Systems: Ecosocial Feedback in Multifunctional Agriculture (0709613), National Aeronautics and Space Administration New Investigator Program in Earth-Sun System Science (NNX06AE85G), the National Institutes of Health supported Minnesota Population Center (R24 HD041023), and the Resident Fellowship program of the Institute on the Environment. We thank the farm families and community members who shared their experiences with us. We appreciate B. Vondracek and T. Arnold as long term collaborators on this project; S. Campbell for interviewing assistance; S. Graves, A. Nessel, S. Huerd for logistical support; K. Clower, A. Berland, D. Bonsal, G. Brand, and J. Immich for fieldwork, GIS, intellectual engagement, and team support over the years. The authors gratefully acknowledge the assistance of the editor and anonymous reviewers. Responsibility for the opinions expressed herein is solely that of the authors.

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