Modeling Steady-State Irrigated Production

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Abstract

In this paper we evaluate the intensive, extensive, and dynamic margin response to sustainable agricultural practices. We define sustainable agriculture as a system in which the resource and pollution stocks associated with production have a steady-state solution consistent with a resource-use path resulting in long run utility maximization. As an empirical application we consider two state variables, fertility levels and groundwater stocks, and a two-crop rotation system, alfalfa-cotton. Agricultural production leads to a fundamental tradeoff represented by the rotation between net-nitrogen using crops and net-nitrogen fixing crops. In addition, nitrogen using crops generally have higher net returns than nitrogen fixing crops, but nitrogen fixing crops have a higher water use per unit revenue. It follows that rotation shifts that favor nitrogen fixing crops result in greater groundwater depletion. To achieve sustainability in this context, one must simultaneously strike a steady-state balance, or at least a repeated cycle, between the rates of fertility change and changes in stocks of groundwater. We estimate the sustainability problem in three stages. First we estimate the rotation dynamic first order conditions. Next we incorporate the estimated rotation parameters into a calibrated economic production model that reflects the implicit crop production costs and calibrates to the base observed solution. Finally, we use the outputs from the calibrated production model to drive the equations of motion for groundwater use and fertility changes. We estimate the model with 13 years of geo-referenced field data in California's Central Valley and simulate the effect of changing rotations on the ability to achieve sustainable groundwater and nitrogen use, and the implicit social costs of achieving sustainability.

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Introduction

Agriculture by its very nature seeks to increase the productivity of specific species by reducing the ecological entropy of the natural ecosystem. This reduction in entropy can be measured in terms of biodiversity or energy flows which are changed by the process of agriculture, a process that can be viewed as the addition of both energy and information to change an ecosystem. Early agriculture was initiated by crop selection, cultivation, irrigation, and rotation. Over the past 80 years the first three agricultural practices have bloomed and developed beyond all recognition, while the final aspect of rotations, traditionally used to maintain fertility and control weeds and diseases, has been steadily reduced in its importance to highly productive irrigated agriculture by the substitution of energy, chemicals and information. The remarkable productivity that this process has engendered is well known.

However, there is a growing concern over the depletion of natural resources and contamination of the environment by external effects of conventional high-input agriculture. The question arises as to whether the current system is sustainable. It is our view that the question of sustainability rests on whether an equilibrium steady-state natural resource use and economic feasibility exists. If such feasibility does not exist with the current technology, what technological shifts would enable an irrigated agricultural system to move towards the steady-state of water use, water and land quality maintenance, and economic viability? The central tenant of this paper and the resulting model is that sustainable irrigation systems can only be achieved by substituting rotational fertility and pest controls for some of the current level of applied chemical technology. In simple economic terms we propose that sustainability in irrigated agricultural systems can only be achieved by moving back around the isoqant production curve towards a greater reliance on crop and probably livestock rotations.

For purposes of simplicity and empirical convenience, we locate our empirical example in an agricultural region of Southern California called Kern County, and identify fields rotated with two major crops, namely, alfalfa and cotton. Similarly we characterize the effect on the agricultural resource base in terms of water quantity, measured in this case by depth to groundwater, and water quality measured by the principal pollution in the region, namely the concentration of nitrates in the groundwater. We focus on these two effects because we feel that they dominate the resource base used in irrigated agriculture in many parts of the world.

The contributions of this paper are three-fold, (i) quantify the dynamics of agricultural rotations, (ii) incorporate the dynamics of agricultural production into a calibrated optimization model, and (iii) use the model to estimate the dynamic steady-state and implicit costs of sustainability. We consequently offer contributions in applied modeling, estimation and calibration methods, and policy application. The paper is structured as follows. First, we discuss and define sustainability to put the policy application in this paper into context. Next, we present our three-step modeling and estimation framework. We conclude with a policy example for the study region of Kern County and discuss application to other regions and externalities.

Global Costs of Unsustainable Production

Sustainable practices require that resource use follows a steady-state dynamic solution which results in long run utility maximization. In the absence of this sustainable path, we expect to deplete or degrade the available resource. We see this trend in a number of areas and applications.

In many regions of the world with irrigated agriculture current levels of water use are unsustainable. We can measure sustainability by the current rate of overdrafting of groundwater supplies. A recent study Gleeson et al.(2012) used a worldwide hydrologic model to estimate that almost a quarter of the world's population, 1.7 billion people, live in regions where groundwater is being overdrafted and used in an unsustainable manner. They also show that many of the overdrafted regions are those in which water supplies are most critical and urban and agricultural water stress is the highest. In California, the United States Geological Survey has recently released a study using satellite images that shows the rate of subsidence in California's Central Valley is greater than previously estimated (Sneed et al, 2013). The USGS estimates subsidence at more than 1 foot per year in some areas, creating substantial strain on California's state and federal water conveyance infrastructure.

In addition to overuse, surface and groundwater global supplies are threatened by quality degradation due to unintended salinity or chemical pollution. In the Central Valley of California Harter et al. (2012) show that nitrate pollution of groundwater stocks has risen to the level where it poses a severe health hazard to several agricultural communities. Salinization is the oldest water quality problem facing irrigated agriculture and has been responsible for removing several established irrigation systems and civilizations. A recent study by Schoups et al. (2005) estimates the scope of the global problem salinity affects between 20 and 30 million hectares. They show that salinity is a growing concern for irrigated agriculture along the Westside of California's Central Valley.

Groundwater overdraft and water quality degradation are difficult to quantify on a broad scale. Pitman and Lauchli (2002) estimate that at least 20% of the 227 million hectares of world-wide irrigated land suffers from reduced yields due to secondary salinization. Ghassemi et al. (1995) estimate the cost, in constant 1995 dollars, to be at least $12 billion. In addition to the costs of salinization, contamination by heavy metals and pesticides may be a more serious long-term threat to groundwater. These contaminants move slowly through the aquifer and are essentially irreversible once established. Other pollutants such as nitrogen and salinity can be treated if groundwater is pumped and used on crops which are tolerant to salts and heavy metals and enable some removal of these contaminants by the crop harvest.

We think the contribution of irrigated agriculture towards world food production and the threat of unsustainable production on the long-term prospects for irrigated agriculture warrant a formal and empirically-based modeling approach. Such an approach will help encourage future research on what the process of achieving sustainable irrigated agriculture involves, and may show what technological shifts would be needed to achieve sustainability in both water quantity and quality while maintaining viable economic production.

Defining and Modeling Sustainable Irrigated Production

The lack of importance of rotations to most agricultural economists is shown by the standard microeconomic analyses of agricultural production that define their classification of response in terms of the intensive and extensive margins production. MacEwan and Howitt (2013) argue that there is a third margin of adjustment in agriculture that reflects the positive or negative intertemporal effects of continuous or rotational cropping. They term this dynamic effect on agricultural productivity the "dynamic margin", and propose that a full intertemporal microeconomic analysis should include both the intensive and extensive static margins, in addition to the dynamic margin. They argue that only in the context of all three dimensions can one correctly reflect productivity and the user cost of the resources used in agriculture.

To evaluate the intensive, extensive, and dynamic margin response to sustainable agricultural practices, we define sustainable irrigated agriculture as a system in which the resource and pollution stocks associated with production have a steady-state solution that is consistent with a resource-use path that results in long run utility maximization. There is a substantial body of literature which defines sustainable systems in a more general economic equilibrium. Our approach defines sustainability as only depending on the sustainability of the utility of the consumers. This definition of sustainability has several attractive features, most notably it is consistent with patterns of resource use that may be systematically depleting the natural resource stock, as long as it is invested sufficiently well in alternative capital assets that maintain or grow the utility of consumers. Essentially, the utility approach treats renewable resources as extractive resources with finite horizons if their productivity, compared with alternative uses of the capital, is low. A classic paper showing the logical conclusion of this approach is by Spence (1974) who long ago noted that the reproductive rate of Blue Whales is below the rate of return of treasury bills, and thus the optimal long-term equilibrium is to drive Blue Whales into extinction and turn them all into treasury bills. We refine the strict utility-maximization approach and take a more ecological viewpoint of sustainability and define it in terms of a path that results in steady-state of water quantity and quality, while maximizing net returns and presumably long run utility from an irrigated agriculture system.

Agricultural production leads to a fundamental tradeoff which, since the advent of the Norfolk Four Course rotation in the 18th century, is represented by a rotation between net-nitrogen using crops and net-nitrogen fixing crops. In addition, nitrogen using crops generally have higher net returns than nitrogen fixing crops, but nitrogen fixing crops have a higher water use per unit revenue. It follows that rotation shifts that favor lower applied nitrogen requirements will result in reduced leaching of nitrates but greater groundwater depletion. In most cases, the adoption of crop intensification technologies results in greater use of both nitrogen and water. Sustainable intensification recognizes that, to offset these, we must have a change in the rotation to preserve the physical steady-state between groundwater and nitrogen use. The sustainability problem is, in this context, one of simultaneously striking a steady-state balance, or at least a repeated cycle, between the rates of nitrogen pollution and changes in stocks of groundwater.

We can think of this problem in several dimensions. The existence of steady-state equilibrium of groundwater and nitrate levels can be visualized using a phase diagram. The existence of steady-state depends on the starting levels of nitrates and groundwater and in the, yet unknown, rates-of-change and use of these resources in production. The problem is further complicated by the static intensive and extensive margin, which means the grower has the ability to shift land use and input use intensity. Shifts around the farm-level production surface, even along the same isoquant, presumably lead to a different dynamic system and steady-state equilibrium.

As an empirical application we consider two state variables, water quality in terms of nitrate levels in the groundwater, and groundwater stocks measured by the depth of groundwater in the aquifer. We model a two crop rotation system, alfalfa and cotton, observed over a set of fields on a single farm where fields are assumed to have a uniform physical capital endowment. While fallow is often included in the rotation for short periods, it is excluded in this example for empirical simplicity. We use this framework to simulate the effect of changing rotations on the ability to achieve sustainable groundwater and nitrogen use, and the implicit social costs of achieving sustainability. In addition, we conjecture that different intensification technologies will notably change the ability to achieve steady-state resource use.

We develop a sequential-estimation framework for the agriculture sustainability problem that includes three stages. First, we estimate the rotation dynamic first-order conditions using geo-referenced field-level data in Kern County and the method developed by MacEwan and Howitt (2013). Their approach uses the dynamic first order conditions to infer the expected yield change above or below the expected average, adjusted for soil type salinity and water availability, which explains the observed actions of the farmer and switching crops. Next, we incorporate the estimated rotation parameters into a farm-level calibrated economic production model that reflects the implicit crop production costs and calibrates to the rotational path that is observed in the base data. This stage uses standard calibration methods such as in Howitt et al (2012) that utilize prior econometric estimates of the elasticities of supply, elasticities of substitution and elasticities of the demand. In the last stage, we use the outputs from the calibrated production model to drive the equations of motion for groundwater use and fertility changes.

Dynamic Switching Crop Rotation Problem

To quantify the dynamic margin of adjustment we need to first understand the inter-temporal effects of crop rotation. We apply a method proposed by MacEwan and Howitt (2013) that imposes the dynamic first-order conditions of the observed rotation in order to estimate the dynamic switching costs. Their approach uses a three-step procedure where rotation systems are first identified using a sequence identification algorithm, the corresponding dynamic first-order conditions are derived, and then they estimate the corresponding rotation parameters. We are able to leverage our empirical framework and identify fields in an alfalfa-cotton based rotation, thereby circumventing the first step. Alfalfa is treated as a fixed four-year perennial crop.

We specify the rotation estimation problem as follows. Consider alfalfa as a four year crop, and define crops alfalfa and cotton as i and $k \in \{a, c\}$. We denote the crop-specific prices as p_i, yield as y_i, and variable costs of production as F_i. Equation (1) defines the profits generated from the field planted in crop *i* for year *t*, in the absence of rotation effects. Average yields and production costs are assumed constant over time.

$$\pi_{t,i} = p_{t,i} y_i - F_i \tag{1}$$

Annual crop yields vary due to a range of stochastic factors including weather shocks and management effects. We estimate the average yield variance from a time-series of county-specific average yields, σ_i^2, and allow stochastic yield shocks to follow a stationary normal distribution, $\varepsilon_i \sim N(0, \sigma_i^2)$. Equation (2) represents field profits with stochastic average yields.

$$\pi_{t,i} = p_{t,i} \left(y_i + \varepsilon_i \right) - F_i \tag{2}$$

In practice, crop rotation affects both crop yield and production costs. For empirical simplicity we allow for inter-temporal crop yield effects and fix average production costs. We allow for a one-period rotation effect lag in the model. In other words, the previous crop is the only factor that affects today's crop yield. We introduce the parameter $\Gamma_{i|k}$ for the yield carry-over effect and we measure the rotation effects as deviation from the mean, $\bar{y}_i$. The *i*, *k* entry of the matrix Γ represents the yield adjustment from planting crop *i* today given that the farmer planted crop *k* in the previous year. We allow the parameters to represent both positive and negative agronomic effects from rotating crops. We can now define the current period profits,

$$\pi_{t,i} = p_{t,i} \left(\left(\bar{y}_i + \varepsilon_i \right) - \Gamma_{i|k} \right) - F_i \tag{3}$$

Rotation effects may be positive or negative, depending on the relationship between the crop planted in the current and previous period. In our example, cotton extracts a relatively large amount of nutrients from the soil, whereas alfalfa replaces soil nutrients. Cotton-cotton rotation decreases average yields and requires additional nitrogen application, whereas alfalfa-cotton requires lower nitrogen application. We assume that soil quality and salinity are constant across all fields in our dataset. As we discuss below, we estimate our model using data from a subset of fields on a single farm and consequently feel that this assumption is a reasonable empirical simplification.

We can derive the corresponding set of Euler conditions that must hold for the observed base alfalfa-cotton rotation. Variations on the base rotation system result from economic factors including changes in relative prices, costs, resource constraints, or changes in field-specific physical capital. We consider the effect of changes in some of these factors in the policy simulations in the following sections of this paper. Given *n* fields we can write the corresponding set of Euler equations which must hold at any time *t*, where we have suppressed the time-subscript.

$$\pi_{n,a|c} \geq \pi_{n,a|c} \tag{4}$$

$$\pi_{n,c|a} \geq \pi_{n,a|a} \tag{5}$$

Equations (4) and (5) describe the first-order switching conditions of the field-level crop rotation problem. We discuss estimation of these conditions in a subsequent section.

Dynamic Calibrated Optimization Model

The rotation model tells us the dynamic switching cost of the cotton-alfalfa rotation. To estimate sustainability and grower response to policies, we require a framework that allows for simulation of policy alternatives. We specify a calibrated optimization model of the alfalfa-cotton farm-wide operation.

We specify the calibrated optimization farm model using the method of Positive Mathematical Programming (PMP), after the procedure in Howitt et al (2012). We make a modification to the calibration procedure to account for the dynamics of crop rotation. Standard PMP uses available data in the form of supply elasticities, average production costs, and observed land use in order to calibrate model parameters. The calibrated model reproduces the observed base year solution in inputs and outputs. This procedure works as expected so long as the observed production process is in steady-state equilibrium. We argue that the standard PMP procedure omits the dynamic effects of crop rotations. We consequently adjust the calibration process.

Cotton and alfalfa production, in the absence of rotation effects, follows a Constant Elasticity of Substitution (CES) production relationship. The CES allows for limited substitution between inputs. We allow four inputs to production: land, labor, other supplies (fertilizer), and water. Water is available from two sources, groundwater and surface water. We can write the CES as,

$$Y_i = \tau_i \left[\beta_{i,land} x_{i,land}^{\rho_i} + \beta_{i,labor} x_{i,labor}^{\rho_i} + \beta_{i,supply} x_{i,supply}^{\rho_i} + \beta_{i,water} x_{i,water}^{\rho_i} \right]^{\upsilon/\rho_i}, \tag{6}$$

and we use exponential PMP land cost functions,

$$C_i(x_i) = \delta_i e^{\gamma_i x_{i,land}}. \tag{7}$$

The calibration procedure follows the standard three-step PMP procedure detailed by Howitt et al (2012). To account for the observed rotation we include the observed lagged crop acreage in the first-step calibration procedure. We specify the rotation problem with a one-period lag, thus the previous season observed acreage allocation influences current season yields. We assume that each field on the farm has homogenous production conditions (absent rotation effects). Consequently, it is the average proportional allocation of acreage that contains necessary rotation information and we can calibrate the farm-wide model by taking a rotation-adjusted average yield for the two crops. We define $XB_{t,i}$ as observed land use in time period *t* for crop *i*. We calibrate the model to period *t*, taking into account lagged crop acreage in time period *t-1* and the estimated rotation switching costs. Let φ denote the proportion of fields in first, second, or third year alfalfa and we can define the rotation yield adjustment, $R_{t,i}$, for alfalfa,

$$R_{t,a} = \frac{\left(\Gamma_{a,a}\left(\varphi XB_{t-1,a}\right) + \Gamma_{a,c}\left((1-\varphi) XB_{t-1,a}\right) \right)}{XB_{t-1,a}}, \tag{8}$$

and for cotton,

$$R_{t,c} = \frac{\left(\Gamma_{c,c}\left(XB_{t-1,c} - (1-\varphi) XB_{t-1,a}\right) + \Gamma_{c,a}\left((1-\varphi) XB_{t-1,a}\right) \right)}{XB_{t-1,c}}. \tag{9}$$

Equation (8) shows the farm-wide average alfalfa yield after accounting for the observed rotation. Some proportion of fields, φ, are alfalfa stands in first, second, or third year of production. These fields will stay in alfalfa for period *t*, given our assumption of a four-year alfalfa rotation. We can let $\varphi = 0.75$ if we assume an initial uniform distribution of fields across the farm. Equation (9) shows the farm-wide average cotton yield. Again, we observe some proportion of fields rotated from alfalfa into cotton $(1-\delta)$ and it follows that the other fields were rotated as continuous cotton. Let $\bar{y}_{t,i}$ denote observed average yield in period *t*, then we calculate the rotation-adjusted yield for cotton and alfalfa in the calibration period *t* as,

$$YR_{t,i} = \bar{y}_{t,i} + R_{t,i}. \tag{10}$$

The resulting calibration problem is what we term "quasi-dynamic PMP." We proceed with the three-step calibration procedure and sequential diagnostic process to first derive the shadow values on the resource and calibration constraints, calibrate the exponential PMP cost functions given observed average response elasticities, and finally calculate the CES parameters. The quasi-dynamic aspect of this calibration procedure is that the observed yields in the base-year *t* are adjusted to account for lagged observed planting decisions. Consequently, the dynamic rotation effects are brought into the resource and calibration shadow values and carried through the PMP calibration procedure.

We can write the calibrated farm profit maximization problem for any period *t* (suppressing the time subscript) as

$$\begin{aligned}
&\max\ p_i Y_i - C_i(x_{i,land}) - \sum_{j \neq land} \sum_i \omega_j x_{i,j} \\
&\text{subject to} \\
&\sum_i x_{i,j} \leq B_j \\
&\sum_i x_{i,water} \leq \mathrm{GW} + \mathrm{SW}
\end{aligned} \tag{11}$$

We have defined $x_{i,j}$ as amount of input *j* used to produce crop *i* at cost ω_j, and B_j as the resource availability constraint. We let ω_{water} be equal to the weighted average water cost between surface and groundwater in the region. Finally, GW and SW correspond to groundwater and surface water use on the farm.

The grower manages the farm to maximize profits subject to resource availability, resource costs, and average crop prices. In this framework we are able to estimate the static intensive and extensive margin response to policies. Additionally, we have incorporated the dynamic margin of adjustment through the lagged observed crop planting decisions and yield switching costs. The model will calibrate to any year *t* observed land and input use, given the observed lagged crop acreages.

Dynamic Nitrate and Groundwater Model

Finally we link the calibrated farm profit maximization model, with rotation switching costs, to a dynamic framework for nitrates and groundwater. Nitrogen-based fertilizers are essential for modern cropping rotation systems and help ensure that we are able to meet global food demand. However, when fertilizer application exceeds plant demand and denitrification capacity of the soil this can lead to leaching into the groundwater. Point and non-point sources of nitrate contamination include fertilizer and manure, dissolved nitrogen in irrigation and septic tanks and dairy lagoons. In this paper we model a simplified dynamic framework for nitrate concentrations in groundwater and isolate the effect of fertilizer application on the Kern County farm over an assumed closed groundwater basin.

We model a system where nitrogen is applied as fertilizer to the crops in the rotation as a fixed average requirement in pounds per acre. We assume zero runoff and a fixed proportion for plant uptake, leaving the remaining proportion available for leaching. Denitrification, immobilization, and mineralization are modeled as a function of applied water and depth to groundwater. Increased irrigation water application increases leaching, and increased depth to groundwater leads to greater denitirfication.

Alfalfa increases and cotton decreases available soil nitrogen and thus potential nitrate leaching. As the ratio of alfalfa to cotton changes across the farm there will be a corresponding shift in the total amount of nitrates leached into the groundwater. The rate of change depends on the alfalfa-cotton ratio and relative differences in applied nitrogen and applied water. Define $AN_{t,i}$ as applied nitrogen to crop *i* in period *t*, and nf and nl as the crop use adjustment and leaching factors specific to the farm. Recall that $x_{i,j}$ is amount of input *j* used for crop *i* and we can define the nitrate dynamic equation as:

$$N_{t+1} = N_t + \frac{\sum_i nf \cdot AN_{t,i} \cdot x_{i,land} - \sum_i N_t \cdot x_{t,i,water}}{nl \cdot \left(TDL_t - RC_t\right)} \tag{12}$$

Alfalfa has higher evapotranspiration than cotton and thus requires more irrigation water. We include a dynamic feedback between depth to groundwater and pumping cost. We calculate the change in depth to groundwater as,

$$AF_{t+1} = RC_t - \sum_i (1 - DP_i)\, x_{t,i,water} \tag{13}$$

Where AF_{t+1} is acre-feet of recharge in period *t+1*, RC_t is recharge in period *t*, DP_i is the deep-percolation factor for each crop, and $x_{t,i,water}$ is water applied to crop *i* in period *t*. Finally, the change in depth depends on the area of the groundwater basin, BAS, and we can calculate the change in depth as

$$CHG_{t+1} = \frac{AF_t}{BAS}. \tag{14}$$

Pumping costs will vary with changes in depth to groundwater. We calculate the total cost of groundwater as the sum of fixed, O&M, and energy costs. Energy costs are based on a blend of agricultural power rates in the area. We can write average groundwater cost per acre foot in year *t+1*, as

$$c_{t+1,i,gw} = fixed + \left[\left(\frac{1.02ce}{eff} \right) + OM \right] TDL_t, \tag{15}$$

where $fixed$ is the fixed cost of groundwater pumping per acre-foot representing the amortized fixed costs of the pump and well. The parameter ce is the cost of electricity per kilowatt-hour. Well efficiency (eff) captures the effectiveness of wells to yield water accounting for energy loss due to friction, etc. OM represents operation and maintenance costs. Finally, TDL_t is the total dynamic lift in feet in year *t*, which includes both static lift and dynamic drawdown.

As the ratio of alfalfa to cotton increases we expect the farm to use more water and apply less nitrogen. Consequently, nitrate contamination will decrease and the groundwater table will decrease. The converse is also true. For a sustainable policy we seek to reach a steady-state balance between the rates-of-change of these two factors consistent with long-run utility maximization.

Data and Estimation

At this point we have specified a series of models used to estimate agricultural sustainability. The first stage is the estimation of a rotation switching model. This model, which uses the lagged crop as an indicator variable for the current fertility level, can be estimated either by direct observation of crop switching behavior of optimizing producers, or indirectly using crop growth models to simulate the effects of lagged crops. In the second model stage, parameters describing the effect of the lagged crop are incorporated into a calibrated economic production model that reflect the implicit crop production costs, and calibrates to the base observed solution. In the third stage of the model, the outputs from the calibrated production model are used to drive the equations of motion for groundwater use and fertility changes. The fertility equation of motion is approximated by nitrates leached into the groundwater. The groundwater state variable is measured by the depth to groundwater and the equation of motion is driven by natural recharge the system, aggregate pumping levels, and the amount of deep percolation to the groundwater basin.

We estimate the models using a set of geo-referenced land use data for Kern County, California. Agriculture in the region is irrigated with water coming from State and Federal surface water projects and groundwater in addition to local surface supplies. The data include all irrigated agricultural land in Kern County between 1997 and 2012. We exclude years prior to 2000 due to a change in county reporting methods. On each field and year we observe the crop grown, field size in acres, farm owner, and farm manager of the field. We are able to uniquely identify and track fields across time. We extract a subset of fields in an alfalfa-cotton based rotation in a region of the Western-edge of Kern County.

The estimation procedure used in the dynamic rotation problem is described in MacEwan and Howitt (2013) and summarized here. The dynamic first-order conditions result in an ill-posed estimation problem and we use the method of Generalized Maximum Entropy (GME) to estimate the parameters (Golan et al 1996). Given that one has incomplete observations about a statistical process, an information-theoretic consistent method to recover parameters for inference is to impose probabilistic structure on the model in such a way that it is consistent with observed data and imposes as little additional information as possible. Following this principle, we specify a truncated uniform support space for the parameters of plus or minus 100 percent of average yield and maximize the Entropy measure of the system. Table 1 summarizes the estimated parameter values for the dynamic crop rotation problem and shows the marginal yield effect implied from the observed rotation when crop (row) follows crop (column). For example, cotton-cotton results in an average reduction of 0.035 tons/acre which is a 4.9% decrease in average yields. When cotton follows alfalfa, average yields increase by 0.024 tons/acre, or 3.4% above average yield.

Table 1. Crop Rotation Parameters Yield Adjustment (tons/acre)

	Alfalfa	Cotton
Alfalfa	-0.2839	0.4056
Cotton	0.0248	-0.0354

We estimate the calibrated optimization model using the method of PMP as described in Howitt et al (2012). The calibration procedure involves three steps: a linear program to calculate resource and calibration dual values, a least-squares parameters calibration program that includes exogenous acreage response elasticity estimates, and a series of parameter calculations used in the fully-calibrated CES model. Rotation effects are incorporated as a fourth-step where we calculate the average adjusted crop yields, given the observed rotation, to incorporate into the first-step of the PMP procedure. The end result is a fully-calibrated CES model that includes dynamic crop rotation effects and satisfies the economic and numerical calibration checks proposed in Howitt et al (2012).

Table 2. Optimization Model Parameters

Optimization Model Parameters	Value	Units
Alfalfa Acreage Response Elasticity	0.51	-
Cotton Acreage Response Elasticity	0.64	-
Alfalfa average AW	4.48	af/ac/year
Cotton average AW	3.26	af/ac/year

The nitrate and groundwater equations of motion are parameterized using exogenous information available from county data. The dynamic equations work in a feed-back loop with the calibrated optimization model and track nitrates and groundwater levels across time. The combined framework allows us to estimate the static intensive and extensive margin, in addition the dynamic margin. Tables 3 and 4 summarize the nitrate and groundwater parameters used in the model.

Table 3. Nitrate Parameters

Nitrate Dynamics Parameters	Value	Units
Nitrate Crop Use Factor	0.6	factor
Nitrate Leaching Factor	100	factor
Alfalfa Applied Nitrogen	0	lb/ac
Cotton Applied Nitrogen	180	lb/ac
Applied Nitrogen Cost	0.084	$/lb

Table 4. Groundwater Parameters

Groundwater Dynamics Parameters	Value	Units
Deep Percolation Factor Alfalfa	0.13	factor
Deep Percolation Factor Cotton	0.1	factor
Natural Recharge	0.02	af/year
Groundwater Basin Size	1000	ac

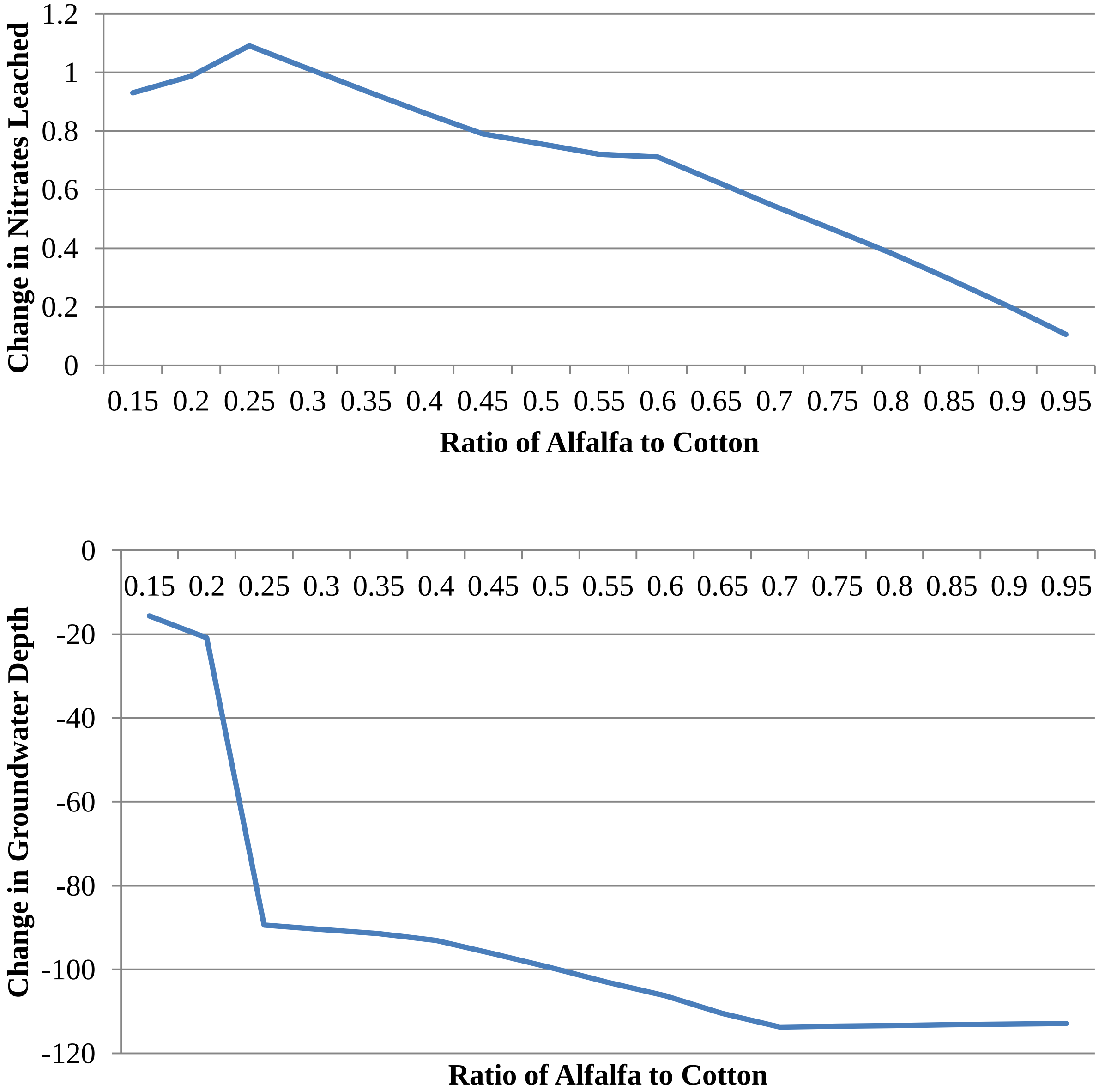
Aggregate Rotation Dynamics and Sustainability

Before we proceed with policy simulations we want to emphasize the interaction between rotations, production, and externalities. In this section we fix the alfalfa – cotton ratio on the farm and consequently fix the average farm rotation. Conceptually, we can simplify our set of control variables to changing the ratio of alfalfa to cotton acres over a given unit of land. As the ratio of alfalfa to cotton increases, the level of nitrogen applied decreases along with the excess nitrates that percolate to the groundwater for two reasons. First, on average, cotton acreage is smaller and thus the total burden of nitrogen applied is reduced. Second, the increased alfalfa area will fix increasing quantities of nitrogen which then can be utilized by the cotton. At some point in the alfalfa to cotton ratio will reach equilibrium where the quantity of nitrogen being removed from the groundwater in the irrigation water pumped is equal to the quantity percolating down from the cotton acreage, and the net nitrogen applied to cotton through artificial fertilizer is removed in the crop itself. Essentially when the cotton crop that was grown to make your jeans requires no more imported nitrogen than that embodied in the fiber of your jeans, the system will be in nitrate, and thus water quality, steady-state.

Figure 1 illustrates the trade-off between nitrate pollution and groundwater levels, holding other factors constant. As the ratio of alfalfa to cotton increases there is a reduction in fertilizer application and a corresponding decrease in nitrates leached into the groundwater. However, alfalfa is also more water-intensive than cotton and this requires the grower to deplete the groundwater resource at an increased rate. As the depth to groundwater increases, the total dynamic lift and pumping costs increase.

A similar logic applies to the use of water to grow crops, but interestingly, the water use function has the opposite slope to the nitrate function for given shift in the alfalfa to cotton ratio. As in the nitrogen example, think of an increase in the alfalfa to cotton ratio which reduces the nitrogen burden on groundwater, but will, in this case, increase the pumping burden on groundwater due to the higher evapotranspiration requirements of alfalfa. Alfalfa is typically irrigated twice a month for seven months per season, as opposed to cotton which has a shorter growing season and is deliberately stress irrigated at the end of the season to improve the yield in terms of the ratio of boll to vegetative growth.

Figure 1. Change in Nitrates and Groundwater Depth as Rotation Shifts



We want to strike a steady-state balance between groundwater depletion, nitrates, and farm profitability. As the grower shifts to a more alfalfa-dependent rotation this leads to lower profitability. Although cotton is the higher-value crop, alfalfa monoculture will further decrease yields.

Policy Simulations

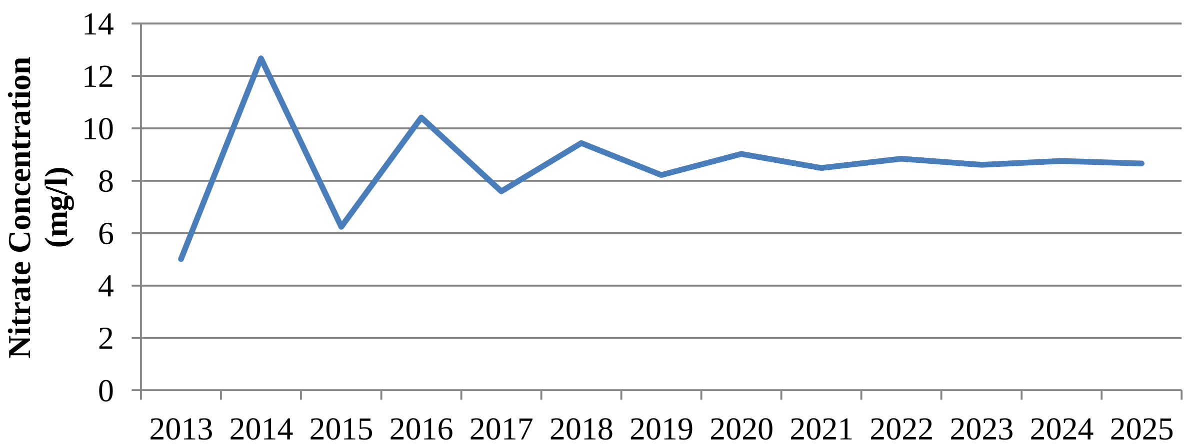
In this section we simulate the dynamics of the rotation system. We simulate the model for the years 2013 – 2025 using observed acreage decisions for 2009 – 2012 as initial conditions for the rotation dynamics. In all simulations we hold relative crop prices and production costs constant to isolate the effect of water quality and quantity. Surface water supplies are held constant at the calibrated baseline average. In future iterations of this model we intend to include stochastic surface water deliveries, reflecting the uncertain nature of district deliveries and seasonal precipitation. Similarly, average crop yields are assumed known and held constant in the analysis.

Nitrate Dynamics

An acceptable level of nitrates in the groundwater is in the range of 3 – 5 mg/l. Concentrations above this level are known to increase the risk of disease and cancer. We normalize the level of nitrates initially in the groundwater basin to be 5 mg/l to simulate a groundwater basin with existing high levels.

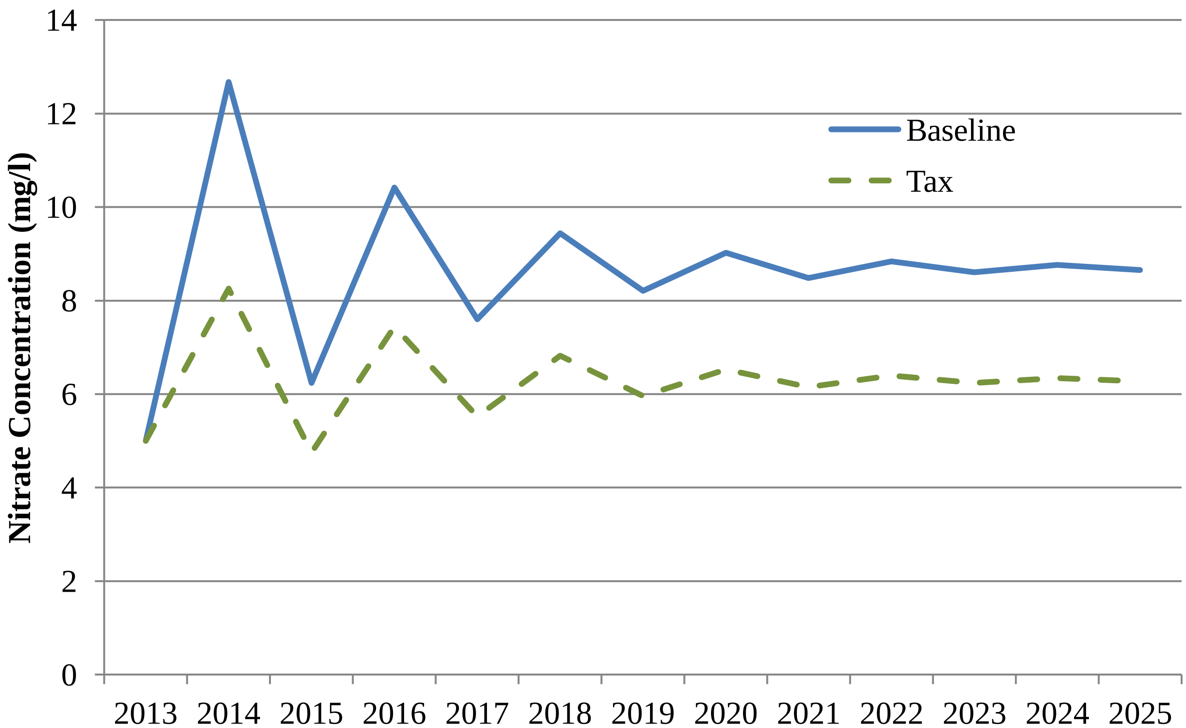
Figure 2 illustrates nitrate levels in the groundwater under baseline conditions from 2013 – 2025. As shown, there is a generally increasing trend in nitrates in the groundwater basin. We can see the cyclical rotation underlying the simulation and the system trends toward a level of just under 10 mg/l concentration, above acceptable levels.

Figure 2. Groundwater nitrates under no policy action



It is clear from figure 2 that the level of nitrates in the groundwater exceeds acceptable levels under the current production system. A commonly proposed strategy to reduce nitrates is to discourage excess application of fertilizers. We can simulate this effect with a tax per pound applied nitrogen. To illustrate this situation we impose a tax of $30/lb of applied nitrogen. Figure 3 illustrates nitrate levels under the baseline simulation and under a tax of $30 per pound of applied nitrogen.

Figure 3. Groundwater nitrates under no policy and fertilizer tax



The fertilizer tax reduces the relative profitability of cotton and encourages a shift toward alfalfa. If the grower were only able to adjust along the static intensive and extensive margins then we would expect a corresponding decrease in cotton yields and farm profitability. The presence of a rotation, included in our model framework, allows for adjustment along the dynamic margin and substitution of alfalfa for cotton as part of a multi-year rotation. This may partially or totally offset some of the yields losses, thereby allowing the grower to move toward more sustainable groundwater nitrates at a lower cost to farm profits and the regional economy.

Figures 4 and 5 illustrate the intensive margin response to a fertilizer tax. Baseline average applied nitrogen per acre for cotton is 180 pounds per acre. Under a fertilizer tax we see a substantial intensive margin response as the grower reduces applied nitrogen. This has a corresponding cotton yield effect (movement around the CES surface) which can be partially offset by increased alfalfa rotation. We see again the cyclical effect of crop rotation and reduction in fertilizer use, decreasing from an average of 171 lb/ac to 121 lb/ac.

Figure 4. Cotton applied nitrogen per acre under no policy action

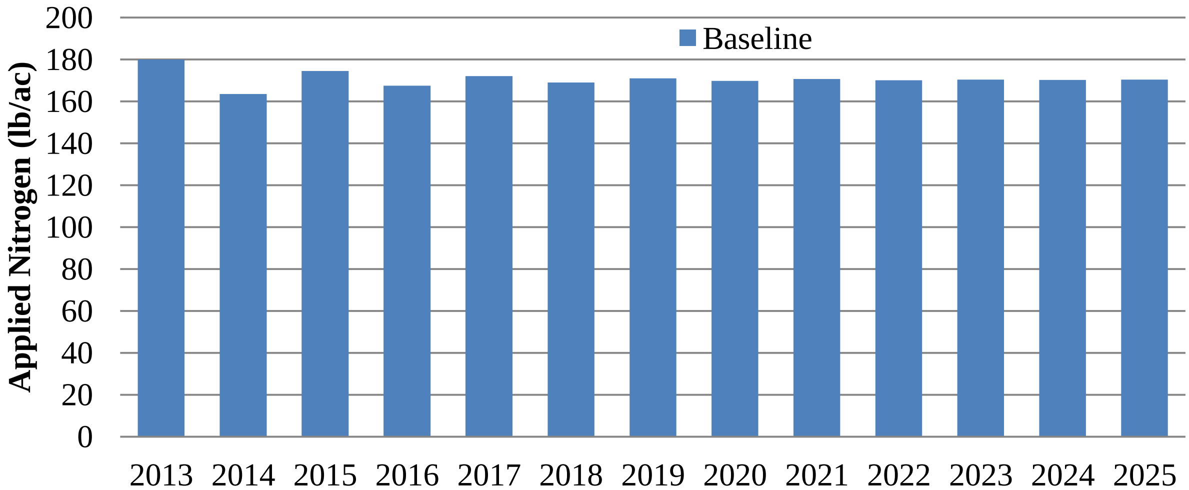
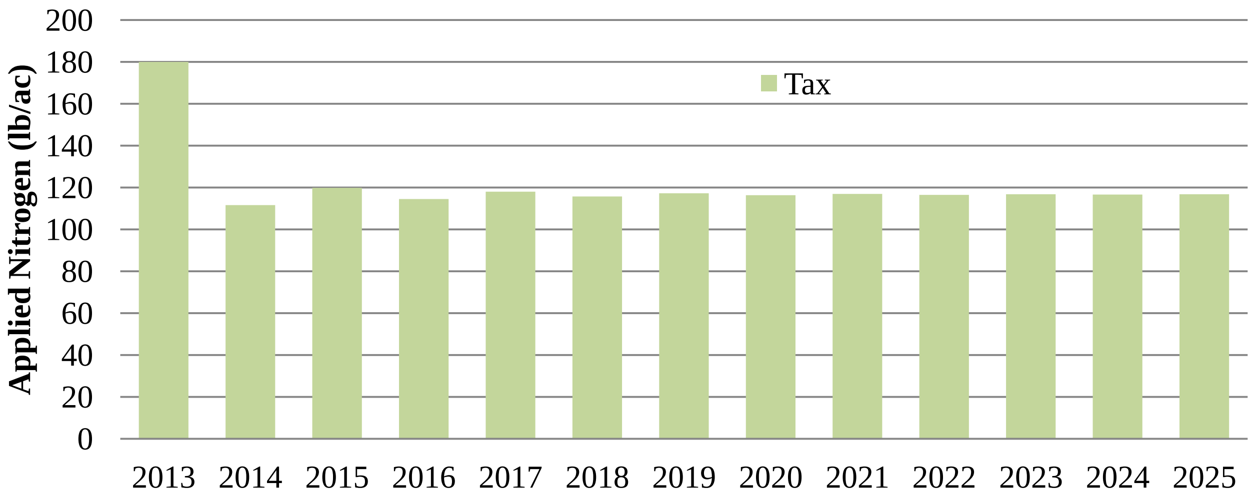


Figure 5. Cotton applied nitrogen per acre under fertilizer tax

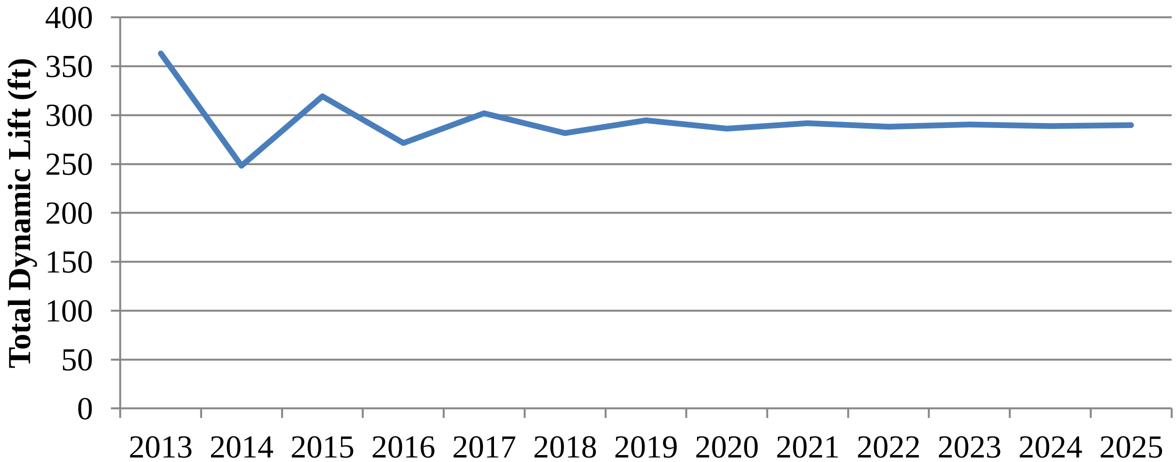


Groundwater nitrate levels are reduced under a fertilizer tax. The grower substitutes away from cotton toward increased alfalfa in the rotation and there is a corresponding effect on both cotton and alfalfa yields. Importantly, alfalfa has higher water requirements than cotton, which increases groundwater use and may further deplete the aquifer. A steady-state solution requires balancing grower profitability, nitrate levels, and groundwater use.

Groundwater Dynamics

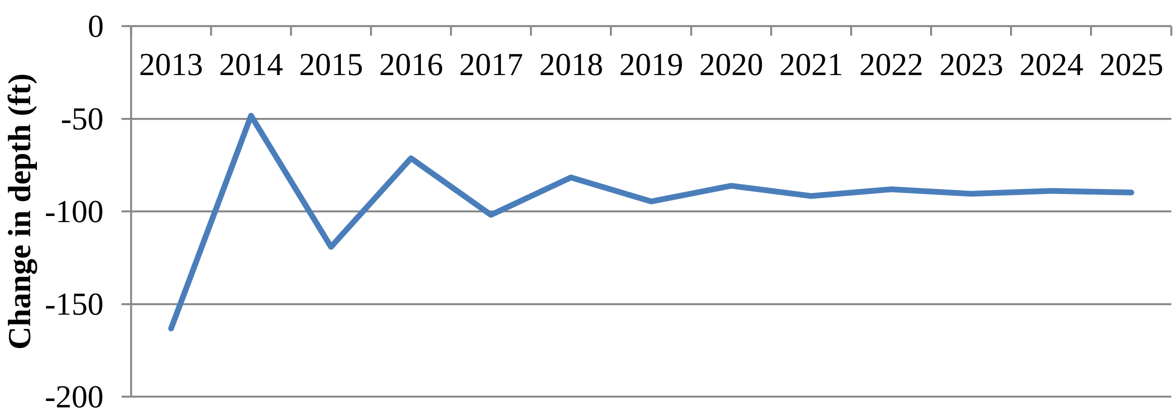
In addition to nitrate levels we are also interested in management of the underlying aquifer. The farm receives annual surface water deliveries that are sufficient to meet less than 40 percent of observe base-year crop demand. The grower makes up the remaining water requirements by pumping groundwater. Increased pumping leads to drawdown of the aquifer and increased dynamic lift, which translates into higher pumping costs and lower farm profits. Figure 6 illustrates the (dynamic) depth to groundwater under the baseline policy simulations.

Figure 6. Baseline aquifer dynamic depth



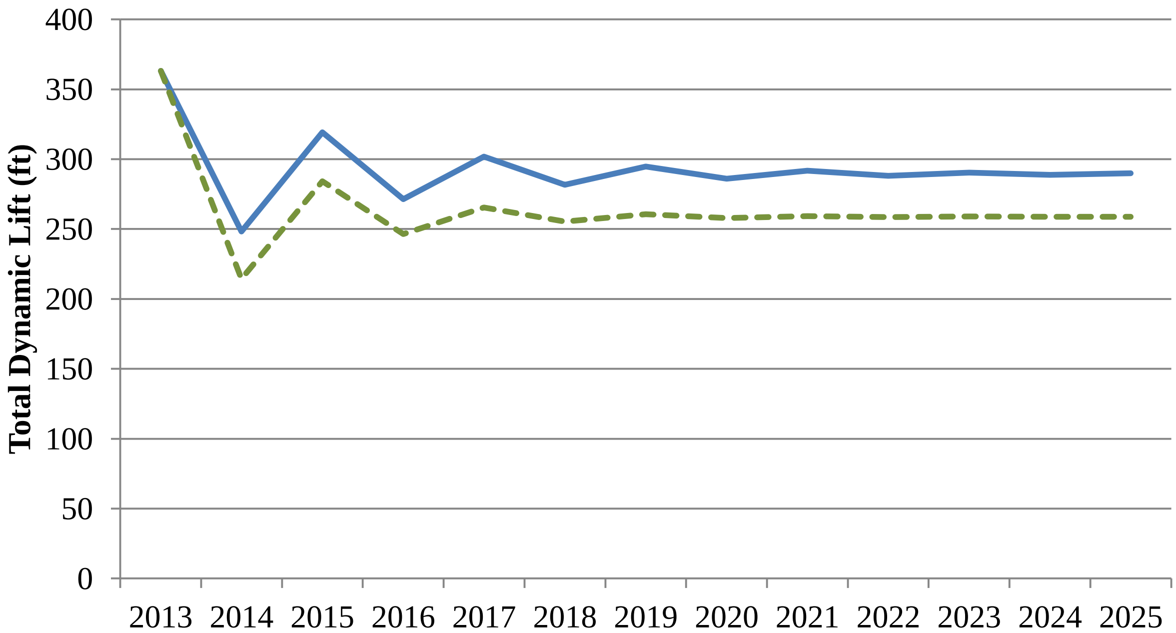
In the absence of policy intervention we see the aquifer trending toward an apparent steady-state of around 300 feet of dynamic lift. With pump efficiency, maintenance costs, and electricity prices this translates into a cost of $123 per acre foot of irrigation groundwater. By comparison, surface water deliveries are available in the region between $20 and $70 per acre foot, we use a cost of $30 per acre foot in the model. Figure 7 illustrates the annual change in total dynamic lift.

Figure 7. Annual change in depth



Again, we see the cyclical pattern driven by the underlying alfalfa-cotton rotation. There is large variation in year-to-year change in dynamic lift and a corresponding change in pumping costs. Of course, the farm in our example is assumed to lie over a closed groundwater basin which is why we see such large seasonal variability. To prevent drawdown we can impose a groundwater extraction charge on the grower. Here we simulate the model with a charge of $25 per acre foot. Figure 8 illustrates the results.

Figure 8. Groundwater depth under baseline and groundwater charge



A groundwater pumping charge of $25 per acre foot reduces the depth to groundwater. The grower reduces applied water per acre and substitutes toward the less water-intensive cotton in the rotation. The average total dynamic lift over the simulation period decreases from 294 feet to 269 feet. It is of note that some of the more stable groundwater basins in California impose a groundwater charge on agricultural users. In Santa Clara County, the Santa Clara Valley water district imposes a charge of just under $20 per acre-foot. This combined with other management efforts has worked to stabilize groundwater levels in a region historically plagued by substantial subsidence.

Total surface water supplies are held constant in the analysis. If instead we were to simulate additional surface water available we could estimate the corresponding change in groundwater depth and the implicit benefits of the additional surface water. As with the nitrogen tax, there are intensive and extensive margin adjustments underlying the policy simulations.

Summary and Steady-State Solution and Social Costs

One definition of a steady-state sustainable solution requires that the rate of change in nitrates and depth to groundwater are constant and consistent with long-run utility maximization for the grower. We can alternatively conceptualize sustainability from a physical perspective and impose threshold levels of groundwater levels and nitrates. We will extend this work in the future to model the formal dynamic steady-state solution. Other areas for further refinement include incorporating a sequential dynamic PMP procedure, incorporating a dynamic feedback between groundwater quality and crop yields and production costs, and expanding the model from the farm to a larger basin.

In summary, we have proposed a three-step estimation framework to evaluate sustainable policies. The framework allows for estimation of the intensive, extensive, and dynamic margin response. We estimate grower response to policies designed to encourage a more sustainable agriculture and discuss further steps to estimate the full steady-state sustainable solution.

In the framework presented in this paper, to reach steady-state of fertility can only be achieved by rotating net nitrogen using crops, which may or may not need additional fertilizer, with net nitrogen increasing crops such as legumes. In general, net nitrogen using crops such as cotton are characterized by higher profits per unit land, and lower water use per unit land. Conversely, net nitrogen increasing crops such as dry beans or alfalfa, have lower net revenues per acre than cotton, but a high water requirement per acre than cotton. We have shown this explicit trade-off between the rates of change of fertility stocks and resource stocks and we have presented the sustainability problem as one of simultaneously striking a steady-state balance between the rates of fertility change and changes in stocks of groundwater.

We feel that the framework presented in this paper will be of value for evaluating sustainable intensification strategies, for example in developing countries. In most cases the adoption of crop intensification technologies results in greater use of nitrogen and water. Sustainable intensification recognizes that, to offset these, we must have a change in the rotation to preserve the physical steady-state between groundwater and nitrogen use. Intensification that is also sustainable must balance both the rotation and the productivity of new technology.

References

Ghassemi, Fereidoun A., A.J. Jakeman, and H.A. Nix. 1995. "Salinisation of land and water resources: Human causes, extent, management and case studies." UNSW Press, Sydney, Australia, and CAB International, Wallingford, UK.

Gleeson, T., Yoshihide Wada, Marc F.P. Bierkens, and Ludovicus P.H. van Beek. 2012. "Water balance of global aquifers revealed by groundwater footprint." Nature (488) (August): 197-200

Golan, Amos, George Judge, and Douglas Miller. (1996), Maximum Entropy Econometrics: Robust Estimation with Limited Data, Chichester, England: John Wiley & Sons.

Harter, Thomas and Jay R. Lund (PI's). 2012. "Addressing Nitrate in California's Drinking Water." Prepared for the California State Water Resources Board. California Nitrate Project, Implementation of Senate Bill X2 1. Center for Watershed Sciences University of California, Davis.

Howitt, Richard. E., Josué Medellín-Azuara, Duncan MacEwan, Jay R. Lund. 2012. "Calibrating disaggregate economic models of agricultural production and water management." Environmental Modelling & Software (38) (December): 244-258.

MacEwan, Duncan. and Richard E. Howitt. 2013. "An Empirical Model of Crop Rotations." University of California. Department of Agricultural and Resource Economics. Davis, CA.

Pitman, Michael G., & André Läuchli. (2002). "Global impact of salinity and agricultural ecosystems." Salinity: environment–plants–molecules. Dordrecht: Kluwer, 3-20.

Schoups, Gerrit, Jan W. Hopmans, Chuck A. Young, Jasper A. Vrugt, Wesley W. Wallender, Ken K. Tanji, Sorab Panday. 2005. "Sustainability of irrigated agriculture in the San Joaquin Valley, California." Proceedings of the National Academy of Sciences, USA (102): 15352–15356.

Sneed, Michelle, Justin Brandt, Mike Solt. 2013. "Land Subsidence along the Delta-Mendota Canal in the Northern Part of the San Joaquin Valley, California, 2003-10." U.S. Geological Survey Scientific Investigations Report 2013-5142, 87 p.

Spence, Michael A. 1975. "Blue Whales and Applied Control Theory," in System Approaches and Environmental Problems, H. W. Gottinger (ed.), Vandenhoeck and Ruprecht (Gottingen).