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Dynamic - Economic aspects - Mathematical models

Value Differentiation

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1. Introduction

During the past decade, agricultural economists have begun to describe changes occurring in American agriculture. Fundamentally, the system is shifting from one based on homogeneous commodities to one based on heterogeneous products. The mass consumer markets developed over the course of the prior century are fragmenting into specialized product niches (Manchester 1992, Kinsey 1994). Food processors and retailers must precisely identify their targeted consumer groups in order to successfully compete in this market environment. Rapid improvements in information technology have greatly facilitated and possibly contributed to this marketing shift, as well as to improved quality control and more cost-effective production at all levels of the agrofood chain. Information technology may have encouraged the increased vertical coordination that has tightened relations among levels of the production and marketing chain. These changes have all facilitated serving consumer niche markets with suitably customized products. Biotechnology is anticipated to further lower production costs and increase the ability to control product attributes. There appear to be synergies, or complementarities, across these changing activities. That is, moving farther in the direction of one change appears to increase the value of undergoing the other changes. Taken as a whole, this process is one of value differentiation. Value differentiation is the process by which agrifood chain actors isolate, match and exploit heterogeneity in consumer preferences and in product attributes. This product heterogeneity may originate in any stage of the production process.

Agricultural economists have described exhaustively the changes in agricultural production and marketing (Barry 1995, Boehlje 1995, Boehlje 1996, Manchester 1994, Urban 1991, Zilberman, Sunding and Khanna 1996). Some observers credit technological change, particularly information technology and biotechnology, with driving the transformation process, but do not evaluate the nature of the resulting changes (Streeter 1991, Urban 1991). A closely related body of work uses the transaction costs framework, initiated by Coase (1937) and developed by Williamson (1975) and others, to provide an explanation for the features of the transformation process (Barkema 1993, Barkema 1994, Drabenstott 1994). This literature has explained the exogenous forces underlying the transformation of agriculture, but does not attempt to explain the nature of the system's response to these forces.

The unevenness of the transformation process across products increases the difficulty for economists of analyzing value differentiation. Some sectors have been hardly affected by the process, while others have already dramatically changed. The extent to which predictions have outrun actual changes in certain products, such as pork, obscures the actual factors necessary for transformation. The simultaneous changes observed in products like fruits, vegetables and broilers, and the cumulative nature of their effects upon the system make it difficult to isolate separable cause and effect relationships. Existing hypotheses regarding incentives to integrate production and processing vertically, such as Perloff and Rausser (1983) or Hennessy (1996) cannot explain the nature, speed or extent of the transformation process as a whole. More generally, economic analyses of changes in agriculture tend to focus on a single specific change, such as the movement from spot markets to contracting, the effects of market power, or the increased importance of proprietary intellectual property, rather than examining the overall transformation process.

The emphasis on description rather than formal analysis in the agricultural economics literature related to the integrated process of changes in the agrofood chain is due in large part to the inadequacy of conventional marginal economic analysis. The very analytical requirements (e.g. continuity, differentability) that have made marginal analysis such a powerful tool in so many contexts limit its applicability to multicausal, integrated processes. The failure of standard economic tools to explain agricultural systems has long been reflected in the orientation of the agribusiness literature (see, for example, Goldberg (1968)).

Oriented toward agrofood decisionmakers, the agribusiness literature has focused on analyzing product systems and their evolution rather than on largely independent questions of market power and innovation. In this paper, we propose to bridge the gap between the problem-oriented agribusiness systems literature and the agricultural economics literature. We introduce an analytical framework that is not dependent on marginal analysis, or on differentiability more generally. Moreover, it provides a testable explanation of the interactions among the changes in agrofood systems observed but not explained by agribusiness researchers.

We use a framework that captures the major components of the agricultural transformation process, and identifies its effects. The observed and predicted changes may be grouped into four processes that are the effective components of value differentiation at each level of the food chain. The four components are the determination of customer preferences, the detection of product attributes, the production of these attributes, and coordination with other stages of the production chain, in order to deliver products with the desired attributes to final consumers. We develop an analytical framework based on the existence of complementarities across these four activities. In such a framework, changes that promote any one of these activities may promote all of them. This framework can explain the observations of the existing literature and provides conditional qualitative predictions regarding the evolution of the agrofood industry.

Our framework addresses the overall transformation process. We capture the interactions at the heart of value differentiation by using supermodularity. Supermodularity has been used by Milgrom and Roberts (1990) and Milgrom, Qian and Roberts (1991) to examine developments in manufacturing (such as just-in-time inventory systems) and how they are related. Conceptually, our work is linked to the increasing returns work of W. Brian Arthur (Arthur 1994, Arthur 1996). As we do, Arthur promulgates a framework where a system can undergo periods of extremely rapid change.[1]

[1] Under the increasing returns specification, there are economies of scale *across* firms. Initial product development costs are quite high, but the marginal costs of producing and selling an additional unit of output are low. The first entrant to such a market can attain a position of such dominance that he will not be challenged by competitors. In "knowledge-based" products, the product becomes more valuable to each user the larger the total number of users (e.g. fax machines). In some cases, once a given technology has been adopted, it is costly to switch technologies. Thus, users can become locked into a technology that is likely inferior, as may have been the case with the QWERTY keyboard (David 1985). This has implications for the producers of such technologies. There are large gains to being the first standard for a new technology,

Another formulation for such interactions have been characterized in the economic literature is as network externalities. Among consumers, the adoption of a new standard may be interpreted as a coordination problem. On the supply side, firms have an incentive to expand their user base through tactics such as penetration pricing, where the initial price of the product is low in order to expand the user base (Katz and Shapiro 1986). Alternatively, firms may choose to cooperate and select and use a single product standard, so that their products are all mututally compatible (Katz and Shapiro 1985).

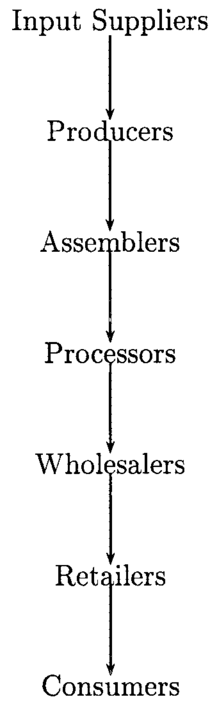
These other works bear some resemblance to Rostow's work on the stages of development and takeoff points for an economy. While Rostow's linear progression of development has been abandoned by later development theorists, his conception of a takeoff point bears a striking resemblance to the dynamic consequences of our framework. In particular, he proposes that once an economy accumulates sufficient savings for investment, the necessary infrastructure, and a government capable of managing a more regionally integrated society, it will begin to grow and to reallocate resources from agriculture to industry and services (Rostow 1960). In our framework, once a sector has increased its levels of complementary activities to a point where the marginal gains to further increases are mutually reinforcing, the levels of all of the complementary activities will rapidly increase.

2. Modeling Value Differentiation

The food production chain can be described according to the roles played by a few basic actors: Input suppliers provide genetic material, fertilizer, etc. Producers engage in activities such as raising and harvesting crops, milking cows or fattening animals to slaughter weight. Assemblers organize the product for use by processors. Processors take this output and modify it to create food products, such as flour, bread, cheese and meat. These food products are then sold to wholesalers

and to accumulating a user base early on entirely apart from the structure of production costs. Increases in a standard's base lead to further increases in its value to consumers and its user base. Even in an industry that begins with more than one technology choice, ultimately one standard may dominate the industry, as occurred in videotapes.

FIGURE 1. Stages of the Food Production Chain



and retailers (see Figure 1). For discussion purposes, assemblers and processors will be jointly referred to as processors, and wholesalers and retailers as marketers.

These stages are represented by a vertical production chain with S stages, indexed by s. The quantity q is assumed to remain unchanged as it moves through the production chain. A firm engages in one or more stages of production. In each stage, a firm can increase product differentiation at some non-negative cost. This cost is affected by the firm's research and technology choices, as well as exogenous innovations, and is part of the firm's total cost of producing a given amount q differentiated by the attribute bundle z_s. We focus on product differentiation, or the identification and exploitation of product heterogeneity, rather than on some measure of product "quality". That is, we address product characteristics for which consumers will pay, rather than implicitly ranking product characteristics. As such, our analysis reflects the intuition of the horizontal or spatial product differentiation literature in industrial organization, rather than the vertical differentiation literature.

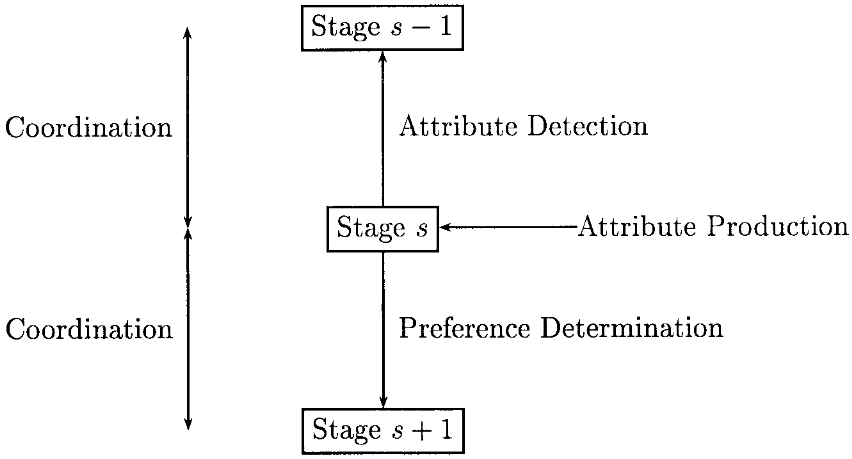
When the product passes from stage $s - 1$ to stage s, stage s must discover whether or not the product possesses the attributes required for its production process, which is costly. The cost of discovering product attributes may involve costs of grading, obtaining adequate supplies with necessary attributes, testing for specified attributes, and similar activities.

There is a similar process which goes in the opposite direction: each stage of the production chain must determine what sorts of attributes are desired by the downstream level. At the intermediate production levels, it is costly for firms to determine the product attributes desired by the buyers of their output. At the final demand level, it is costly for the firm to increase its knowledge of consumers' attribute preferences, indexed in terms of z. For example, a grocery store may choose to collect information about its customers by introducing "club cards" that allow the store to collect information about the purchases of individual customers. To do so, the store must invest in the cards and needed tracking equipment, the labor and expertise to analyze the results, and must induce customers to sign up for the cards through discounts and other promotions that are tied to the card. Exogenous consumer preferences are designated by τ. Increases in τ are characterized as an increased willingness to pay for differentiated product attributes.

The attribute detection and preference determination processes are commonly believed to be influenced by the degree of coordination among stages of the production chain. A greater degree of coordination may reduce the costs of determining whether an input possesses specific attributes, or of determining the input needs of the downstream stage.[2] For example, precommitment arrangements between strawberry shippers and grocery retailers allow the retailers to specify that the strawberries are shipped in their preferred package size. These processes are illustrated for a single stage of the production chain in Figure 2.

[2] Hennessy (1996) models the interaction between the degree of vertical coordination and the cost of discovering product quality.

FIGURE 2. The Value Differentiation Process at Stage s



The firm must select technology variables that govern the costs of production, attribute detection, preference determination, and coordination. These technology decisions are affected by the general technology available, such as information technology and infrastructure. General technology is designated by ξ. Technology is costly. Increases in the available general technology reduce the cost of a specified technology bundle to the firm. For example, in the processing tomato industry the widespread availability of cellular phones at low prices has decreased the cost of coordinating in-field harvesting with the immediate needs of the processing plant. If a firm does not operate in some stage s, then it costs nothing to choose a technology with zero production costs and no output. The firm's selection of its stages of production and their degree of integration based on costs of attribute detection, preference determination, and coordination is a continuous version of the Coasian firm decision between markets and integration.

Profits for each link in the production chain s are a function of the costs of engaging in preference determination for stage $s+1$, the detection of the attributes of the input received from stage $s-1$, the production of output attributes in stage s, and the degree to which stage s coordinates with other stages of production. For a firm in the production chain, its profits are the sum of its profits at all the stages of production in which it is involved, $\sigma \subset S$, where S is the set of all stages of production. The firm's profit function may be written as follows, where subscripts indicate values for a particular stage s and no subscripts indicates values for all the firm's stages of production.

$$\Pi(p,x,z,t) = \sum_{s\in\sigma} pq(p_{s+1,s}, z_s, t) - c(q(p_{s+1,s}, z_s, t), z_s, t) - k(x_s, z_s, t) \tag{1}$$

using the following definitions:

s	stage of production
σ	firm's set of stages of production
S	set of all possible stages of production
$p_{s+1,s}$	price of output of stage s
z_s	attribute differentiation index at stage s
t	vector of variable parameters, (τ, ξ)
τ	exogenous consumer preferences
ξ	exogenous technology set
x_s	vector of decision variables for stage s, $(\zeta, \rho, \mu, I_{s,s-1}, I_{s+1,s}, \delta, \iota)$
ζ	attribute production cost variable
ρ	proprietary research expenditures as share of total
μ	attribute detection cost variable
$I_{s,s-1}$	degree of integration between stages $s-1$ and s
$I_{s+1,s}$	degree of integration between stages $s+1$ and s
δ	preference discovery cost variable
ι	coordination technology cost variable

When the components of the above profit function have certain properties, the four activities identified as elements of value differentiation will be mutually reinforcing, or complementary. That is, increasing the production of desired product attributes at a stage s increases the value of detecting pre-existing attributes as well as the other component activities. The transformation of agriculture is described as a shift from one cluster of activities to another cluster. The existing descriptive literature has identified a number of changes that are simultaneous, or nearly so; the mutual complementarity of these component activities would explain such observations.

2.1. **Supermodularity and Complementarity.** We formalize the notion of complementarities using the mathematical concept of supermodularity. Supermodularity captures the idea that jointly undertaking certain activities will create benefits that could not be realized by undertaking each activity separately; that is, there are benefits created by adopting the complementary activities as a group. Equivalently, the marginal revenue product of any one activity understates the benefit of its adoption if the other complementary activities are adopted simultaneously. The additional benefits captured by simultaneously performing the activities are popularly termed synergies.

Formally, a function $f : \Re^n \Rightarrow \Re$ is **supermodular** if for all $\boldsymbol{x}, \boldsymbol{x'} \in \Re^n$,

$$f(\boldsymbol{x}) + f(\boldsymbol{x'}) \leq f(\boldsymbol{x} \vee \boldsymbol{x'}) + f(\boldsymbol{x} \wedge \boldsymbol{x'}) \tag{2}$$

where $\boldsymbol{x} \wedge \boldsymbol{x'}$ is the vector of maximum elements whose ith element is defined as $x_i \wedge x'_i$, or the maximum of x_i and x'_i, and $\boldsymbol{x} \vee \boldsymbol{x'}$ is the vector whose ith element is defined as $x_i \vee x'_i$, or the minimum of x_i and x'_i. The Cobb-Douglas production function, for example, is supermodular in its arguments, provided all exponents are non-negative.

The following example illustrates the applicability of supermodularity to changes in agriculture. In the broiler industry, new shipping techniques have been developed over the past forty years,

TABLE 1. Complementarities in the Broiler Industry

water absorption	ice baths	old methods
low	30	22
high	27	20

such as ice baths, which increase the distance that fresh unfrozen chicken can be shipped. Since consumers as a whole prefer purchasing fresh chicken rather than frozen chicken, the development of these techniques increased processors' returns from the chicken they sold. The broiler industry is also characterized by substantial vertical integration and coordination, so that the same firms that process and sell chicken also purchase or in some cases develop their own genetics, which influence broiler carcass traits. Over time, broilers have been bred so that their carcasses absorb less water (Havenstein, Ferket, Scheideler and Rives 1994). This trait reinforces the gains from new shipping technologies, since the reduced carcass water absorption results in a more desirable product after shipping. At the same time, the new shipping methods allow the processor to utilize this carcass trait over a larger fresh chicken market. That is, the gains from the two practices jointly is larger than the gains from each of them separately. This is illustrated in Tbl. 1. Note that supermodularity is reflected in the fact that the sum of the differences between the two off-diagonals and the lower right-hand corner is less than the difference between the upper left-hand corner and the lower right-hand corner.

The invention of the mechanical tomato harvester and the breeding of tomato varieties with very narrow maturity windows provide another example of complementary innovations. Without the plant breeding innovation, the mechanical tomato harvester would not have been an technological advance, since the harvester destroys the plants. With varieties for which tomatoes all ripen simultaneously, or nearly so, the loss of the tomato plants is not costly. The harvester, on the other hand, increases the profitability of growing varieties that ripen in a narrow maturity window.

2.2. **Understanding Value Differentiation Using Complementarities.** The essential components of agricultural change identified by agribusiness analysts are exactly the components that have proven difficult for economists to articulate and evaluate using standard marginal techniques. Marrying the two literatures, the theory of complementarities as formalized using supermodularity is capable of addressing these changes. Following the systems orientation of the agribusiness literature, it is based on the observation that production, organization, and management practices tend to occur in clusters. A firm's responses to exogenous changes are mutually reinforcing across these areas, leading to these activity clusters. Supermodularity captures the intuition of the agribusiness literature that relationships among the observed changes in agriculture are important, and explains why it is difficult to assign causality among them. It also has analytical advantages over more traditional techniques; supermodularity allows comparative statics to be performed in more general settings than a marginal analysis would permit. It is distinct from such concepts as returns to scale and economies of scope.[3] Following the agricultural economics literature, the value differentiation framework generates testable hypotheses. We develop the framework in terms of a formal hypothesis from Topkis (1995), and explore its implications for agriculture in the following discussion and corollaries.

Proposition 1. *Let $t \in T$, $x_s \in X$, where T and X are sublattices so that the parameters and non-price, non-quality decision variables are each contained in sublattices. Let $z_s \in Z_s$, and let Z_s be a chain. Let demand $q(p_{s+1,s}, z_s, t)$ be increasing in $(-p_{s+1,s}, z_s, t)$ and supermodular in $(p_{s+1,s}, z_s)$. Let $p_{s+1,s}m - c(m, z_s, t)$ be increasing in m, and $c(m, z_s, t)$ be convex in m and supermodular in (m, z_s, t). Let $k(z_s, x_s, t)$ be submodular in (z_s, x_s, t). Then the following statements are true:*

1. *$\pi_s(p_{s+1,s}, z_s, x_s, t)$ is supermodular in $(p_{s+1,s}, z_s, x_s, t)$ when 1.) the firm takes $p_{s+1,s}$ as given and 2.) the firm chooses $p_{s+1,s}$.*

[3] The supermodularity of a function is not related to its returns to scale; supermodularity is defined exclusively in terms of ordinal rank, whereas returns to scale are cardinal. Note that any function of a single variable is trivially supermodular; hence supermodularity cannot be dependent on whether a function is concave or convex. While conceptually the idea of complementary activities for a firm is quite close to the idea of economies of scope, there are formal differences between the two which will not be addressed here. For more information on how supermodularity relates to other economic concepts, see Milgrom and Roberts (1990). For more information on the formal conditions under which supermodularity holds, see Milgrom and Shannon (1994). Topkis (1978) is a seminal reference in this area.

2. *If all stages $s \in \sigma$ are supermodular, then $\Pi(p, z, x, t)$ is supermodular in (p, z, x, t) when 1.) the firm takes p as given and 2.) the firm chooses p.*

3. *When the firm takes $p_{s+1,s}$ as given, the firm's profit in stage s after optimizing over its decision variables, $\pi_s(p_{s+1,s}, t) = max_{z_s \in Z, x_s \in X} \Pi_s(p_{s+1,s}, z_s, x_s, t)$ is supermodular in (p, t).*

4. *When $p_{s+1,s}$ is a decision variable for the firm, the firm's profit in stage s after optimizing over its decision variables, $\pi_s(t) = max_{z_s \in Z, x_s \in X, p_{s+1,s} \in P} \Pi_s(p_{s+1,s}, z_s, x_s, t)$ is supermodular in (p, t).*

5. *Total profits for the firm after optimizing over its decision variables are supermodular in its parameters.*

An informal discussion of the assumptions and their applicability follows, while technical definitions and the proof are in the appendix. The differentiation variable, z_s, is a chain if any two possible values can be ranked. Intuitively, for this condition to hold it is necessary to be able to quantify the degree of product differentiation, or otherwise rank the differentiation of product attributes. This may be done, for example, by indexing the degree of specialization for related products, or the number of varying product characteristics as a share of total relevant product characteristics. The specified properties of demand simply say that price and the degree of differentiation are substitutes, and that decreases in price affect demand more when the product is less differentiated, while increases in differentiation affect demand more when prices are high. The specification of stage s operating profits, determined by the quantity and degree of differentiation produced, require it to be in a region of positive operating profits. Operating costs increase at an increasing rate as the amount produced increases, and it is more costly to produce a larger amount of a more differentiated product. The second cost component may be conceptualized as technology costs that are dependent upon the chosen degree of differentiation but are independent of the amount of product produced: the costs of investing in preference detection technology, attribute determination technology, proprietary research, coordination technology and integration. The submodularity of technology costs means that the marginal cost of producing a higher differentiation level z_s decreases with increases in the variable technology decisions and the general set of available technology.

The proposition provides an analytical basis for the intuition of the descriptive literature that changes are not only observed together, but they are somehow related. The identified activities are complementary. Each activity positively affects the returns to the others. Accordingly, jointly adopting these activities or increasing the level of each will result in greater increases in profits than increasing each activity individually. Further, once a firm has optimally chosen its production technology, product differentiation, and production quantity, increases in the general technology set or consumer preferences will positively affect the returns to all of the complementary activities. Thus, a relatively small shift in an exogenous variable might lead to relatively large changes in the behavior of the system.

A simple example of such a case is when attribute detection, attribute production, and preference determination have separate cost functions from each other for each stage of production, and each is characterized by the necessary properties for the relevant variables. Attribute detection and preference determination are affected by the degree of coordination with neighboring stages of production. Further, each stage, including final consumers, is willing to pay more for the product the more closely it corresponds to the desired attribute bundle. In this case, the chosen amount of preference determination is dependent on the degree of integration between stages s and $s+1$ and the cost of determining preferences. Essentially, this means that the more specific the desired product attributes are, the more costly it is to determine what attributes are desired by consumers or by intermediate levels of the food chain. Further, the more specific the attributes the more expensive it is to determine an additional increment of desired attributes. The successful and unsuccessful attempts of food product companies to ascertain consumer preferences and introduce new products that meet these preferences illustrate this point. (Unfortunately, failed products such as New Coke and Crystal Pepsi receive the most attention.)

The attribute detection process may be conceptualized in a similar fashion. The more specialized the good, the more costly it is to determine its initial attribute bundle. For example, it is more costly to determine whether or not produce is organically grown than to determine that it has acceptable levels of blemishes to be sold fresh. Similarly, it is more costly to determine the lysine content of corn intended for livestock feed than to simply purchase commodity grain. Generally, it becomes more and more costly to detect additional product attributes, so that the marginal cost of determining attributes increases with the specificity of the desired attribute bundle.[4] For example, while it is more costly to determine the suitability of strawberries intended for the fresh market than for the frozen market, it is even more difficult to determine which fresh strawberries may be shipped long distances and which are suited only for local sales. The shippability of strawberries is determined by the practices of the individual grower in ways that are largely unverifiable when the strawberries are delivered, so that a shipper can determine shippability only through costly experimentation and experience with each grower.

Emerging and anticipated improvements in genetics, other inputs and production techniques are commonly predicted to lead to a more specialized agricultural production sector. This conventional wisdom notes the movement from mass to niche markets and predicts an increase in this movement. Further, it predicts that the differentiation will come increasingly early in the production chain. Implicitly, this argument assumes that producing differentiation is costly. It also assumes that it is possible, indeed necessary, to differentiate products at different levels of the production chain. Further, it recognizes that it may be most profitable to produce different degrees of differentiation at different levels of the food production chain. Some products, such as organic produce and

[4] Some product certification processes arguably place the burden of detection on the seller, rather than the buyer. In this case, however, one would expect that the costs of meeting this certification standard are reflected in the price of the product. Further, if the buyer desires products with more specific attributes than those certified, he must still invest in additional detection. Consequently, there is a marginal cost that the buyer considers when deciding whether or not to change his desired input attributes.

free-range chicken, must be differentiated at the production level. Others, such as cornflakes, are differentiated at the processing and marketing level. Still other products, such as yellow-skinned chickens, are differentiated at the production, processing and marketing levels. At the production level, the chickens are fed marigolds to produce a yellow coloration. At the processing level, the chickens are packaged under a brand name. At the marketing level, the yellowness of the chicken is then used as a way to differentiate the brand of chicken. In each case, differentiation occurs at the level(s) of the chain where it is most cost effective (or simply feasible) to do so. This observation is reflected in the value differentiation model. Further, proprietary research is introduced as a variable affecting the profitability of producing specific attributes.

The firm must also consider the costs of adopting new technologies which alter its cost parameters. Even when the technologies under consideration are parts of different processes, it may be cheaper to adopt a bundle of technologies rather than to adopt each one independently. For example, calibration costs may be less if technologies are simultaneously changed than if the firm adopts them individually and must recalibrate their production process with each adoption.

The above discussion provides examples of the features we would observe for an agrifood system characterized by complementarities across activities, as specified in Proposition One. We can use the definition of complementarity based on supermodularity to make predictions about the behavior of such a system.

2.3. **Is value differentiation biased in favor of certain levels of the production chain?**

The model of the value differentiation process provides insight into some of the policy concerns regarding value differentiation and associated changes in agriculture, including the increased importance of proprietary intellectual property and increased vertical coordination. At their core, these issues address the possibility that the transformation process may be biased in favor of certain levels of the production chain. This is illustrated by the concern regarding proprietary research.

Increasingly, these innovations are privately funded and controlled. One specific hypothesis regarding the transformation process is that it will favor innovators who control the underlying genetic stocks or who conceive new ways of collecting consumer information (Boehlje 1996, Zilberman, Yarkin and Heiman 1997). A portion of their gains likely comes at the expense of others in the production system. Similarly, increasing vertical coordination has often translated into greater off-farm control of on-farm production. This has led to speculation that value differentiation results in farmers losing control of their management decisions and the corresponding returns.

The model may be used to examine these questions. The basis of the model is a profit-maximizing firm, who decides if it will adopt value-differentiating technologies and activities. Firms' decisions across levels of the chain are dependent on each other, in the sense that their alternatives are jointly determined. The model predicts the following regarding which stages will integrate as part of their endogenous response to an exogenous shock or change in production technology decisions:

Corollary 1. *Firms with a greater degree of value differentiation at their stage(s) of production are more likely to increase their degree of vertical coordination under the value differentiation process.*

The proof is in the appendix. One would expect to see firms who are increasing their share of value differentiation added to the product to increase their vertical coordination between adjacent stages of the production process, and to use this increased vertical coordination for greater control over product attributes.[5] Monsanto's purchase of Holden Foundation Seeds in 1997 is an example of this sort of vertical coordination. By obtaining Holden's genetic stock, Monsanto increased its

[5] Note that the analysis identifies the relationship between vertical coordination and the value differentiation process; it is not intended to explain every case of the ownership of different, even adjacent, stages of the production chain by a single firm for other reasons. In particular, if a given stage of production is realizing significant complementarity-driven benefits, one would expect additional capital to enter that stage in order to realize these benefits. It seems highly probable that at least some of this new capital would come from entities that already have operations in other stages of the production chain. Unless this investment alters the coordination between stages, however, it is not associated with value differentiation. That is, ownership of multiple stages of the production chain is not sufficient evidence for the existence of the complementary activities that comprise the value differentiation process. Vertical coordination must contribute to the ability to identify product quality in order to embody value differentiation.

ability to differentiate further its genetically engineered products with other traits. The corollary emphasizes that supermodularity is a concept regarding *changes* in the system, rather than levels.

2.4. **Which factors promote value differentiation?** There are two sources of exogenous change: consumer preferences and the general technology set. In the descriptive literature, both of these forces are predicted to enhance value differentiation, leading to a higher value of z_s and more integration. Structuring the profit function as supermodular allows the model to be used to identify conditions under which this will be true. Interpreting Proposition One, we obtain the following corollary:

Corollary 2. *Exogenous changes in technology and consumer preferences will further the value differentiation process when these exogenous changes increase the marginal returns of the component complementary activities, including preference determination, attribute detection, attribute production, and coordination.*

The prediction of the descriptive literature will be true when exogenous changes increase the marginal returns of the complementary activities, including quality detection, preference detection, quality production, research and integration. One such exogenous change is the rise in the number of two-career and single-parent homes. These lifestyle changes are perceived to have led consumers to emphasize convenience and ease of preparation in their food choices. These considerations have led to greater value differentiation, as purchases of basic foodstuffs have been replaced by partially or fully-prepared foods and entire meals. Consumers' increased emphasis on convenience appears to increase the marginal product of the activities in the value differentiation process.

Biotechnology and information technology are commonly viewed as exogenous forces that will increase the marginal returns to the activities in the value differentiation process, much like the changes in consumer lifestyles discussed above. The effects of these general technologies depends, however, on their applications. Biotechnology innovations such as Bt corn and cotton are designed to reduce production costs rather than to aid in tailoring product attributes. The effects of such cost-oriented innovations on the progress of value differentiation are a priori unknown. These products may simply lower the cost of producing a base commodity with little differentiation, and not affect quality and the value differentiation process. Alternatively, consumer refusals to use bioengineered products, such as the European Union's ban on Roundup Ready soybeans, may indirectly aid value differentiation in oilseeds and grains by forcing the creation of methods to maintain product identity at each stage of the production chain.

Potentially, these products may slow the value differentiation process, for two reasons. First, the bioengineered products may reduce the cost of producing a specified attribute bundle $\bar{z}_s$, but not reduce the cost of producing a more differentiated product. Accordingly, the marginal cost of producing $\bar{z}_s + \delta$ is increased by the reduction in production costs for $\bar{z}_s$ due to the innovation. This marginal cost increase may cause such bioengineered products to slow value differentiation. Similarly, if biotechnology results in a more homogenous product at the production level, the marginal benefit of improving attribute detection may be reduced. Consequently, an increase in available biotechnology does not result in an increase in the marginal returns to all of the complementary activities. In this case, innovation does not further value differentiation.

Formally modeling the value differentiation process allows the predictions of the descriptive literature regarding the effects of exogenous changes to be clarified. The forces identified as promoting value differentiation may not do so. The predictions of the descriptive literature are overly broad. The model demonstrates that it is important to understand the interaction between an outside force and value differentiation before predicting its effect. In particular, cost-reducing innovations do not necessarily contribute to value differentiation.

What the model cannot do in this reduced form is to predict the precise outcome of a particular exogenous change. The exact magnitude of its impact is dependent upon the structural forms underlying this reduced form model. By using supermodularity, however, we can characterize conditions under which the direction of these changes can be predicted. This limitation is a general characteristic of theoretical models.

3. Conclusions and Implications

Value differentiation is characterized by complementarities across activities that aid firms in identifying desired products and delivering these products to consumers at the lowest possible cost. The exogenous changes in technologies and tastes that are commonly identified as the forces of change cannot account for the nature of the process, which includes four complementary activities: attribute detection, preference determination, attribute production and coordination. This model of the value differentiation process incorporates the insights of the descriptive literature into an analytical framework, which allows us to assess the extent of value differentiation in a given product, provide qualitative predictions, and address policy concerns.

Formalizing the observations of the descriptive literature using supermodularity provides a model that is reduced-form but nonetheless has some predictive power, and hence provides testable hypotheses. Proposition 2 shows that exogenous shocks which increase the marginal values of the core value differentiation components will have a favorable effect on value differentiation. While technological innovations that reduce the costs of unit production may benefit their inventors, users, and others, their effect on the value differentiation process is determined by how they affect firms' decisions regarding these processes, not by their effect on the cost of producing units of a given degree of differentiation. The value differentiation framework allows for a systemwide evaluation of the factors affecting firms' decisions.

The model's predictive power is conditional upon exogenous shocks to the system. Given a shock or the absence of a shock, the model can describe the system's path. The model cannot predict the timing and nature of an uncontrollable exogenous shock that will be sustained by a subsector. Given its parameters, a subsector that begins to transform can do so very rapidly, resulting in a revolutionary rather than an evolutionary pattern of change. Similarly, a subsector that sustains a differentiation-promoting shock, such as a fall in the cost of more finely defining consumer preferences, is likely to rapidly increase its use of the entire cluster of complementary activities. A relatively small exogenous shock can induce relatively large changes in firms' activity choices, due to these complementarities.

3.1. **Implications for Firms.** The nature of the value differentiation process implies that firms need to identify and engage in the entire cluster of complementary activities in order to capture these non-differentiable benefits. Innovation does not guarantee success in value differentiation; if an innovating firm does not engage in the full set of complementary activities, its ability to fully capture the benefits of its innovation is limited. Further, we would expect such a firm to not perform as well as a competing innovative firm which did engage in the full set of complementary activities.

For the sector as a whole, innovations which create value through differentiating products along valued product dimensions are likely to create the most value. Due to firms' incentives, however, these are not necessarily the innovations we would expect firms to pursue. Innovations which promote a firm's other activities are likely to result in the largest gains for a firm, so these are the types of innovations most likely to occur.

3.2. **Implications for Marketing Orders and Commodity Groups.** Like individual firms, commodity-level organizations need to address the nature of the value differentiation process. These organizations should seek to identify and engage in the complementary activities that will allow them to create product value and capture this value for their members. Further, the firm-level implications above contain a cautionary message for these organizations; if commodity groups do not aggressively pursue value differentiation, as private firms have already begun to do, then they and their members are unlikely to benefit from the associated changes.

3.3. Implications for Government Policy. Assume that the government desires to promote value differentiation,which is a normative question not addressed here. In that case, the relative size of the exogenous shock and the ensuing outcome indicates that the government may be able to influence the path of value differentiation through judicious attempts to shock a subsector. This in turn suggests a criterion for the allocation of government research funds; the government should allocate funds to products which possess a full set of complementary activities. In practice, this means that the government will maximize social surplus by providing public research funds to products where firms already engage in proprietary research and development. As noted previously, firms will not necessarily seek the innovations with the largest sectoral returns. A more challenging focus for government research efforts would be augmenting private efforts in those industries with low levels of one or two complementary activities.

This suggestion is a version of the suggestion that governments can pick winners. History has demonstrated that this is a very treacherous undertaking, so treacherous that perhaps it ought not to be undertaken at all. Unidentified, interaction effects, such as the complementarities we identify above for the American agrofood sector, are likely an important cause of the difficulty of picking winners. *If* the government desires to attempt to pick winners, it should utilize a model such as the one developed here, which focuses on interactions across activities.

3.4. Evaluating Returns to Research. While choosing winners may be a risky undertaking, evaluating social returns to government research helps policymakers determine their winning investments ex post. Our framework implies that returns to research may need to be broadly defined in order to be accurately measured. Research which promotes value differentiation will have benefits above and beyond its direct marginal product. Although it may be difficult to precisely evaluate the contribution of research if other value differentiation-promoting changes are present, it is important to not dismiss these non-differential benefits completely when estimating returns to research.

Appendix: Definitions and Proofs

A **sublattice** may be defined as follows: A set X is a partially ordered set if it is a set with a reflexive, antisymmetric and transitive binary relation $\leq$. For any two elements of X, $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$, their least upper bound (if it exists) is called their **join**. Their greatest lower bound is called their **meet**. A partially ordered set is a **lattice** if it contains the meet and join for all possible pairs of elements. If X is a lattice, and S is a subset of X, S is a sublattice of X if it contains the meet and join for every pair $\boldsymbol{s}_1, \boldsymbol{s}_2 \in S$.

A chain may be defined as follows: if $X \subseteq \Re^n$ and if $x \in X$ and $x' \in X$ imply that either $x \leq x'$ or $x' \leq x$ then X is a chain.

Proposition One

Proof. The first, third and fourth statements are direct applications of theorem 3.5 in Topkis (1995). The second and fifth statements hold because the sum of supermodular functions is supermodular (property proved in Topkis (1978)). □

Corollary One

Proof. The proof follows directly from the application of supermodularity to the complementary activities in the value differentiation process in Proposition One. Vertical integration and differentiation are complementary activities at stage s. That is, stage s profits are supermodular in these decision variables. Hence, increase in these activities should be observed together. □

Corollary Two

Proof. Corollary Two follows directly from Statement Five in Proposition One. If the parameters are ordered (belong to a sublattice), and possess the necessary properties specified in the proposition, then increases in the parameters will further value differentiation. □

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