Estimating Perennial Crop Supply Response: A Methodology Literature Review

Jonathon Siegle[1]
Gregory Astill[2]
Zoë Plakias[3]
Daniel Tregeagle[4]

[1]Department of Agricultural, Environmental and Development Economics, The Ohio State University, Columbus, USA.

[2]USDA Economic Research Service, Kansas City, USA.

[3]Department of Economics, Western Washington University, Bellingham, USA.

[4]Department of Agricultural and Resource Economics, North Carolina State University, Raleigh, USA.

Corresponding Author: tregeagle@ncsu.edu

Received 28 March 2023; received in revised form 3 November 2023; accepted 23 November 2023.

Estimating Perennial Crop Supply Response: A Methodology Literature Review

Abstract

Perennial crops are important both economically and as a component of a healthy and nutritious diet (e.g., many fruits and nuts). However, the study of perennial crop production and farmer response to output price changes (i.e., supply response) is complex thanks to the dynamic nature of investment and decision making in these industries. The body of literature relevant to perennial crop supply response is also small relative to that of annual commodity crops. In this article, we contribute the first literature review on perennial crop supply response modeling in more than 30 years. We catalog advancements in estimating perennial crop supply response and discuss the application of these methods and trade-offs economists should be aware of when using them. In addition, we highlight future modeling developments that may be valuable to the field, with the hope this research will encourage additional economic research on this interesting and important topic and in turn provide new insights for perennial crop producers and policymakers.

Keywords: perennial crops, supply response, survey of literature

JEL Codes: Q11

1. Introduction

In this article, we contribute the first literature review on perennial crop supply response modeling since Akiyama and Trivedi (1987), cataloging advancements in estimating perennial crop supply response, as well proper application of these methods, pitfalls economists should be aware of when using them, and future modeling developments that may be valuable to the field. A broad field in economics aims to estimate agricultural supply response to changes in output price, agronomic factors, and other shocks. Modeling this supply response in the complex setting of perennial crops requires unique frameworks because these crops can be harvested year after year from established plantings. Furthermore, perennial crops are both nutritionally and economically important globally.

Most fruit, berry, and tree nut crops are grown as perennials and are highly nutrient dense. World Food Prize laureate Per Pinstrup-Andersen wrote that “creating incentives for consumers to change their diets to meet both energy and nutrient needs, such as research to increase productivity and reduce unit-costs of those foods that could most effectively add the nutrients that are deficient” is the best option we have to help provide all humans with access to “a diversified diet that meets all energy and nutrient requirements” (Pinstrup-Andersen, 2007). Over a decade later, in his Fellows Address to the Agricultural and Applied Economics Association, Chris Barrett called healthy diets “today’s primary agri-food systems challenge,” highlighting the importance of micronutrient-dense fruits, berries, tree nuts, vegetables, and legumes in healthy diets globally (Barrett, 2021).

In addition, many perennials are high-value and increasingly traded on international markets. In the United States, perennial crops are grown on 1.5% of crop acres, but they make up about 15% of the value of crops sold (USDA NASS, 2019). Because perennial crops are some of the highest value agricultural commodities traded on international markets, they are important sources of income for many developing economies that export them. Worldwide, fruits, tree nuts, and cocoa products make up 9% of the value of exports (USDA FAS, 2023). Among the $200 billion of US food imports in 2022, 18% were fruits, tree nuts, or cocoa products and another 6% was coffee (USDA ERS, 2023).

Understanding how growers of these nutritionally and economically important crops respond to incentives requires us to have rigorous measures of their supply response. There are many cases when it is useful to estimate the supply response to new conditions, such as a policy intervention to control plant diseases (Singerman et al., 2017), restrictions on planting for farm support programs (Balagtas et al., 2014), or a new trade deal (Demko & Jaenicke, 2018). While there are a multitude of published models to estimate the supply response for annual commodity crops (e.g. Rao, 1989; Haile et al., 2014; and Iqbal & Babcock, 2018), these models cannot be used to estimate perennial crop supply response because the choice to plant perennial crops is akin to a long-term capital investment. Estimating the causal impact of perennial crop price on quantity changes requires factoring in all other drivers of production decisions—for example, climate, pest and disease risk, market structure, technology adoption, and the cost of other inputs—over the lifetime of the capital investment.

We may expect the law of supply to hold in the long run—i.e. that acreage would increase with price. However, consider the case in which the owner of a Florida orange grove experiences unusually high prices for several years because citrus greening disease is ravaging groves in neighboring counties. Citrus greening, also known as huanglongbing (HLB), is a disease spread by the Asian Citrus Psyllid that is a major concern for Florida citrus growers. Because the disease could be spread to a new area at any time, the manager faces risk of a long-term crop failure, in which case they would not be able to profit from high prices. Under such a threat, they may decide to plant no new trees. And in spite of the high prices, owners of already impacted groves may decide to not replant their infected trees. In this scenario, supply becomes increasingly price inelastic due to a novel disease. A study that did not allow for this leftward shift or decreased elasticity of supply, or just interpreted the disease as increasing marginal costs, might incorrectly presume that Florida's orange supply may survive at a new equilibrium where higher prices make up for the costs of the disease. Indeed, as of 2022, Florida orange production has continued to fall, even as on-tree prices have recovered in recent years (USDA NASS, 2022).

The body of literature relevant to perennial crop supply response is small relative to that of annual commodity crops. However, within this smaller body of research, there have been a series of important innovations in modeling perennial crop supply response that have yet to be systematically reviewed. We fill this gap in the literature with the present review. In section 2 we define supply response. In section 3 we delineate the uses, benefits, and shortcomings of the common frameworks used in supply response models. In section 4 we dig into two aspects of modeling that are important in light of perennial crops' long life cycle: orchard capital management and profit expectations. Section 5 considers how models of perennial supply response are contextualized in more complex models via horizontal and vertical linkages. We conclude with a discussion of the current state of the perennial crop supply response literature and opportunities moving forward, of which there are many.

2. Defining Supply Response

Supply response is generally referred to as the elasticity of the quantity of some specific commodity supplied with respect to its own price (Ball, 1988; Babcock, 2015). However, the definition of agricultural 'supply response' in the literature varies across authors and settings (Rao, 1989). Supply may be responding to changes in its own price, the price of substitute or complementary goods, agricultural policies, or environmental factors such as weather or disease pressure. In the context of perennial crops, it is particularly important to be precise about the meaning of this term. For annual crops the price elasticity of supply generally refers to the sensitivity of short-run production to price received. In contrast, perennial crops require long-run capital investment to yield short-run outputs, so for perennial crops it is necessary to distinguish between a short-run response (within year adjustments) and a long-run response (plantings and removals of trees, which affects the bearing acreage, i.e., capital). Failing to distinguish between these short-run and long-run responses could lead researchers or those stakeholders who use their research outputs to misinterpret the source of production changes, with implications for policy- and decision-making.

Regardless of the specific formulation, economists generally assume that perennial crop farmers choose inputs, production levels and plantings to maximize profits within the capabilities of their farm. For the sake of exposition, we consider the economic choice set of an orchard manager, which can be expressed mathematically through a constrained optimization problem, such as the following short-run profit function:

$$\pi = P * Q - C(x), \qquad s.t.\ Q < F(x|K) \tag{1}$$

where P is price received, Q is output, K is capital (specifically, trees), x represents variable inputs, $C()$ is the short-run cost function, and $F()$ is the short-run production function. The condition $Q < F(x|K)$ limits the orchard manager to realistic production levels given a fixed capital stock of trees. In the short run, the only choice variable in equation (1) is x, the short-run variable inputs. In the long-run, K, the capital stock (i.e., number of trees) can also be a choice variable.

In keeping with convention for annual crops, the short-run price elasticity of supply, ε, for perennial crops is generally defined as the percent change in quantity supplied over a percent change in price received over a sufficiently short period of time such that K and the parameters of *F()* are constant:

$$\varepsilon = \frac{\%\Delta Q^{*}}{\%\Delta P} \tag{2}$$

The term ε expresses the flexibility of decisions (choices of variable inputs x) such as intensifying input use and/or harvesting effort in response to changes in prices received, which affect the quantity produced, Q^*. To increase Q^* substantially, more trees must be planted, land must be allocated and/or machines must be purchased, each of which adjusts the firm's stock of capital, K. Long-run price elasticity of supply uses the same form as (2), but with K also varying. The heart of the issue for perennial crops is that the biological growth process of trees creates 'asset fixity,' meaning the stock of 'orchard capital' is slow to adjust and perennials can take much longer to reach the long-run than annuals (Basu & Gallardo, 2021).

While the above formulations say something about agricultural production (i.e., quantity of output), this quantity response can be decomposed into yield response and acreage response (Babcock, 2015). Acreage response[1] is an especially important determinant of perennial crop production. Because perennial crops may require several years of establishment before their first harvest and multiple harvests can be obtained over the plants' productive life, planting decisions

[1] To conflate trees with acreage requires us to assume that planting density of trees is constant. Theoretically, there may be cases where the optimum planting density depends on factors relevant to the research question. However, acreage is the common definition of capital in both public data sources and the literature.

affect production over multiple harvest periods and, more than annuals, removal decisions may be distinct from harvest decisions. For these reasons, the literature frequently directly considers the investment (i.e., acreage) response of orchards to changes in price received:

$$\varepsilon_K = \frac{\%\Delta K^*}{\%\Delta P} \tag{3}$$

Thus, the short-run price elasticity of supply (2) measures the sensitivity of short-run production to price received, while the investment response (3) aims to capture the sensitivity of long-run changes in capital investment to price received.

Many studies do not calculate the investment response ε_K explicitly but rather estimate a 'net planting function' describing changes in bearing acreage or a similar variable as a function of price received and other relevant variables. This net planting function can then further be decomposed into a planting function and a removal function. Some studies further delineate the age classes of an orchard, i.e., how many trees there are of each age, as tree age is an important determinant of yield. The youngest trees will have zero yield for several years until the tree reaches maturity, and trees in these youngest age classes are generally referred to as non-bearing acreage (in contrast to bearing acreage, which is the acreage of mature fruit-bearing trees).

Both the price elasticity of supply and the investment response of supply are rooted in the orchard manager's multifaceted optimization problem and most formulations of this problem abstract away from some element of the orchard manager's decision context. More comprehensively, (3) is a partial derivative of a multidimensional space: the investment response function encompassing all relevant state and action variables. We can rewrite (3) into a more detailed planting elasticity to note this:

$$\varepsilon_K(K_t, Z, P) = \frac{\%\Delta K_0(K_t, Z, P)}{\%\Delta P} \tag{4}$$

where ΔK_0, the net change in plantings, is conditional on a vector of acreage stocks across age classes K_t, price P, and a vector of other relevant variables, Z. Other ways to make supply response more conditional include interacting K_t, Z and P to allow for multiplicative and nonlinear effects. However, including interactions between price movements and these other variables is surprisingly rare in this literature. Notable exceptions include Brown et al. (2004) who derived interactions between the slopes of regional demand and French and Matthews (1971) who used interactions between prices received and harvested acreage.

In the perennial crop literature, we see a variety of approaches, and we contend that it i s important for authors to be intentional and explicit about the type of supply or investment response they are seeking to measure and ensure their estimation strategy is consistent with this desired result. Conditioning supply response on observable variables brings these parameters closer to their theoretical underpinnings in (1). However, estimated elasticities such as (4) and calibrated models built on optimization problems such as (1) remain different research products, as we discuss in the following section.

3. Common Approaches to Estimating Perennial Supply and Investment Response

There is no one single accepted approach to estimating perennial supply response and its composite parts discussed in the previous section. As with any research, the goals of the work and specific questions asked will determine the methods, but given the complexities of perennial crop supply response and the challenges of estimation, this literature is relatively heterogeneous even compared to the literature on supply response for annual crops. There are several key factors that determine or distinguish the approaches used by researchers.

One key factor that determines the estimation approach is whether the question or goal of the work has some forward-looking element (*ex ante*) or is entirely backward-looking (*ex post*). Carpentier et al. (2015) touch on similar concepts in their review of modeling agricultural production. Forward-looking or *ex ante* research considers questions like “What could be…?” or “What would happen if…” Backward-looking or *ex post* research, in contrast, considers questions like “What happened…?” However, it should be noted that these approaches are not mutually exclusive; most *ex ante* studies involve at least some *ex post* components in order to calibrate the models to observed data and ground them in reality.

A second factor that determines the approach is data availability. In general, data availability is a substantial constraint in this work. Fewer data are collected on perennial crops compared to annuals, and often when data are collected the many types of data needed to fully describe the characteristics of investment and production outlined in the previous section are not available (Just & Pope, 2001).

A third key factor that determines the approach is the assumptions about decision-maker behavior. If a researcher assumes—or wishes to impose or test—for optimizing behavior consistent with theory, then a model which derives from or allows imposition of this theory is necessary (*which* theory is irrelevant here but will be discussed later in the paper). This approach contrasts with approaches that seek to explain observed phenomena or predict future phenomena based on past observation but are agnostic about the relationship of past or future behavior to established economic theory of optimization.

Together, these three key factors can help us characterize the universe of models used in estimation of perennial supply response and the options for researchers (see Figure 1).

[Figure 1 about here]

In Figure 1, we can see that on the *ex ante* side of the tree (left), theoretical consistency matters for determining modeling approach, and whether data are abundant or scarce is irrelevant. However, on the *ex post* side of the tree (right), it is the interaction of data availability and desire for theoretical consistency that determines the choice of model. It should also be noted that data abundance or scarcity is an intentionally ambiguous term and is endogenous to the research question. Rather than thinking of strict cutoffs or definitions for whether data are scarce or abundant, it might be more realistic to think of data availability as a spectrum; the methods feasible to answer a research question shift as data relevant to that research question become relatively more scarce or more abundant. Notably, these key factors highlighted in Figure 1 do not specifically relate to perennials. Section 4 of the paper delves specifically into the two unique aspects of perennials—orchard capital management and profit expectations—which must be considered in the context of whichever approach is used for estimation.

The simplest approaches to perennial response involve one or more regressions estimated individually with production or net plantings as the dependent variable. For example, Spreen et al. (2014) ask the *ex post* question, what has been the impact of HLB on new citrus plantings in Florida? The authors' estimated planting function includes lagged new plantings, grower prices, and a dummy variable for the year that citrus greening was discovered in Florida. This regression estimates how much lower acreage allocation was in the post-disease period than prior, after controlling for the effect of price trends. These are generally used for *ex post* analysis, but at times may also be used for *ex ante* prediction following estimation—indeed Spreen et al. (2014)

do this using an existing spatial equilibrium mathematical programming model of the world market for orange juice they had developed in earlier work (McClain, 1989; Spreen et al., 2003).

Multiple equation approaches are often used when more data are available. For example, Roosen (1999) estimates the short and long run response of U.S. apple production by region and market channel using three-stage least squares. Devadoss and Luckstead (2010) estimate plantings, removals, and yield for apples in Washington State using theoretically-derived estimating equations and derive expected profits assuming rational expectations. In addition, some (not all) *ex post* analyses derive the form of their regression model from a theorized optimization problem and its Karush-Kuhn-Tucker conditions or Euler-Lagrange equations. Examples of this approach in perennial crop supply include Wickens and Greenfield (1973), Dorfman and Heien (1989), and Devadoss and Luckstead (2010). Finally, vector autoregression can also describe dynamic interrelationship between variables such as yield, price, and plantings.[2] Akiyama and Trivedi (1987) develop a vector error correction model, a type of vector autoregression where variables are stationary in their differences, for plantings and removals.

The advantage of regression approaches is in their (relative) simplicity, although that is also their weakness, as they may not be able to sufficiently characterize the multidimensional nature of orchard capital management (see Section 4). Furthermore, models of this type cannot be easily extended past a change in market structure and may have strong implicit assumptions. Researchers using these approaches will have to consider a series of important questions. How do prior prices inform expectations? How do we read capital constraints from a time series of acreage information? How do we define the dependent variable and why? What variables can represent opportunity cost?

[2] Ghanem and Smith (2022) is a useful resource on the subject.

The importance of various age classes of trees discussed in the prior section, combined with the paucity of detailed data on age classes, has led to the use of state space models as another method of *ex post* estimation. In a state space model, the observation equation sets the end-product of the data generating process as a function of 'state' variables that update along the panel according to their previous values and in response to covariates.[3] This format uses that researcher-provided structure to estimate response functions in the presence of missing data on subcomponents of the variables of interest.

For example, Knapp and Konyar (1991) use a state space approach to estimate the effect of expected profitability and existing acreage by age-class on plantings and removals for alfalfa plants, while only observing total acreage and total production. Similarly, Kalaitzandonakes and Shonkwiler (1992) set their observation equation as total plantings, for which they have data, equal to the sum of replacement plantings and new plantings. By utilizing a structure that set investment plantings and replacement plantings as states that evolved in response to distinct sets of shocks, they were able to separately estimate the effect of key variables on these distinct aspects of orchard management.

The primary advantage of state space models is their ability to do more with less; the defined measurement equation can extract and model component variables (e.g., plantings vs. removals from yearly acreage counts). State space models are also able to handle missing data in time series with relative ease. Of course, these models come with trade-offs. In place of disaggregated observations, state space models require a set of identification restrictions, making the model conditional on these assumptions and subject to the risk of error if the assumptions behind these identifying restrictions are not well founded. In addition, trying to estimate too

[3] See Durbin and Koopman (2012) for an introduction to state space models.

many unobserved state variables can lead to low identification power. State space models thus require a delicate balancing act between the use of observed data and researcher-imposed assumptions.

In the *ex ante* arena, two main approaches are mathematical programming and structural simulation. Mathematical programming approaches generally involve characterizing an orchard manager's objective function and constraints and solving for the optimal investment or other inputs given these assumptions and exogenous parameters. Structural simulation involves characterizing the market using a set of equations, calibrating these equations to observed data, and then predicting the impacts of various shocks to exogenous parameters given these relationships. Thus, while mathematical programming approaches are consistent with the theory of optimizing behavior by producers, structural simulations generally are not because although they do impose some assumed relationships reminiscent of theory, they do not impose optimizing behavior. The objective functions of mathematical programming models may be extended in a variety of ways. Spatial equilibrium trade models are a subset of mathematical programming models where the objective is to maximize total societal welfare and the choice variables are prices and quantities in each region. Real options models extend the producer's objective function to incorporate risk and the degree of irreversibility of investment decisions.

For example, Zhao et al. (2007) ask the *ex ante* question, what could happen if apple maggot spread in Washington State? To answer this question they develop a theoretically-consistent dynamic optimization model (which they call a simulation in their work, but which in fact is a mixed complementarity problem, a type of mathematical programming). The authors define profit-maximizing growers to represent each production region; apple maggot infestation impacts these growers by increasing production and export costs in infected regions. The total yield from tree stocks each year interacts with modeled demand functions to generate the next year's prices. They then consider the price and welfare impacts if the spread of the pest could be controlled by policy, contrasting historical results with the results of the same representative growers reacting to these counterfactual scenarios. Historical data are used to calibrate the model to a single year (i.e., to ensure that values generated by the model are consistent with observed values), and various data sources are used to estimate or directly source parameter values needed for calibration. In contrast, Jiang et al. (2017) develop a dynamic equilibrium displacement model of the U.S. pear market that incorporates acreage response and explores various shock scenarios. Although solved through a wholesale market clearing condition, optimization by producers is not imposed within this structural simulation model.

The strength of both mathematical programming and structural simulation approaches is their ability to incorporate a range of scenarios and provide insights that may be of interest to policymakers and decisionmakers. However, both model types require substantial knowledge of the market and many types of data (although it may be cross-sectional) to calibrate the various aspects of the model. In many cases, exogenous parameters for these models are taken from prior literature; of course estimating model inputs from observed data would require substantial work but may yield pay-offs with increased model accuracy. Calibration usually involves adjusting the exogenous model parameters until the model outcomes match one or more observed years of data, although there do not seem to be agreed upon calibration standards (or agreed upon metrics with which to determine a particular standard is achieved) within this literature. Mathematical programming models may allow some trade off of calibration data for calibration assumptions. The weakness of these models is that they are only as good as their assumptions (including exogenous parameters). Furthermore, complex mathematical programming models may fail to converge, requiring the researcher to adjust the model and eliminate, simplify, or change elements they had deemed important.

In addition, for models that reach beyond the orchard or farm sector (discussed in more detail in Section 5), the researcher may decide to simulate different types of actors with different methods. In the literature on perennial crop supply response, spatial equilibrium trade models, noted above as a subset of mathematical programming models, are a particularly common use of this hybrid methodology. Papers such as Spreen et al. (2003), Spreen et al. (2014), Jiang et al. (2017), and Tozer and Marsh (2018) use mathematical programming to allocate fruit across demand regions and simulate the prices received while accounting for trade barriers. Meanwhile, the supply of fruit comes from the yield of existing tree stocks that update according to a planting function estimated by linear regression. In these hybrid approaches, each of these submodels are updated annually using previous results from the other; plantings using last year's prices, and spatial equilibriums using total yields changing with bearing acreage. While these models do not allow for anticipatory effects, this dynamic updating allows these models to trace the path of perennial crop stocks over time.

For additional information about the evolving approaches to perennial crop supply response, we refer the reader to earlier reviews on this topic. Askari and Cummings (1976) provide an exhaustive review of agricultural supply response models that use the Nerlovian supply response framework prior to 1976, including an extensive chapter on perennial crop supply response, discussing many of the challenges to its estimation that continue to this day. Their 1977 companion paper provides an index of the papers included in their 1976 book and a summary of the estimated supply elasticities. Akiyama and Trivedi (1987) provide the most recent overview of the alternative approaches to incorporating investment decisions specific to perennial supply response estimation. There are many more reviews and surveys of agricultural supply response in general that do not focus on the issues of perennials in particular (e.g. Rao, 1989, Babcock, 2015, Carpentier et al., 2015, among many others).

4. Notable Subjects in the Perennial Crop Supply Literature

In the discussion above of commonly used methodologies for estimating perennial crop supply, we have mentioned several pertinent issues fundamental to perennial crops. Orchard stocks are more complex than a single capital variable *K*, instead featuring a suite of ages of crops and actions (planting, replanting, removal, and aging through inaction) that alter those stocks. These orchards are optimized for returns in the context of international supply chains. Perhaps most fundamentally, while theoretical optimization of plantings should be over *future* prices, the data available to both managers and researchers includes only *past* prices. The following sections each focus on one of these fundamental issues and include examples of how the literature has addressed these issues.

4.1 Orchard Capital Management

Perennial crops' most distinguishing feature relative to annual crops is their natural lifecycle. A perennial crop will go through an establishment period that does not produce harvest, followed by multiple harvest seasons before the plant either dies or becomes uneconomical to keep. This means that perennial crops are a form of durable capital, and current output becomes a function of a series of past investment decisions (Askari & Cummings, 1976). The stock of 'orchard capital' can be divided into a number of age classes, or vintages (Akiyama & Trivedi 1987), where each age class of the crop is a distinct capital holding. These age classes may have different operating costs and yields depending on the planting system selected when the orchard is established. Extensive research has examined the productivity and cost effectiveness of orchard planting systems including various V-shaped pruning strategies (DeJong et al., 1999; Day et al., 2005), high density planting using dwarfing rootstocks (Elkins et al., 2008; Lordan et al., 2019), and various trellis systems (Krewer et al., 2006).

Each year the orchard manager may adjust their capital stock by investing (planting new trees) or disinvesting (removing existing trees). In addition, the capital stock of perennial crops may diminish due to plant disease, pests, adverse weather, or other exogenous events. The relative benefits of expanding or contracting orchard capital investment depends not only on firms' long-term expectations (discussed in more detail in the next subsection), but also on the composition of their 'portfolio' of crop age classes, available management strategies for crop risks, and other firm characteristics. This subsection discusses papers that have dealt with the vintage nature of perennial cropping systems and their implications for orchard capital management.

A simple example of incorporating the 'perennials as capital' concept econometrically is to include variables representing present acreage stocks as control variables in estimates of net planting functions. For example, several papers have estimated net planting functions that include non-bearing acreage—the acreage still in the establishment period—as a covariate (Kalaitzandonakes & Shonkwiler, 1992; Pompelli & Castaneda, 1994). Alternatively, the planting function may control for the proportion of acreage that is 'old' (French & Bressler, 1962) or a suite of similar variables breaking down stocks by age (Alston et al., 1980). Typically, researchers do not interact these with price variables, implying that these capital variables affect planting/removal decisions but do not change how sensitive those decisions are to price. The model of French and Matthews (1971) is unusual for including an interaction between price and average harvested acreage in their acreage change equation, although they eliminated it from their final specification due to correlations between their interacted variable and other covariates.

For each direction of a shock's implied effect on orchard profitability, the manager endogenously decides how to address it through adjusting the age-structure of their existing orchards via replanting trees and through adjusting their total stock of orchard capital via removals or new plantings (although these last two choices also affect the age distribution). As Akiyama and Trivedi (1987) point out in their vintage capital model, without further parameterization and structural modeling, even the sign of the response of new plantings to a change in profits is indeterminate. An increase in expected future profitability will increase the desired capital stock, which would stimulate new plantings. On the other hand, the increase in expected profits also makes the existing capital more profitable, leading to a delay in removals and replantings, which disincentivizes new plantings, leaving the net effect ambiguous.

Several papers address this by separating long-term and short-term profit expectations: the former is assumed to only affect new plantings, while the latter is assumed to only affect removals and replantings. French and Bressler's (1962) seminal work estimated separate regressions for plantings and removals; plantings were estimated as a function of 5-year average returns, standing in as long-term profit expectations, while removals were estimated as a function of current returns (short-term expectations), the proportion of old trees, and urbanization. Several other papers use similar strategies (French & Matthews, 1971; Alston et al., 1980; Knapp & Konyar, 1991). However, this literature has not converged on a theory of expectation formation specific enough to demarcate between changes in long-term and short-term expectations; these historical works instead rely on *ad hoc* researcher decisions and/or testing increasingly lagged price information until statistical significance is lost.

The yield of a perennial crop will typically vary over its bearing years. Expected yield may be calculated by an inner product of average yields and crop stocks by age class. This yield variation by age class works to motivate vintage capital management and papers aiming to estimate heterogeneous effects across age classes. For example, Zhao et al. (2007) seek to model the welfare impacts of the spread of apple maggot, which increases production cost, across groups and time. Allowing for heterogeneous age structure, as opposed to an aggregate bearing acreage, allows them to isolate the impact of fighting apple maggot infestations on net plantings and on removal decisions by age class. French et al. (1985) estimate the effect of recent returns on removals across ages of peach trees, as opposed to just total removals. Moreover, some research questions relate to shocks that have differential effects by age-classes. For example, citrus greening disease spreads faster through groves of young trees than older ones (Gottwald et al., 2010). Zapata et al. (2022) include this fact in their simulations estimating the profitability of recommended management practices for citrus greening.

Detailed data that disaggregates net plantings by plantings, replantings, and removals are not always available. In this case, most papers restrict their analysis to an overall stock of orchard capital, perhaps making a distinction between bearing and non-bearing acreage. However, state space models are a method used to make age-structured inferences using aggregate data. Knapp and Konyar (1991) use aggregate production and acreage data for California asparagus in state space observation equations to estimate unobserved new plantings and removals by age class. Similarly, Kalaitzandonakes and Shonkwiler (1992) use a state space model to estimate new plantings and replantings without direct data on either; instead, total plantings as the sum of the two serves as the model's measurement equation.

In total, these results imply a set of supply response elasticities by age class, operationalized through plantings, removals, and replantings, that are each dependent on a vector of existing stocks and another vector of profit expectations across time. The degree to which the researcher is able to separately identify each supply response elasticity depends on the data available and the methods used.

Models attempting to simulate optimized orchard behavior with further complexity typically do so using Mathematical Programming methods or using some decision rule derived from optimization theory. Knapp (1987) constructs a dynamic equilibrium model for perennial crops where removals and new plantings are assumed to maximize long-term social surplus due to a competitive market among growers. Applying that model to California alfalfa, they find that relatively stable total output obscures changes between age classes. While aggregate yield is stable, this was not due to a constant share of the crop in each age-class, but rather cyclical evolutions in age-class crop share that roughly balanced out in terms of yield. The emergent property of self-correcting cycles in production was an early discovery in this field (French & Bressler, 1962), but understanding these cycles through vintage capital management reveals under-explored topics for research and policy analysis. Perennial crop industries could be unusually vulnerable at points in these cycles where a new 'generation' is timed to be planted, confounding how the timing of cause and effect of historical shocks should be understood. Moreover, the shape of a perennial crop industry's cycle could hinge on non-agronomic factors such as the degree of income-smoothing desired, itself a function of alternative methods to protect or invest orchard finances.

Another plausible cause for delays between shock and effect is the durability of perennial crops and the costs to remove them. Because investments in perennial crops are largely irreversible, adjustments may not occur when expected net revenue equals opportunity cost, but at some threshold sufficient to compensate orchards for the risks involved (Wesseler & Zhao, 2019). Irreversible investment is analyzed through the ‘real options’ framework introduced by Arrow and Fisher (1974) and Henry (1974). Following Hertzler (1991) and Dixit and Pindyck (1994), Price and Wetzstein (1999) apply the real options framework with Ito stochastic control to calculate entry and exit thresholds for Georgia peach trees, assuming that price and yield follow random Brownian motion. Their model of peach trees as an irreversible sunk-cost investment shows large potential gaps between the expected profits that would spur entry and exit. Subsequent studies have used real options to analyze, *inter alia,* the optimal harvest sequence of a perennial within a season (Blank et al., 2001), investment and disinvestment in new perennial crop varieties (Richards & Green, 2003), entry and exit decisions (Luong & Tauer, 2006), and switching between perennial and annual crops (Song et al., 2011).

An alternative *ex post* strategy to applying orchard capital management concepts utilizes the marginal Net Present Values (NPV) of perennial stocks (Trivedi, 1987). With assumptions about profit expectations, these can be calculated using observable statistics for all age classes of the crop, including new plantings represented by age zero. Wickens and Greenfield (1973) derive a planting equation based on NPV of planted trees, and Dorfman and Heien (1989) expand on this concept to include adjustment costs and price risk. Gotsch and Burger (2001) consider the decision rule for the optimal tree age of replacement to be the NPV of a series of trees replanted at that age is greater than a similar series of replantings one year younger. Gotsch and Burger take the maximum of these, the optimal NPV of an everlasting series of the optimal tree age, to use in regressions explaining new areas of cocoa planted and thus the speed of adoption of an improved cocoa variety.

Perennial crops can prematurely die or lose productivity for a number of reasons, including natural disasters and plant disease. Some papers include tree death as either a control in an *ex post* estimation (e.g. Kalaitzandonakes & Shonkwiler, 1992) or as a precipitating event for a simulation starting out of equilibrium (e.g. Tozer & Marsh, 2018). Zapata et al. (2022), who run a structural simulation of citrus greening disease, simulate risk to citrus trees as a function of pre-determined management strategies. In general, however, endogenous risk to trees and its implications for supply response alongside risk management has not received much attention in the literature.

Feinerman and Tsur (2014) tackle crop death in the context of drought risk—specifically, drought risk to apples, olives, and avocados in northeast Israel. They develop a 'drought vulnerability index' describing the maximum probability of a crop-killing drought that the crop can face while remaining profitable. They derive the value of this index as a function of the length of the nonbearing establishment period, natural cycle length, the ratio of fixed costs to average profits, and interest rates. The expected present value relative to drought hazard is then used to estimate the benefits of stabilizing the water supply using recycled water. This analytical framework could be applied to other types of tree risk. Furthermore, some events such as the introduction of a plant disease to the study area, may change *expectations* of future tree death, and thus enter supply response models through different vectors than already observed tree deaths or expected prices received.

Papers such as these describe how an orchard or growing region's stock of perennial crops evolves in more detail than the canonical Nerlovian planting functions (described in the next section). By disaggregating growing regions to the level of individual orchards, an economist may consider further research topics on farm finances and business structure, and how these affect supply response. However, the lack of public orchard-level data means that most papers in this subfield are not able to tackle orchard capital management with this level of precision.

A notable exception is the work of Brady and Marsh (2013), who used a novel data set of land ownership and cover to analyze supply changes at the level of the landowner. They show substantial entry and exit within aggregate statistics, and that characteristics of firms entering and exiting, such as size, differed between Washington's mature apple industry and its newer wine grape industry. Their findings are consistent with predictions from the manufacturing literature, including their result that the degree of importance of entries and exits is more significant in the newer sector—wine grape vineyards—than the more mature industry of apple orchards. With the appropriate data, results and methods from other subfields of economics outside of agricultural economics can be successfully applied to research on perennial crop supply, as has been demonstrated by both Brady and Marsh (2013) here and the work by Akiyama and Trivedi (1987) inspired by the vintage capital literature.

4.2 Profit Expectations

Profit expectations are a crucial input for any producer making decisions with uncertain outcomes in the future. The long biological lags in perennial crop production and the long-lasting impacts of investments in orchard capital make the role of profit expectations all the more important. In most cases, the actual expectations held by producers during decision-making are unobservable to the econometrician, so a model of expectation formation must be used. This section discusses alternative models of expectation formulation used in the perennial crop supply response literature and argues that considerable work on this topic remains for future researchers. While the key metric for producer decision-making is expected profit and all of its components, including input costs, for simplicity we only discuss expectations around output price received. However, the approaches discussed here can be adapted to model the expectation of any component of the production decision. In practice, output price expectations encompass most of the literature's attention in this area.

For many annual crops, the need to identify an explicit model of expectation formation can be avoided, in principle, by the use of futures prices for that crop (Gardner, 1976). Although the evidence for this approach is mixed (Nerlove & Bessler, 2001), the issue is irrelevant for the majority of perennial crop growers due to the lack of futures markets for these crops. Those futures that are related and available, such as futures for Frozen Orange Juice Concentrate, are not available long enough in advance to meaningfully inform or hedge planting decisions.

The two main approaches to modeling price expectations are *adaptive expectations* and *rational expectations*. The related approach of *quasi-rational expectations* is a more empirically tractable approach to implementing the ideas behind rational expectations. *Naive expectations*, where the expected price in the next period is merely equal to the current price, predates these two approaches and is rarely used in the perennial crop supply response literature. Table 1 provides a brief overview of different models of price expectations.

The rational expectations approach, pioneered by Muth (1961, p. 316), assumes that aggregate expectations within an industry are "essentially the same as the predictions of the relevant economic theory." In other words, if each agent in a rational expectations model makes decisions based on some expectation forecast, the expected outcome of the entire model is the same as the aggregate of the individual agents' expectations. Given the model's information set, there are no profitable opportunities to improve forecasting. Thus, producers in a rational expectations model will respond to anticipated changes to the structure of their market, such as changes in policy or the spread of diseases. Assuming rational expectations as a modeling axiom allows price expectations to be extracted retroactively from observed behavior, as in Knapp (1987).

[Table 1 about here]

The rational expectations approach does not provide a general formula for expectation formulation. The optimal forecast needs to be derived from the particular model at hand, a task that increases in difficulty with the complexity of the model. Quasi-rational expectations is a more empirically tractable alternative to a full rational expectations model, where the future value of the exogenous variable is predicted using the best-fitting ARIMA model (Nerlove & Fornari, 1998). Knapp and Konyar (1991) compared models of naive expectations and quasi-rational expectations for estimating the supply elasticity of alfalfa in California; their final results use naive expectations as the quasi-rational expectations model found an implausibly low supply price elasticity.

The other main approach, adaptive expectations, was pioneered by Nerlove (1956; 1958) and is the more common of the two in this literature. The adaptive expectations approach assumes that expectations adjust based on the 'miss' between the previous expectation and the observed price. Desired output is thought to be a function of expected price and other covariates, and actual output partially adjusts to changes in desired output. The prototypical adaptive expectations setup and its initial results were reviewed by Nerlove (1979):

$$A_t - A_{t-1} = \gamma(A_t^* - A_{t-1}) \tag{5}$$

$$P_t^* - P_{t-1}^* = \beta(P_t - P_{t-1}^*) \tag{6}$$

$$A_t^* = a_0 + a_1 P_t^* + a_2 Z_t + U_t \tag{7}$$

where *t* denotes crop year, A_t is actual area under cultivation, P_t is actual price of the crop per unit, a superscript * signifies desired acreage or predicted price, Z_t is a vector of profit covariates, and U_t represents unobserved factors affecting area. The coefficients $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ are the coefficients of expectation and adjustment, respectively, and are typically expected to be within the bounds of (0,1); this range earns these models the label ‘partial adjustment’ models.

French and Matthews (1971) directly applied Nerlove’s model to perennial crops, while Akiyama and Trivedi (1987) used an error correction model approach to adapt the expectations process around adjustment to meet desired production after substantial nonbearing, establishment lags. Nickell (1985) showed that such an error correction model can be derived from a dynamic cost of adjustment model.

Through algebraic substitution, equations (5)-(7) result in a planting function of past acreage, prices received, and other covariates. This equation only includes observable variables and can easily be estimated via an *ex post* regression. However, empirical results have not always matched a direct application of this Nerlovian theory. For example, Wickens and Greenfield (1973) estimate a supply equation for coffee based on theory informed by coffee’s specific yield curve, biennial cycle, and investment dynamics. Wickens and Greenfield note that the relative sign and magnitude of the coefficients on lagged price information to current output match the implications of their theoretical work but would not be implied by a direct application of equations (5)-(7).

In practice, modern estimations of planting functions rarely provide explicit adaptive or rational expectations justifications for their regressions of output on lagged price and acreage information. The planting functions in modern papers are typically *ad hoc*, with structure considerations reserved for other parts of the model. The source and structure of farmers' expectations for future profits remain understudied despite their importance to perennial crops.

How important are these theories of price expectations for understanding supply response for perennial crops? Quasi-rational, adaptive, and naive expectations offer a similar approach to estimating perennial supply response functions: observed past prices serve as signals for market trends and thus influence planting decisions. The particular choice for the expectation formation function depends on the researcher's beliefs about expectation formation in the market, need for simplicity, and desire for a theoretical basis for the expectations. Regardless of the motivation for choosing one expectation model or another, all these approaches forecast future expectations using past data, so are not forward looking and do not incorporate anticipated changes to the market.

However, most research and policy questions directly imply a shift in market structure. Indeed, projects estimating the impact of a new trade agreement (e.g., Spreen et al., 2003; Devadoss et al., 2009) or the introduction of a new threat to perennial plants (Zhao et al., 2007; Spreen et al., 2014) intrinsically rely on data variation surrounding points of change in the market or the ability to predict how producers would react to such a change. Such a point of change recontextualizes how orchard managers might consider a current or past price when forming their expectations for future prices. Therefore, it is reasonable to expect distinct supply response elasticities before, after, and during those points of change. Theories on price expectation formation may offer a theoretical basis for projecting these changes in price sensitivity. Alternatively, modelers may utilize functional forms that allow for differing supply responses based on market context or the manner in which prices are moving. For example, Spreen et al. (2014) allow HLB introduction to depress plantings by a fixed magnitude, while Saylor (1974) allows price increases and decreases to have asymmetrical effects. However, the literature lacks combined *ex ante*/*ex post* analysis testing whether orchard managers' sensitivity to price changed because of changes to market structure or capital risk. Moreover, we are not aware of studies adopting a full rational expectations approach, which allows producers' expectations to explicitly incorporate anticipated future shocks.

This discussion of price expectations focused solely on predicting expected prices, but higher moments of the price generating process may also be important to orchard decision making. Profit variance penalties have been used in structural objective functions in other agricultural economics literature. For perennials, Dorfman and Heien (1989) incorporate the degree of uncertainty into their regressions by including the sample variance of the present value of almond tree acres over the proceeding eight years. They counterintuitively find a positive association between that variance and proportional additions to bearing acreage. Their approach remains a rare standout in the perennial crop literature. Structural changes in the market serve not only as points of uncertainty but may structurally alter expected price variance. This change is particularly direct for policies such as crop insurance or price supports, but indirect sources of change such as liberalized trade or spreading diseases could be explored in higher moments. The variance and skew of potential prices received, as well as the expected negative correlation between prices and individual yield, could all affect orchard investment decisions along with average price trends.

5. Perennial Supply Response in the Context of Horizontal and Vertical Linkages

With some notable exceptions, perennial crop firms typically make up a small proportion of total supply and do not have the market power to set prices for their output. This observation has been used to argue competitive equilibrium is a pareto optimum, an assumption which enables aggregation (e.g., see Knapp, 1987). However, the relatively small size of an individual grower does not mean that individual orchards or regions exist in isolation, nor does it imply a perfectly competitive market. For example, even when a producer or buyer of producers' output (e.g., a processor or packer) has a small market share overall, they may have a large market share in the geographic region in which they operate. Orchards trying to sell their product may face trade barriers or intermediaries, such as processors, that do have market power. Indeed, many contemporary papers in the perennial supply response literature include either horizontal linkages to other firms or regions, vertical linkages within the supply chain, or both.

While these contexts are not unique to perennial crops, they raise important questions related to the inherently long planning horizon for perennial crops. For example, how do expectations of market power over time affect investment decisions? What are the incentives to make strategic investments to gain market power or improve trade position? How do issues of asset fixity or sunk costs impact investment response to trade policy? This section discusses examples of the literature in perennial crop supply dealing with these topics, as well as some intersections with other factors of perennial crop supply.

Orchards that compete in the same consumption market will 'crowd out' others, lowering prices received. In models that simulate future orchard planting behavior based on price expectations, we may expect competing supply to influence the elasticity of supply response to shifts in demand or average yield. Willett's (1993) econometric model of the U.S. apple industry is an illustrative example of accounting for this using reduced form econometrics. Willett estimated an equation for net imports of apples and apple products alongside a series of other functions representing yield and prices received, then used these equations to solve for market equilibrium. The endogenously generated prices received were used to update bearing acreage for the next period.

Willett's (1993) paper is a particularly parsimonious example because imports are estimated *ex post* without modeling the changes in foreign bearing acreage (e.g., through a spatial trade equilibrium model). Assuming stationarity, *ex post* estimations of multiple regions' production, plantings, and the resulting sale price can be estimated using a state space or structural vector autoregression model. Such approaches rely on a constant trade regime, but barriers to trade may increase or decrease in response to trade deals or changing transportation costs (e.g., Roosen, 1999). The preponderance of literature on trade barriers for perennial crops is concerned with policy barriers such as tariffs and quota systems. Behrman (1968), Goddard (1991), Spreen et al. (2003), Brown et al. (2004) and Luckstead et al. (2015) are examples of papers in this field inspired by proposed trade agreements.

Most prominent modern papers dealing with trade and perennial crop investment utilize a spatial equilibrium trade model (SETM), a type of mathematical programming model. These models allocate production across consumption regions to maximize total societal welfare and generate endogenous prices based on this allocation. Complications such as tariffs, quotas, and differing market demands can then be directly incorporated into the objective function or constraints.[4] Devadoss et al.'s (2009) analysis of the international apple market provides an illustrative example of a spatial equilibrium trade model. They begin with linear demand and supply functions for apples for each production and consumption region using a Bayesian model with constraints on elasticities to price and income. They then simulate the market allocation by maximizing social monetary gain with costs imposed by tariffs and transportation. With a detailed set of relational transportation costs and market elasticities, their simulated free trade scenario describes changes in bilateral trade flows as well as aggregate prices. For example, they estimate that under free trade, U.S. apple prices would increase due to a broad increase in net exports despite China's lower transportation costs to several major markets.

In studies that dynamically update fruit supply with a planting function, such as those by Spreen et al. (2003), and Spreen et al. (2014), prices received for perennial crops directly (and prices for the products made from perennial crops, indirectly) feed back into the model to set the supply for future years' spatial equilibria. Modeling these interactions across regions may be especially important when factors uniquely affect certain regions. For example, if disease or natural disasters ravage a particular region, then the potential social welfare and investment rewards for mitigating those damages depends on the presence of alternative producing regions. Depending on the correlation of yield between regions, changing trade relationships could especially affect expectations on the variance of output prices and the correlation a grower faces between their yields and prices received. While those later topics have been discussed in relation to perennial crops by Dorfman and Heien (1989), their intersection with trade is underexplored.

Along with horizontal linkages, vertical linkages are important in many perennial crops industries; the orange juice industry, for example, has drawn attention from many researchers.

[4] For foundations of SETM models, see work by Samuelson (1952) and Takayama and Judge (1964, 1971).

An early advancement in modeling vertical linkages in perennial crop supply comes from the international orange juice market model introduced by McClain (1989) and further developed and utilized by Spreen et al. (2003; 2014). The model incorporates multiple consumer and grower regions, as well as an explicit 'blending' module (using proprietary processor data), in which oligopolistic processors demand orange varieties in specific mixtures to create fruit juice with desirable properties. By modeling processors in this detail, the model allows for precise and distinct prices received for orange crops by region and variety.

Focusing specifically on the topic of market power in this industry, Luckstead et al. (2015) formulate a strategic trade model of the oligopolistic competition between orange juice processors in the new empirical industrial organization (NEIO) tradition.[5] From the first-order conditions of representative processors objective functions, they derive functions for supply from Florida and São Paulo processors to the U.S. market and from São Paulo to the European market. They use these to estimate the conjectural elasticity for processors in each region, which is the change in quantity of juice supplied in one region in response to a change in quantity of juice supplied by processors in the other region. This conjectural elasticity is allowed to vary over time; estimates indicate increasing seller market power for both Florida and São Paulo processors. Wang et al. (2006) similarly investigate the buyer market power of orange processors in the market for oranges. They find evidence of oligopsonistic power over growers, with power shrinking during orange shortages from local freezes.

Neither of these two studies mentioned in the previous paragraph estimates the impacts of these market power phenomena on *long-run* orange supply and investment, despite the fact that dynamic market power would have implications for investors' perceptions of long-run risks and

[5] Further details on their econometric strategy can be found in Devadoss et al. (2013).

prices received. This fact demonstrates an inherent challenge in models that contextualize perennial supply response models within a more complex set of horizontal and/or vertical linkages. Specifically, the researcher may face a trade-off, sacrificing detail at the orchard level (as discussed in subsections on orchard capital management and profit expectations) in order to provide detail about linkages while maintaining model tractability or convergence.

6. Summary and Opportunities Moving Forward

Each of the preceding sections covers a pertinent topic in estimating perennial crop supply, a representative sample of the literature tackling that topic, and some brief discussion of their implications. In summary, perennial crops' most distinguishing feature, their natural lifecycle over several growing years, intersects with many aspects of agricultural economics. Unaddressed, these intersections can confound estimations of orchard managers' responses, in plantings and in immediate production, to changing policies and market conditions.

In the last several decades since the literature review by Akiyama and Trivedi (1987), the field has made considerable strides in areas such as estimation of spatial trade equilibria, separate estimation of practices such as removals and replanting, and modeling the distribution of welfare effects across space and time. However, while great progress has been made in these subjects individually, there is still considerable space for research in the intersections between these topics. Most of the research questions discussed in this review involve a structural market change, through which perennial crop orchards must navigate with durable investments. These firms manage their holdings in perennial crops in the context of the rest of their portfolio, option and exit values, price uncertainty, and the risk of plant death alongside the direction of long-term demand trends. The challenge at hand is how to better model this complex setting and provide new insights for orchard managers and policymakers.

Research can rise to this challenge in several ways. First, the field currently has several decades of published empirical estimations of supply response elasticity across a variety of crops. Collecting and back testing these models against modern data may reveal what factors are the most important to address in future work; the points in time where new data most severely diverge from old estimates could be clues to which changes in market structure have the most intense confounding effects.

Perennial crops share many theoretical similarities with other economic fields such as vintage capital and macroeconomics. Papers such as Akiyama and Trivedi (1987) and Brady and Marsh (2013) were directly inspired by results from other fields in economics. Looking to more recent developments in those fields could inspire new literature in perennial crop supply response.

The theoretical underpinnings of expectation formation were a recurrent component of the older papers cited here, but modern papers are more likely to present *ad hoc* regression models. Perennial crop supply response may be a setting for novel tests of hypotheses of expectation formation, suggesting an opportunity for researchers to revisit these concepts in new theoretical work. Several overlapping explanations for partial adjustments have been proposed in the literature, including Nerlovian expectations, thresholds for signals to overcome investment risk (Price & Wetzstein, 1999), adjustment costs and others; work contesting these forces to determine which are empirically most relevant to perennial crops would both aid future research and inform any policy decisions concerned with the responsiveness and stability of perennial crop supply.

For *ex post* estimations, it may be valuable to consider whether shocks considered in the research question may lead to structural changes in the market of study and thus invalidate coefficients from 'training' periods. A parsimonious solution could include allowing for more interactions between covariates; for example, higher risk of tree death results in fewer expected bearing years to profit from high prices, so we might expect an interaction between variables representing predictions of market prices and risks to trees. For hybrid models, such as spatial equilibrium trade models updated by reduced-form planting equations, it may be valuable to consider how orchards may anticipate, hedge against, or otherwise be affected by changes in the spatial equilibrium.

Finally, incorporating measures of investment risk may be useful in both *ex post* and *ex ante* models of investment in perennial crops. Plant disease and climate change are direct sources of changes to risk, but other concepts could indirectly affect uncertainty to returns. For example, the ability to smooth returns over years through negative correlation between yield and price could be affected by changes in trade or other factors of orchard capital management.

Acknowledgements

The authors thank Brian Adams (USDA ERS) and two anonymous referees for helpful comments and suggestions. This material is based upon work that is supported by U.S. Department of Agriculture Cooperative Agreement number 58-3000-1-0095. This research was supported by the U.S. Department of Agriculture, Economic Research Service. This research was supported in part by the intramural research program of the U.S. Department of Agriculture, National Institute of Food and Agriculture, Hatch project number 1024582. The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy.

Data Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

References

Akiyama, T., & Trivedi, P. K. (1987). Vintage production approach to perennial crop supply: An application to tea in major producing countries. *Journal of Econometrics*, 36, 133–161. https://doi.org/10.1016/0304-4076(87)90047-9

Alston, J. M., Freebairn, J. W., & Quilkey, J. J. (1980). A model of supply response in the Australian orange growing industry. *Australian Journal of Agricultural Economics,* 24(3), 248–67. https://doi.org/10.1111/j.1467-8489.1980.tb00581.x

Arrow, K. J., & Fisher, A. C. (1974). Environmental preservation, uncertainty, and irreversibility. *The Quarterly Journal of Economics,* 88(2), 312–319. https://doi.org/10.2307/1883074

Askari, H., & Cummings, J. T. (1976). *Agricultural supply response: A survey of the econometric evidence*. Praeger.

Askari, H., & Cummings, J. T. (1977). Estimating agricultural supply response with the Nerlove model: A survey. *International Economic Review,* 18(2), 257–292. https://doi.org/10.2307/2525749

Babcock, B. A. (2015). Extensive and intensive agricultural supply response. *Annual Review of Resource Economics,* 7, 333–348. https://doi.org/10.1146/annurev-resource-100913-012424

Balagtas, J. V., Krissoff, B., Lei, L., & Rickard, B. J. (2014). How has U.S. Farm policy influenced fruit and vegetable production? *Applied Economic Perspectives and Policy,* 36(2), 265–86. https://doi.org/10.1093/aepp/ppt028

Ball, V. E. (1988). Modeling supply response in a multiproduct framework. *American Journal of Agricultural Economics,* 70(4), 813–825. https://doi.org/10.2307/1241922

Barrett, C. B. (2021). Overcoming global food security challenges through science and solidarity. *American Journal of Agricultural Economics,* 103(2), 422-447. https://doi.org/10.1111/ajae.12160

Basu, R., & Gallardo, R. K. (2021). Economic issues related to long-term investment in tree fruits. *Choices,* 36(2), 1–7. https://www.choicesmagazine.org/UserFiles/file/cmsarticle_774.pdf

Behrman, J. R. (1968). Monopolistic cocoa pricing. *American Journal of Agricultural Economics*, 50(3), 702–19. https://doi.org/10.2307/1238269

Blank, S. C., Orloff, S. B., & Putnam, D. H. (2001). Sequential stochastic production decisions for a perennial crop: The yield/quality tradeoff for alfalfa hay. *Journal of Agricultural and Resource Economics,* 26(1), 195–211. https://www.jstor.org/stable/40987103

Brady, M. P., & Marsh, T. L. (2013). Do changes in orchard supply occur at the intensive or extensive margin of the landowner? Paper presented at *2013 AAEA & CAES Joint Annual Meeting, Washington, DC.* https://ideas.repec.org/p/ags/aaea13/150452.html

Brown, M. G., Spreen, T. H., & Lee, J. (2004). Impacts on U.S. Prices of Reducing Orange Juice Tariffs in Major World Markets. *Journal of Food Distribution Research,* 35(2), 26–33. https://core.ac.uk/download/pdf/6988372.pdf

Carpentier, A., Gohin, A., Sckokai, P., & Thomas, A. (2015). Economic modelling of agricultural production: Past advances and new challenges. *Review of Agricultural and Environmental Studies,* 96(1), 131-165. https://hal.science/hal-01884930

Day, K. R., DeJong, T. M., & Johnson, R. S. (2005). Orchard-system configurations increase efficiency, improve profits in peaches and nectarines. *California Agriculture, 59*(2), 75–79. https://doi.org/10.3733/ca.v059n02p75

DeJong, T. M., Tsuji, W., Doyle, J. F., & Grossman, Y. L. (1999). Comparative economic efficiency of four peach production systems in California. *HortScience,* 34(1), 73–78. https://doi.org/10.21273/HORTSCI.34.1.73

Demko, I, & Jaenicke, E. C. (2018). Impact of European Union–U.S. organic equivalency arrangement on U.S. exports. *Applied Economic Perspectives and Policy,* 40(3): 482–501. https://doi.org/10.1093/aepp/ppx048

Devadoss, S., & Luckstead, J. (2010). An analysis of apple supply response. *International Journal of Production Economics,* 124(1), 265–71. https://doi.org/10.1016/j.ijpe.2009.11.024

Devadoss, S., Luckstead, J., & Mittelhammer, R. (2013). Econometric issues related to identification of the market power parameter. *Applied Economics,* 45(32), 4569–4574. https://doi.org/10.1080/00036846.2013.795277

Devadoss, S., Sridharan, P., & Wahl, T. (2009). Effects of trade barriers on U.S. and world apple markets. *Canadian Journal of Agricultural Economics/Revue Canadienne d'agroeconomie,* 57(1), 55–73. https://doi.org/10.1111/j.1744-7976.2008.01138.x

Dixit, A. K. & Pindyck, R. S. (1994). *Investment under uncertainty*. Princeton University Press. https://doi.org/10.2307/j.ctt7sncv

Dorfman, J. H., & Heien, D. (1989). The effects of uncertainty and adjustment costs on investment in the almond industry. *The Review of Economics and Statistics,* 71(2), 263–74. https://doi.org/10.2307/1926972

Durbin, J., & Koopman, S. J. (2012). *Time Series Analysis by State Space Methods*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199641178.001.0001

Elkins, R. B., Klonsky, K., DeMoura, R., & DeJong, T. M. (2008). Economic evaluation of high density versus standard orchard configurations; case study using performance data for 'Golden Russet Bosc' pears. *Acta Horticulturae*, 800, 739–746. https://doi.org/10.17660/ActaHortic.2008.800.101

Feinerman, E., & Tsur, Y. (2014). Perennial crops under stochastic water supply. *Agricultural Economics,* 45(6), 757–766. https://doi.org/10.1111/agec.12120

French, B. C., & Bressler, R. G. (1962). The lemon cycle. *Journal of Farm Economics,* 44(4), 1021–1036. https://doi.org/10.2307/1235524

French, B. C., King, G. A., & Minami, D. D. (1985). Planting and removal relationships for perennial crops: An application to cling peaches. *American Journal of Agricultural Economics,* 67(2), 215–23. https://doi.org/10.2307/1240672

French, B. C., & Matthews, J. L. (1971). A supply response model for perennial crops. *American Journal of Agricultural Economics,* 53(3), 478–90. https://doi.org/10.2307/1238225

Gardner, B. L. (1976). Futures prices in supply analysis. *American Journal of Agricultural Economics,* 58(1), 81–84. https://doi.org/10.2307/1238581

Ghanem, D., & Smith, A. (2022). Causality in structural vector autoregressions: Science or sorcery? *American Journal of Agricultural Economics,* 104(3), 881–904. https://doi.org/10.1111/ajae.12269

Goddard, E. W. (1991). A simulation analysis of supply management in the Canadian apple industry. *Canadian Journal of Agricultural Economics/Revue Canadienne d'agroeconomie,* 39(1), 83–102. https://doi.org/10.1111/j.1744-7976.1991.tb03559.x

Gotsch, N., & Burger, K. (2001). Dynamic supply response and welfare effects of technological change on perennial crops: The case of cocoa in Malaysia. *American Journal of Agricultural Economics,* 83(2), 272–85. https://doi.org/10.1111/0002-9092.00155

Gottwald, T. R., Irey, M. S., Gast, T., Parnell, S. R., Taylor, E., & Hilf, M. (2010). Spatio-temporal analysis of an HLB epidemic in Florida and implications for spread. *International Organization of Citrus Virologists Conference Proceedings (1957-2010)* 17(17). https://doi.org/10.5070/C50JQ6D375.

Haile, M. G., Kalkuhl, M, von Braun, J. (2014). Inter- and intra-seasonal crop acreage response to international food prices and implications of volatility. *Agricultural Economics,* 45(6), 693–710. https://doi.org/10.1111/agec.12116

Henry, C. (1974). Investment decisions under uncertainty: The 'irreversibility effect.' *The American Economic Review,* 64(6), 1006–1012. https://www.jstor.org/stable/1815248

Hertzler, G. (1991). Dynamic decisions under risk: Application of Ito stochastic control in agriculture. *American Journal of Agricultural Economics,* 73(4), 1126–1137. https://www.jstor.org/stable/1242441

Iqbal, M. Z., & Babcock, B. A. (2018). Global growing-area elasticities of key agricultural crops estimated using dynamic heterogeneous panel methods. *Agricultural Economics,* 49(6), 681–90. https://doi.org/10.1111/agec.12452

Jiang, X., Cassey, A. J., & Marsh, T. L. (2017). Economic consequences for tree fruit intermediaries from shocks. *Journal of Agricultural and Applied Economics,* 49(4), 592–616. https://doi.org/10.1017/aae.2017.15

Just, R. E., & Pope, R. D. (2001). The agricultural producer: Theory and statistical measurement. In Gardner, B. L., & Rausser, G. C. (Eds.), *Handbook of Agricultural Economics* (pp. 629–741). Elsevier. https://doi.org/10.1016/S1574-0072(01)10015-0

Kalaitzandonakes, N. G., & Shonkwiler, J. S. (1992). A state-space approach to perennial crop supply analysis. *American Journal of Agricultural Economics,* 74(2), 343–52. https://doi.org/10.2307/1242488

Knapp, K. C. (1987). Dynamic equilibrium in markets for perennial crops. *American Journal of Agricultural Economics,* 69(1), 97–105. https://doi.org/10.2307/1241310

Knapp, K. C., & Konyar, K. (1991). Perennial crop supply response: A Kalman filter approach. *American Journal of Agricultural Economics,* 73(3), 841–49. https://doi.org/10.2307/1242836

Krewer, G., Fonsah, E. G., & Boyhan, G. (2006). A three-year study on the effect of trellis type on yield, fruit size, and economics of blackberry production in Georgia. *Journal of Food Distribution Research,* 37(1), 97–100. http://dx.doi.org/10.22004/ag.econ.856

Lordan, J., Francescatto, P., Dominguez, L. I., & Robinson, T. L. (2018). Long-term effects of tree density and tree shape on apple orchard performance, a 20 year study—Part 1, agronomic analysis. *Scientia Horticulturae,* 238, 303–317. https://doi.org/10.1016/j.scienta.2018.04.033

Luckstead, J., Devadoss, S, & Mittelhammer, R. C. (2015). Imperfect competition between Florida and São Paulo (Brazil) orange juice producers in the U.S. and European markets. *Journal of Agricultural and Resource Economics,* 40(1), 164–78. https://www.jstor.org/stable/44131282

Luong, Q. V., & Tauer, L. W. (2006). A real options analysis of coffee planting in Vietnam. *Agricultural Economics,* 35(1), 49–57. https://doi.org/10.1111/j.1574-0862.2006.00138.x

McClain, E. A. (1989). A Monte Carlo simulation model of the world orange juice market (Publication No. 9021879) [Doctoral dissertation, University of Florida]. ProQuest Dissertations Publishing.

Muth, J. F. (1961). Rational expectations and the theory of price movements. *Econometrica,* 29(3), 315–335. https://www.jstor.org/stable/1909635

Nerlove, M. (1956). Estimates of the elasticities of supply of selected agricultural commodities. *Journal of Farm Economics,* 38(2), 496–509. https://www.jstor.org/stable/1234389

——— 1958. *The dynamics of supply: Estimation of farmers' response to price*. Johns Hopkins University Press.

——— 1979. The dynamics of supply: Retrospect and prospect. *American Journal of Agricultural Economics,* 61(5), 874–888. https://doi.org/10.2307/3180340

Nerlove, M., & Bessler, D. A. (2001). "Expectations, information and dynamics." In Gardner, B. L., & Rausser, G. C. (Eds.), *Handbook of Agricultural Economics* (pp. 155–206). Elsevier. https://doi.org/10.1016/S1574-0072(01)10006-X

Nerlove, M., & Fornari, I. (1998). Quasi-rational expectations, an alternative to fully rational expectations: An application to U.S. beef cattle supply. *Journal of Econometrics,* 83(1–2), 129–161. https://doi.org/10.1016/S0304-4076(97)00067-5

Nickell, S. (1985). Error correction, partial adjustment and all that: An expository note. *Oxford Bulletin of Economics and Statistics,* 47(2), 119–129. https://doi.org/10.1111/j.1468-0084.1985.mp47002002.x

Pinstrup-Andersen, P. (2007). Agricultural research and policy for better health and nutrition in developing countries: A food systems approach. *Agricultural Economics,* 37(1), 187 – 198. https://doi.org/10.1111/j.1574-0862.2007.00244.x

Pompelli, G., & Castaneda, J. (1994). Changes in western U.S. orange acreage and the influence of Brazilian orange production. *Journal of International Food & Agribusiness Marketing,* 6(2), 1–15. https://doi.org/10.1300/J047v06n02_01

Price, T. J., & Wetzstein, M. E. (1999). Irreversible investment decisions in perennial crops with yield and price uncertainty. *Journal of Agricultural and Resource Economics*, 24(1), 173 –185. https://www.jstor.org/stable/40987015

Rao, J. M. (1989). Agricultural supply response: A survey. *Agricultural Economics,* 3(1), 1-22. https://doi.org/10.1016/0169-5150(89)90036-4

Richards, T. J., & Green, G. P. (2003). Economic hysteresis in variety selection. *Journal of Agricultural and Applied Economics,* 35(1), 1–14. https://doi.org/10.1017/S1074070800005897

Roosen, J. (1999). *A regional econometric model of U.S. apple supply and demand*. Staff Paper 317. Iowa State University. https://doi.org/10.22004/AG.ECON.18237

Samuelson, Paul A. (1952). Spatial price equilibrium and linear programming. *The American Economic Review*, 42(3), 283–303. https://www.jstor.org/stable/1810381

Sargent, T. J. (2008). Rational expectations. In Durlauf, S. N., & Blume, L. E. (Eds.), *The New Palgrave Dictionary of Economics* (2nd ed., pp. 155–206). Palgrave Macmillan. https://doi.org/10.1057/978-1-349-95121-5_1684-2

Saylor, R. G. (1974). Alternative measures of supply elasticities: The case of São Paulo coffee. *American Journal of Agricultural Economics,* 56(1), 98–106. https://doi.org/10.2307/1239350

Singerman, A., Lence, S. H., & Useche, P. (2017). Is area-wide pest management useful? The case of citrus greening. *Applied Economic Perspectives and Policy,* 39(4), 609–634. https://doi.org/10.1093/aepp/ppx030

Song, F., Zhao, J., & Swinton, S. M. (2011). Switching to perennial energy crops under uncertainty and costly reversibility. *American Journal of Agricultural Economics,* 93(3), 768–783. https://doi.org/10.1093/ajae/aar018

Spreen, T. H., Baldwin, J., & Futch, S. H. (2014). An economic assessment of the impact of Huanglongbing on citrus tree plantings in Florida. *HortScience,* 49(8), 1052–1055. https://doi.org/10.21273/HORTSCI.49.8.1052

Spreen, T. H., Brewster, C., & Brown, M. G. (2003). The free trade area of the Americas and the market for processed orange products. *Journal of Agricultural and Applied Economics,* 35(1), 107–26. https://doi.org/10.1017/S1074070800005976

Takayama, T., & Judge, G. G. (1964). Spatial equilibrium and quadratic programming. *Journal of Farm Economics* 46(1): 67–93. https://doi.org/10.2307/1236473

Takayama, T., & Judge, G. G. (1971). *Spatial and Temporal Price and Allocation Models*. North-Holland Publishing Company.

Tozer, P. R., & Marsh, T. L. (2018). Dynamic regional model of the U.S. apple industry: Consequences of supply or demand shocks due to pest or disease outbreaks and control. *Agricultural Systems,* 164, 252–63. https://doi.org/10.1016/j.agsy.2018.05.003

Trivedi, P. K. (1987). On understanding investment behavior in perennial crops production. Division Working Paper No. 1987–8. The World Bank. https://documents1.worldbank.org/curated/en/447121467989499982/pdf/multi0page.pdf

USDA ERS (2023). *U.S. Food Imports Data.* U.S. Department of Agriculture, Economic

Research Service. https://www.ers.usda.gov/data-products/u-s-food-imports/

USDA FAS (2023). *Global Agricultural Trade System Data.* U.S. Department of Agriculture, Foreign Agricultural Service. https://apps.fas.usda.gov/gats/default.aspx

USDA NASS (2022). *Florida Citrus Statistics 2020-2021*. Florida: National Agricultural Statistics Service. https://www.nass.usda.gov/Statistics_by_State/Florida/Publications/Citrus/Citrus_Statistics/2020-21/fcs2021b.pdf

USDA NASS (2019). *Census of Agriculture, 2017. United States Summary and State Data, Volume 1, Part 51.* U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf

Wang, H., Xiang, Q., & Reardon, T. (2006). *Market power and supply shocks: Evidence from the orange juice market.* Department of Agricultural Economics Staff Paper 2006-02. Michigan State University. http://dx.doi.org/10.22004/ag.econ.11508

Wesseler, J., & Zhao, J. (2019). Real options and environmental policies: The good, the bad, and the ugly. *Annual Review of Resource Economics,* 11, 43–58. https://doi.org/10.1146/annurev-resource-100518-094140

Wickens, M. R., & Greenfield, J. N. (1973). The econometrics of agricultural supply: An application to the world coffee market. *The Review of Economics and Statistics,* 55(4), 433–440. https://doi.org/10.2307/1925665

Willett, L. S. (1993). The U.S. apple industry: Econometric model and projections. *Agricultural and Resource Economics Review,* 22(2), 137–49. https://doi.org/10.1017/S106828050000472X

Zapata, S. D., Peguero, F., Sétamou, M., & Alabi, O. J. (2022). Economic implications of citrus greening disease management strategies. *Journal of Agricultural and Resource Economics,* 47(2), 300–323. https://doi.org/10.22004/ag.econ.313310

Zhao, Z., Wahl, T., & Marsh, T. (2007). Economic effects of mitigating apple maggot spread. *Canadian Journal of Agricultural Economics/Revue Canadienne d'agroeconomie,* 55(4), 499–514. https://doi.org/10.1111/j.1744-7976.2007.00105.x

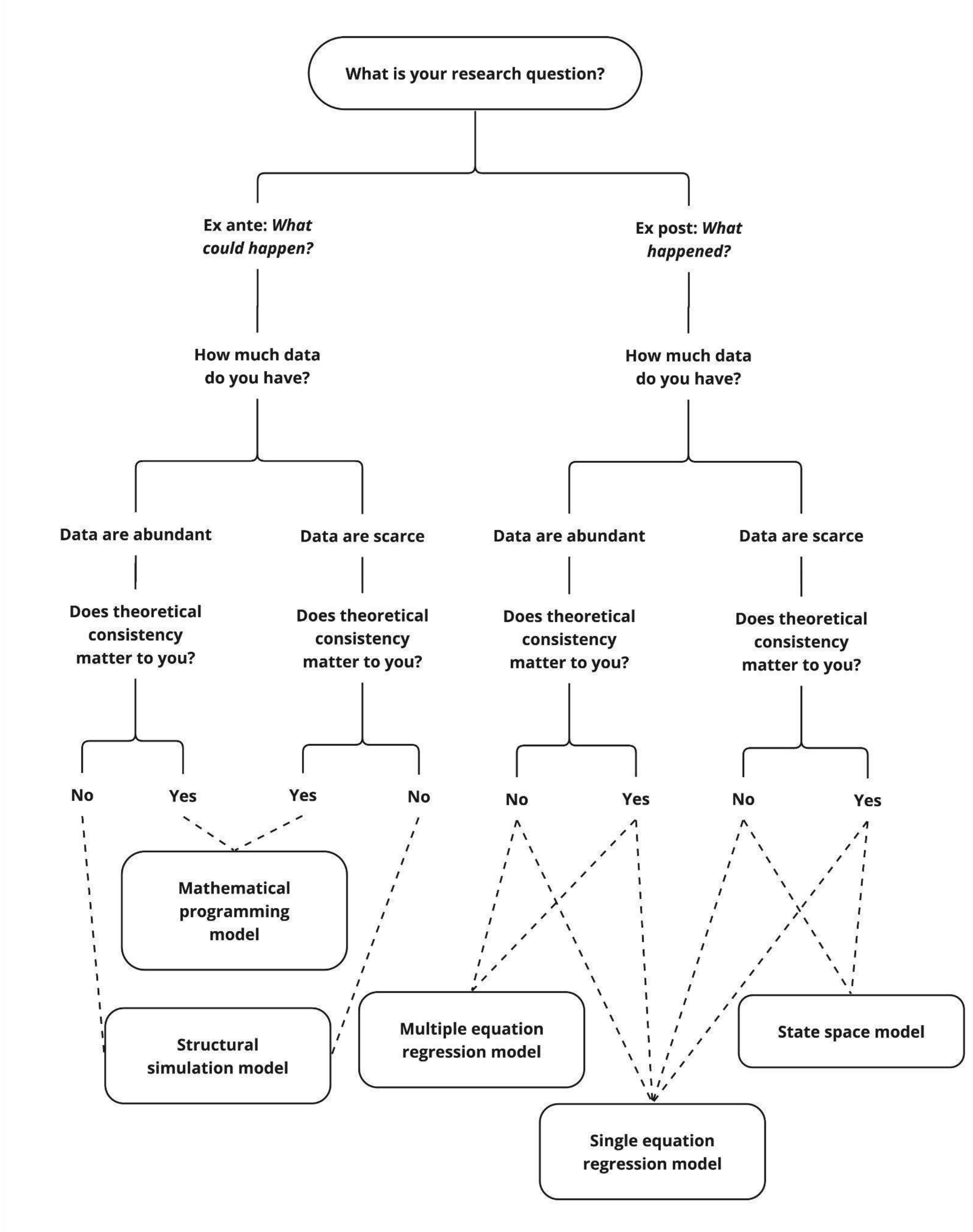
Tables and Figures

Table 1: Models of Price Expectations

Price Expectations Model	**Mathematical Formulation**	**Description**
Naive	$\mathrm{E}(p_{t+1}) = p_t$	Expected price is equal to the previous period's price
Adaptive	$E(p_{t+1}) = E(p_t) + \lambda(p_t - E(p_t))$ Or, equivalently, $E(p_{t+1}) = \sum_{i=0}^{\infty} \lambda(1-\lambda)^i p_{t-i}$	Expected price is a function of the expected price in the previous period and the difference between the realized price and the expected price. Equivalently, expected price is a weighted geometric series of past prices.
Rational	Varies	"Expectations of firms tend to be distributed, for the same information set, about the prediction of the theory,"[1] i.e. "forecasts made by agents within the model are no worse than can be made by the economist who has the model"[2]
Quasi-rational	Best fitting ARIMA model	Expected price comes from the estimates of the best fitting ARIMA process for price

[1]Muth (1961, p. 316), [2]Sargent (2008, p. 1)

Figure 1: Perennial Supply Response Research Method Decision Tree



Appendix A: Descriptions of Cited Empirical Papers

Table A1: Models of Price Expectations

Title	Authors	Year	Journal	Main Model	Objective/Approach	Methodological or Other Contribution
The Lemon Cycle	French and Bressler	1962	*Journal of Farm Economics* (now *American Journal of Agricultural Economics*)	Regression	Tests for cyclical pattern predicted by the 'cobweb theorem' in plantings and removals of California lemon trees	First article to separately estimate plantings and removals
Monopolistic Cocoa Pricing	Behrman	1968	*American Journal of Agricultural Economics*	Regression	Estimates impact of a hypothetical international cocoa pricing agreement, modeling supply and demand with a series of regressions	Early example of non-US application and policy simulation for perennials
A Supply Response Model for Perennial Crops	French and Matthews	1971	*American Journal of Agricultural Economics*	Regression	Develops and tests the Nerlovian model applied to a perennial crop (US asparagus) using a regression format derived from Nerlovian partial adjustment relative to deviations from expected profits	Develops structural base for regressions and conjectures that orchards have a desired output level, which is affected by profitability 'surprises,' formalizing 1962 work in the style of Nerlove's hypotheses

Title	Authors	Year	Journal	Main Model	Objective/Approach	Methodological or Other Contribution
The Econometrics of Agricultural Supply: An Application to the World Coffee Market	Wickens and Greenfield	1973	*The Review of Economics and Statistics*	Regression	Develops and tests model for Brazilian coffee acreage based on the Lagrangian from optimal investment	Questions Nerlovian adaptive expectations, showing that its *ad hoc* assumptions do not mesh with empirical results for coffee--instead starts from the fact of delayed production between planting and first harvest, and derives Lagrangian from the investment-level optimization problem, deriving theoretically-consistent estimating equations similar to those from a Nerlovian model
Alternative Measures of Supply Elasticities: The Case of São Paulo Coffee	Saylor	1974	*American Journal of Agricultural Economics*	Regression	Fits Nerlovian supply functions to Brazilian coffee and contrasts performance against models that allow for irreversible supply	Compares several supply response specifications, including classic Nerlovian distributed lag model, adaptations of model to account for structural changes over time, and adaptations of model to account for irreversible supply (i.e., asymmetric price response)
A Model of Supply Response in the Australian Orange Growing Industry	Alston, Freebairn, and Quilkey	1980	*Australian Journal of Agricultural Economics*	Regression	Estimates plantings, removals, and production for Australian orange industry	Considers input demand that stems from a desired flow of services from trees (durable goods), where flow of services (e.g., yield, profit) is in part determined by age class, providing more detail on the role of age class in planting than prior works

Title	Authors	Year	Journal	Main Model	Objective/Approach	Methodological or Other Contribution
Planting and Removal Relationships for Perennial Crops: An Application to Cling Peaches	French, King, and Minami	1985	*American Journal of Agricultural Economics*	Regression	Estimates planting and removal equations for California Cling Peaches using the desired plantings framework from French and Matthews (1971)	First article (although preceded by a monograph by the same authors) to have detailed data on yield by age class, estimating plantings and removals for 30 age classes
Vintage Production Approach to Perennial Crop Supply: An Application to Tea in Major Producing Countries	Akiyama and Trivedi	1987	*Journal of Econometrics*	Regression	Estimates both short-run and long-run supply response using a vector error correction model, incorporating the interdependence between plantings and removals, with an application to tea production in India, Kenya, and Sri Lanka	First use of vector error correction model to disentangle short-run and long-run supply response for perennials
Dynamic Equilibrium in Markets for Perennial Crops	Knapp	1987	*American Journal of Agricultural Economics*	Mathematical Programming	Uses a dynamic optimization mathematical programming model to estimate cyclical perennial investment in California alfalfa	First use of a dynamic optimization mathematical programming approach to endogenously determine age composition and optimal rotation for perennials
The Effects of Uncertainty and Adjustment Costs on Investment in the Almond Industry	Dorfman and Heien	1989	*The Review of Economics and Statistics*	Regression	Uses regression model derived from optimal investment theory to estimate perennial crop investment accounting for uncertainty and adjustment with an application to California almonds	First to include uncertainty in the estimation of perennial supply response via stochastic prices and yields

Title	Authors	Year	Journal	Main Model	Objective/Approach	Methodological or Other Contribution
A Monte Carlo Simulation Model of the World Orange Juice Market	McClain	1989	University of Florida Ph.D. Dissertation	Structural Simulation	Develops a stochastic dynamic model of the world orange juice market and uses it to simulate the impacts of possible shocks to the market	Early example of a model for perennial crop supply response incorporating vertical and horizontal linkages
A Simulation Analysis of Supply Management in the Canadian Apple Industry	Goddard	1991	*Canadian Journal of Agricultural Economics*	Regression	Econometrically models supply and demand response for Canadian apples to simulate the impacts of a proposed supply management policy in the industry	Example of supply estimation for policy analysis in a perennial crop
Perennial Crop Supply Response: A Kalman Filter Approach	Knapp and Konyar	1991	*American Journal of Agricultural Economics*	State Space	Uses a state space approach and the Kalman filter to model perennial crop investment with an application to alfalfa	First use of a state space model to estimate perennial crop supply and investment, which allows for separate estimation of plantings and removals from aggregate data
A State-Space Approach to Perennial Crop Supply Analysis	Kalaitzandonakes and Shonkwiler	1992	*American Journal of Agricultural Economics*	State Space	Uses a state space approach and the Kalman filter to model perennial crop investment with an application to Florida grapefruit	Another early state space model in the literature that appears to have been developed simultaneously to Knapp and Konyar (1991)
The U.S. Apple Industry: Econometric Model and Projections	Willett	1993	*Agricultural and Resource Economics Review*	Structural Simulation	Develops a dynamic structural model of the U.S. apple industry in order to estimate supply and demand elasticities and simulate the impacts of potential future shocks	Detailed modeling of domestic and international market channels for perennial crops

Title	Authors	Year	Journal	Main Model	Objective/Approach	Methodological or Other Contribution
Changes in Western U.S. Orange Acreage and the Influence of Brazilian Orange Production	Pompelli and Castaneda	1994	*Journal of International Food & Agribusiness Marketing*	Regression	Estimates a single equation perennial acreage response model for oranges in the Western U.S., including influence of production by international competitor region	Example of acreage response estimation approach for a perennial crop
The Impact of Prices and Technology in the Replanting of Perennial Crops	Burger and Smit	1997	*Märkte der Agrarund Ernährungswirtschaft* (translates to *Agricultural and Food Markets*) Note: Although journal is German, article is written in English	Regression	Estimates the optimal timing of perennial replanting with an application to Indian rubber	Example of replanting estimation for a perennial crop, and a short but valuable discussion of key considerations in perennial crop investment
A Regional Econometric Model of U.S. Apple Supply and Demand	Roosen	1999	Iowa State University Staff Paper Series	Regression	Estimates the short-run and long-run response of U.S. apple production by region and market channel using three-stage least squares	Provides region-specific supply elasticities for a perennial crop
Irreversible Investment Decisions in Perennial Crops with Yield and Price Uncertainty	Price and Wetzstein	1999	*Journal of Agricultural and Resource Economics*	Mathematical Programming	Uses a real options approach to determine optimal entry and exit thresholds for Georgia (U.S.) peach producers	First use of real options approach to explore entry and exit decisions for perennial crop producers

Title	Authors	Year	Journal	Main Model	Objective/Approach	Methodological or Other Contribution
Dynamic Supply Response and Welfare Effects of Technological Change on Perennial Crops: The Case of Cocoa in Malaysia	Gotsch and Burger	2001	*American Journal of Agricultural Economics*	Regression	Predicts the welfare impacts of technological change in perennial crop varieties, incorporating the impacts of the change on new plantings, with an application to global cocoa markets	Estimation of welfare impacts associated with perennial crop investments
The Free Trade Area of the Americas and the Market for Processed Orange Products	Spreen, Brewster, and Brown	2003	*Journal of Agricultural and Applied Economics*	Mathematical Programming	Develops a dynamic, spatial equilibrium quadratic programming model of the processed orange market and uses it to predict the impacts of future trade policies	Consideration and incorporation of industry-specific details including processing model, trading regions, and trade policies
Economic Hysteresis in Variety Selection	Richards and Green	2003	*Journal of Agricultural and Applied Economics*	Mathematical Programming	Uses a real options approach to test for economic hysteresis (i.e., maintenance of investments long after motivating price signals that spurred investment) in perennial crop variety choice, with an application to wine grapes in California	Develops an empirical test for economic hysteresis in perennial crop variety choice
A Real Options Analysis of Coffee Planting in Vietnam	Luong and Tauer	2006	*Agricultural Economics*	Mathematical Programming	Uses a real options approach to determine optimal entry and exit thresholds for Vietnamese coffee growers	Example of real options approach to explore entry and exit decisions for perennial crop producers

Title	Authors	Year	Journal	Main Model	Objective/Approach	Methodological or Other Contribution
Market Power and Supply Shocks: Evidence from the Orange Juice Market	Wang, Xiang, and Reardon	2006	Michigan State University Department of Agricultural Economics staff paper	Regression	Develops a structural model of market power for differentiated products to estimate the impact of supply shocks on the market power of orange juice processors	Example of a perennial crop supply response model with vertical linkages using the most contemporary industrial organization approach of differentiated product market models
Economic Effects of Mitigating Apple Maggot Spread	Zhao, Wahl, and Marsh	2007	*Canadian Journal of Agricultural Economics*	Mathematical Programming	Develops a mathematical programming model of the U.S. apple industry to predict the potential impacts of apple maggot spread on market price, production, and welfare given various pest spread and policy scenarios	Example of a mathematical programming model with horizontal trade linkages used to assess pest pressures
Effects of Trade Barriers on U.S. and World Apple Markets	Devadoss, Sridharan, and Wahl	2009	*Canadian Journal of Agricultural Economics*	Mathematical Programming	Develops a spatial equilibrium trade model of the global apple industry to estimate the impacts of existing tariffs and possible future tariff regimes	Uses Bayesian methods to estimate the supply and demand functions for each region and incorporates a primal-dual mathematical programming approach in place of the standard quasi-welfare maximization in order to consider *ad valorem* tariffs
An Analysis of Apple Supply Response	Devadoss and Luckstead	2010	*International Journal of Production Economics*	Regression	Estimates supply response for apples in Washington State using theoretically-derived estimating equations and derives expected profits assuming rational expectations	Consideration of removals, new plantings, and yields for apples and inclusion of related farm outputs

Title	Authors	Year	Journal	Main Model	Objective/Approach	Methodological or Other Contribution
Switching to Perennial Energy Crops Under Uncertainty and Costly Reversibility	Song and Swinton	2011	*American Journal of Agricultural Economics*	Mathematical Programming	Uses a real options framework to consider producers' incentives for switching between a standard annual corn-soybean crop rotation and perennial switchgrass crop	Model allows for reversibility (i.e., ability of perennial crop producer to switch back to annual crop rotation) and compares different stochastic processes for modeling grower returns
Do Changes in Orchard Supply Occur at the Intensive or Extensive Margin of the Landowner?	Brady and Marsh	2013	*Agricultural and Applied Economics Association Annual Meeting Selected Paper*	Regression	Estimates the relative size of entering and exiting vineyard and orchard owners and determinants of entry and exit for vineyard and orchard owners in Washington	Considers decision-making at the level of the landowner rather than the operator, tests hypotheses from the manufacturing investment literature, and suggests that entry and exist (and not just intensive margin changes by incumbents) are an important element to consider in perennial crop supply adjustment
Perennial Crops Under Stochastic Water Supply	Feinerman and Tsur	2014	*Agricultural Economics*	Structural Simulation	Develops a model of expected net benefit of perennial crop investment that incorporates stochastic drought events, applying the approach to several crops in Israel	Incorporates uncertainty in future stream of net benefits from capital investment and risk of capital (i.e., tree) death into perennial crop supply response framework

Title	Authors	Year	Journal	Main Model	Objective/Approach	Methodological or Other Contribution
An Economic Assessment of the Impact of Huanglongbing on Citrus Tree Plantings in Florida	Spreen, Baldwin, and Futch	2014	*HortScience*	Regression	Estimates the relationship of HLB introduction and new plantings using a single regression model of new plantings for Florida citrus	Estimates impact of HLB through inclusion of a dummy variable for presence of HLB in the state of Florida
Imperfect Competition between Florida and Sao Paulo (Brazil) Orange Juice Producers in the U.S. and European Markets	Luckstead, Devadoss, and Mittlehammer	2015	*Journal of Agricultural and Resource Economics*	Regression	Develops a strategic trade model in the NEIO tradition estimated using three-stage least squares to test for the presence of market power in the global orange juice industry and simulate the impacts of various trade policy scenarios	Demonstrates framework for testing for market power of intermediaries in the context of perennial supply response
Economic Consequences for Tree Fruit Intermediaries from Shocks	Jiang, Cassey, and Marsh	2017	*Journal of Agricultural and Applied Economics*	Structural Simulation	Develops a dynamic equilibrium displacement model of the U.S. pear market that incorporates acreage response and explores various shock scenarios	Detailed modeling of domestic market channels and inclusion of several different types of shocks

Title	Authors	Year	Journal	Main Model	Objective/Approach	Methodological or Other Contribution
Dynamic Regional Model of the US Apple Industry: Consequences of Supply or Demand Shocks Due to Disease Outbreaks and Control	Tozer and Marsh	2018	*Agricultural Systems*	Structural Simulation	Develops a dynamic equilibrium displacement model of the U.S. apple market that incorporates acreage response and explores various shock scenarios	Detailed modeling of domestic market channels and inclusion of of different types of shocks, including pest and disease pressures
Economic Implications of Citrus Greening Disease Management Strategies	Zapata, Peguero, Sétamou, and Alabi	2022	*Journal of Agricultural and Resource Economics*	Structural Simulation	Develops a structural, stochastic bioeconomic simulation model of Texas citrus to estimate the economic impacts of various pest control strategies	Incorporates detailed biological modeling of disease and uncertainty associated with pest pressure and management

246