Regulating Water Quality in Irrigated Agriculture: An Input-based Approach to Mitigating Nutrient Contamination From Nonpoint Sources.

Abstract:

This paper presents the theoretical background and initial results of the effect using an input-based approach to regulating non-point source nutrient loads to streams from agricultural lands based on the Erosion-Productivity Impact Calculator (EPIC) model. EPIC was used to determine crop yields for cotton and nutrient loads to surface water and groundwater under various fertilization and irrigation scenarios for a hypothetical setting representing soil and climate conditions found in Fresno County. Non-linear regression identified equations to describe: 1) cotton yield as a function of nitrogen inputs and irrigation water, and 2) nitrogen leaching to surface water and groundwater as a function of nitrogen inputs. Profit optimization for a hypothetical 200 ha farm under "status quo" operation revealed that 56.7 kg/ha of nitrogen would be applied as fertilizer with farm profits of $554,000. A hypothetical scenario to maximize social benefit by taking into account the impact of nitrogen loads to groundwater and surface water was then adopted and a tax was levied on the farm's use of nitrogen fertilizers. Under presumed levels of environmental damage of $50/kg N in surface water and $60/kg N in groundwater, net social benefit was calculated as $341,000. Under the social benefit optimization scenario, farm profits were reduced to $391,000 while net social benefit rose to $399,000 at a fertilization level of 40.1 kg/ha and a tax of $15.7/kg nitrogen inputs. While this an extreme example to illustrate a point, surface waters and groundwaters are sinks of nitrogen resulting in real costs to parties not witnessing benefits of farm production profits. New strategies such as taxes or incentives to implement best management practices should be undertaken to limit the influence of nonpoint source nutrient pollution in the Nation's waters.

Table of Contents:

Regulating Water Quality in Irrigated Agriculture: An Input-based Approach to Mitigating Nutrient Contamination From Nonpoint Sources. 1
Abstract: 1
Introduction: 2
Background, Data & Methods: 3
  Study Area-Fresno County 4
  Hydrology/Hydrogeology of Fresno Region 4
  Modeling Agricultural Production and Nutrient Budgets in EPIC 5
  Soil 5
  Climate 6
  Other Agricultural Characteristics 6
  Other Remarks & Assumptions 7
Analysis & Results: 7
  1. EPIC Model Results Under Various N and Irrigation Levels 7
  2. Determination of the Crop Production and N Runoff Functions 8
  3. Determination of Revenue and Cost Functions Under "Status Quo" Farm Operation 10
  4. Determination of Farm-level Decision-making Under Agency Regulation 12
Discussion: 15
References: 17

Introduction:

The Federal Water Pollution Control Act Amendments of 1972 (Clean Water Act, CWA) has undoubtedly been one of the more successful regulatory interventions of the federal government. The stated goal of the CWA is "to restore and maintain the chemical, physical, and biological integrity of the nation's waters (Flatt 1997)." The primary mechanism for accomplishing this was the creation of a permitting system (NPDES). These permits specify load limits for particular chemicals, technology applicable to each pollutant, the effluent limitations a discharger must meet, and the deadline for compliance. Each pollutant is then monitored with results reviewed by EPA or another governing agency. Administration of this program is shared between EPA and State environmental agencies.

While these programs were affective in controlling "point" sources, places where a polluter discharged directly to stream at a single point, NPDES permitting did not address nonpoint sources (NPS) of pollution such as urban or agricultural runoff.

NPS pollution can take various forms such as pesticides, nutrients, sentiments, salinity, trace elements, and other materials. Agricultural chemicals (herbicides, insecticides, and fertilizers) are used extensively in the United States to increase yields of agricultural crops (Goolsby 1994). Recent reports from the Natural Resources Conservation Service and U.S. Geological Survey indicate that NPS pollution poses the greatest threat to the National's water and that agriculture is the major source of most of these constituents in surface and ground waters (Dubrovsky, Kratzer et al. 1995; Natural Resources Conservation Service 1997). Many agricultural chemicals are partially water soluble and can leach to ground water or run off to surface water (Thurman, Goolsby et al.), such as nitrogen in the form of nitrate (Puckett 1994). **Figure 1** shows some of the major impacts attributable to NPS pollution.

Constituent	**Source**	**Impact**
Nutrients (Nitrogen and Phosphorus)	Fertilizer applications on crops.	Eutrophication in surface waters, drinking water impediment in drinking water (groundwater supplies).
Pesticides	Pesticide applications on crops.	Threat to biota in surface and ground water; threat to both surface and drinking water supplies.
Salinity	Evaporative concentration from irrigation waters.	Increased cost of drinking water purification, reduced agricultural systems, and impairment of aquatic life.
Trace Elements (Selenium, Boron, Arsenic)	Leachate from irrigated soils.	Toxic to humans and aquatic life.
Sediment	Erosion	Loss of soil decreases crop productivity; results in disinfection problems for drinking water supplies; problem for biota, such as salmon species.

Figure 1: Sources and Impacts of Non-point Source Pollution in Irrigated Agriculture

While nitrogen inputs are necessary for proper plant growth, some nitrogen is invariably lost in surface water and groundwater. One study has shown that well-drained soils with high nitrogen input (>6 tonnes/square mile) exceed EPA's nitrate drinking water standard of 10 mg/l in 26% of groundwater wells surveyed (Nolan and Ruddy 1996). Nitrate contamination in drinking water supplies impedes oxygen uptake in infants and can result in "Blue Baby Syndrome." Illustrating the impact to surface waters, over 11.5 million tonnes of commercial fertilizer are applied each year (Puckett 1994). In 1990, 35% of U.S. river miles did not fully support their designated uses assigned by the States. The problem is acute in California where several waterways are listed as impaired under the Clean Water Act for ammonia and nutrient contamination stemming largely from agricultural fertilizer use (State Water Resources Control Board 1999). Eutrophication remains the major threat to surface waters where the increase in algal growth followed by a rapid die-off can consume vast amounts of oxygen in the decomposition process, lowering dissolved oxygen availability for other organisms.

Given that there are negative externalities associated with nutrient loading in surface water and groundwater, it is probable that agencies with some degree of regulatory authority will eventually devise mechanisms for limiting load. One previous study has examined the potential for agency intervention in the form of taxes, quotas, and monitoring (Dinar and Xepapadeas 1998). Our study aims to build off Dinar (1998) by examining the actual loading to surface water and groundwater from a particular agricultural cropping pattern, but applies a simpler economic analysis to maximize regional or social net benefit. The concept of agency intervention is by no means uncommon, particularly with regards to wellhead protection programming to protect drinking water supplies though land use zoning and other limitations (USEPA 1994).

The specific goals of this paper are to:

1. Utilize EPIC to model the influence of irrigation water and nutrient inputs on production,
2. Utilize EPIC to model the nitrate load to surface water and groundwater under various fertilizer application quantities,
3. Using the EPIC output, determine the production function for cotton in a typical Fresno County setting with respect to inputs of fertilizer and irrigation water using non-linear regression in JMP Statistics and MS Excel,
4. Optimize application of fertilizer and irrigation applications to maximize farm profits under "status quo" conditions, and
5. Develop an optimal taxing strategy to maximize social net benefit by incorporating the costs of nutrient loading in waters into the decision-making process.

Background, Data & Methods:

For the first step of this study we are interested in the ability of EPIC to estimate crop yield as a function of irrigation and fertilizer inputs, in addition to estimating levels of nitrogen leaching to ground and surface waters. This requires data on conditions such as soil, climate, and cropping patterns. For this study we have selected a hypothetical farm of 200 ha with the soil and climate of Fresno County. We assume the farm grows only cotton. This section reviews the most important data used in the EPIC model, provides an overview of the EPIC model, and provides some other relevant background information that will be used in the following sections of this paper to perform analyses such as profit maximization.

Study Area-Fresno County

The area study for this experiment will be a hypothetical location with the climate, soil, and agricultural characteristics of Fresno County in the San Joaquin Valley of California. This county derives a large share of its gross income from agricultural activities. Cotton is the No. 3 agricultural commodity and the largest grossing field crop. In 1999, cotton production had a total value of $331,551,000 and was grown on 279,800 acres (Agricultural Commissioner 2001). To grow this cotton, over 3,400,000 pounds of active ingredient pesticides were applied in 1999 (Department of Pesticide Regulation 1999). Irrigated land in Fresno county was reported as 1,153,812 acres in 1997 (U.S. Department of Agriculture 1997).

Hydrology/Hydrogeology of Fresno Region

Fresno sits in the San Joaquin Valley, the lower portion of the asymmetrical Central Valley enclosed by the Sierra Nevada Mountains on the east, the Coast Ranges on the west, the Tehachapi Mountains on the south, and the San Francisco Bay-Delta region on the north. The Pleistocene Corcoran Clay layer of the Tulare Formation divides the groundwater flow system into an upper semiconfined zone and a lower confined zone. Above the Corcoran Clay layer, three hydrogeologic units can be identified: Coast Range alluvium (marine), Sierran sand (micaceous), and flood-basin deposits (Belitz, Heimes et al. 1990).

The Coast Range alluvium is generally oxidized and ranges in thickness from 850 feet along the Coast Ranges to 0 feet closer to the Valley's axis, as shown in **Figure 2**. These deposits range greatly in texture and permeability based on position along the alluvial fan. The Sierran sand is 400 to 500 feet thick in the valley center and thins to the west, as the alluvial deposits of Coast Ranges increase in thickness. The Sierran sand is reduced in the Valley trough. Erosion through time has created a largely interfingered system in the Valley of Sierran sand and

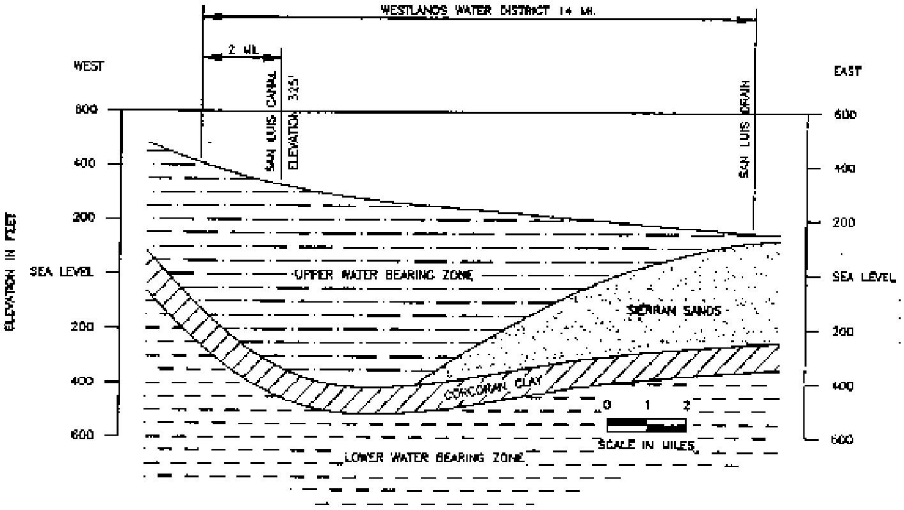


Figure 2: Hydrogeological Cross-Section of Fresno County

Coast Range alluvium. The varied textual and geochemical properties of each have created a fairly complex situation. The Corcoran Clay was formed as lake deposits of clayey silt, and creates a low permeability boundary of 20 to 120 feet in thickness, found 900 feet deep along the Coast Ranges and 400 feet in the valley trough.

Several major human activities should be noted for their influence: “percolation of irrigation water past crop roots, historical pumping from below the Corcoran Clay Member of the Tulare Formation, delivery of surface water, and installation of regional subsurface tile-drain system (Belitz, Heimes et al. 1990).”

Modeling Agricultural Production and Nutrient Budgets in EPIC

The basis of this study is the Erosion-Productivity Impact Calculator (EPIC) model, originally developed to assess the effect of soil erosion on soil productivity (Williams, Dyke et al. 1983). It was first used for that purpose as part of the 1985 RCA (1977 Soil and Water Resources Conservation Act) analysis, but has been expanded and has a large applicability to studies examining agricultural production and nutrient loads under various copping patterns. EPIC is a continuous simulation model that can be used to determine the effect of management strategies on agricultural production and soil and water resources. The drainage area considered by EPIC is generally a field-sized area since weather, soils, and management systems are assumed to be homogeneous. The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control.

The basic equations describing nutrient transport in EPIC have been appended as **Appendix 1**. Full documentation for the model can be obtained from the official web site at http://www.brc.tamus.edu/epic/. Basic model parameters include: soil, climate, cropping (irrigation, fertilization, etc), which we will now review.

Soil

Typical soil types in Fresno County include the Excelsior, Ciervo, Cerini, Panoche, Westhaven, Nahrub, and Lethent soil series. EPIC extracts information from soil series data to calculate water storage capacity of the soil, N transportation in the soil profile, pH, and other

Layer Number	Layer Depth	Bulk Density	Wilting Point	Field Capacity	Sand Content	Silt Content	Organic N Concentration	pH	Sum of Bases	Organic Carbon	Calcium Carbonate	Cation Exchange Capacity	Course Fragment Content	Nitrate Concentration	Labile P Concentration	Crop Residue	Bulk Density Dry	Phosphorus Sorption Ratio	Saturated Conductivity	Organic P Concentration
1	0.01	1.42	0.158	0.29	55.6	20.2	862	8	16.3	1.04	0.5	16.3	1.7	10	30	0.03	1.52	0	0	0
2	0.15	1.42	0.158	0.29	55.6	20.2	862	8	16.3	1.04	0.5	16.3	1.7	10	30	0.43	1.52	0	0	0
3	0.28	1.43	0.19	0.31	41.4	25.7	801	8.2	22.7	0.79	0.8	22.7	0.7	5	10	0.52	1.53	0	0	0
4	0.5	1.41	0.198	0.31	18	45.9	869	8.6	19.2	0.87	2.9	19.2	7.7	5	10	0.41	1.51	0	0	0
5	0.77	1.31	0.17	0.31	17.1	55	667	7.9	16.8	0.67	0.2	16.8	16	5	10	0.17	1.4	0	0	0
6	0.86	1.58	0.222	0.31	3.6	53.1	1010	6.8	20.6	1.01	0	20.6	0.4	5	10	0.03	1.69	0	0	0

Figure 3: Abston Soil Series Properties

characteristics which effect plant growth such as aluminum concentration. For the purposes of the paper we will use attributes of the Abston soil series with similar properties to the local soils. The properties of this soil are shown in **Figure 3**.

Climate

The statistical weather for Fresno was used to simulate temperature, precipitation, wind and other climactic conditions such as solar radiation. Since this is not actual climate data, one should not infer climatic conditions for any one year in interpreting the results. This climate data is shown in **Figure 4** (Department of Water Resources 2000).

Name	Latitude	Longitude	Elevation	Years Max Month Records	Wet Dry Probability Coefficient	Rain Distribution	Speed Distribution	Climatic Factor	Erosion Adjustment Factor
FRESNO WB AP	36.7	120	85.3	0	0	0	0.3	0	1

Month	Air Temperature Average Min	Air Temperature STD Min	Air Temperature Average Max	Air Temperature STD Max	Precipitation Average	Precipitation STD	Precipitation Skew Coefficient	Probability Dry Wet	Probability Wet Wet	Rain Days Average	Rain Half Max	Solar Radiation	Relative Humidity	Average Velocity	Wind Velocity N	Wind Velocity NNE	Wind Velocity NE	Wind Velocity ENE	Wind Velocity E	Wind Velocity ESE	Wind Velocity SE	Wind Velocity SSE	Wind Velocity S	Wind Velocity SSW	Wind Velocity SW	Wind Velocity WSW	Wind Velocity W	Wind Velocity WNW	Wind Velocity NW	Wind Velocity NNW
1	2.68	3.85	12.2	4	54.8	8.4	1.16	0.17	0.51	7.98	8.1	184	3.33	2.52	4	2	5	6	12	10	13	7	6	3	4	2	5	7	10	4
2	4.42	3.54	16.2	3.62	47.1	8.1	1.24	0.15	0.54	7.13	6.3	287	5	2.68	4	2	5	6	11	9	10	7	5	3	3	2	4	8	14	6
3	5.67	3.13	19	4.26	45.8	6.9	0.18	0.15	0.48	6.94	7.6	410	5	3.08	6	2	5	5	7	6	8	6	4	3	2	2	4	10	21	10
4	8.12	2.9	23.2	5.22	27.9	7.4	0.12	0.09	0.45	4.22	5.1	549	6.67	3.3	5	2	3	3	4	4	6	4	4	2	3	2	5	15	27	10
5	11.6	3.06	28.3	5.28	6.5	4.1	1.11	0.04	0.36	1.82	2.3	636	7.22	3.68	4	2	2	1	2	2	4	2	3	2	3	3	7	23	34	8
6	15.1	3.2	32.9	4.81	2.1	3.6	1.07	0.02	0.22	0.75	2.3	695	8.89	3.73	3	1	1	1	1	1	2	2	3	2	3	3	9	29	33	6
7	17.9	2.73	36.6	3.13	0.3	0.5	-1.69	0.01	0.13	0.35	1.5	690	10.6	3.31	3	1	1	1	1	1	3	3	3	2	4	4	11	29	27	6
8	17	2.83	35.4	3.53	0.5	2	0.58	0.01	0	0.31	2.8	626	11.1	3.09	3	1	1	1	2	2	3	3	3	3	4	4	11	27	25	6
9	14.5	2.95	32.3	4.19	4.6	6.1	-0.24	0.02	0.29	0.82	4.6	502	10.6	2.78	3	1	2	2	4	4	5	3	4	3	5	4	10	22	22	6
10	9.93	3.39	26.5	4.68	12.8	7.4	0.9	0.05	0.34	2.18	14.7	366	7.78	2.49	3	2	4	5	9	6	6	4	5	3	4	3	7	14	19	5
11	5.36	3.51	18.4	4.66	32.7	6.9	-0.19	0.11	0.47	5.16	6.1	246	5.56	2.22	4	2	6	8	12	9	9	5	5	3	4	3	5	9	11	5
12	2.68	3.7	12.5	4.11	39.4	7.1	0.88	0.15	0.46	6.74	9.4	159	4.44	2.39	4	2	6	7	12	10	12	7	6	3	4	2	5	7	11	4

Figure 4: Fresno Climate Data

Other Agricultural Characteristics

There are several other economic and agricultural parameters used by EPIC and our analysis of EPIC output. For this study we will assume that there is a farm producing only cotton on a 1 km by 2 km field (200 hectares). Surface water deliveries through the CVP to Westlands Water District of Fresno County cost about $38.69/acre-foot (Westlands Water District). (EPIC's output is in mm-ha of water which can be converted from acre-feet by multiplying by 8.10E-3). We will assume that the only source of water is surface water imported through the CVP, thus we are not examining groundwater pumping, although this study could be extended to look at how groundwater extraction would be altered under an agency intervention. N fertilizer costs $1.00 per kilogram. To operate this field we will assume annual fixed costs of $500/ha just to help make comparisons in the results more realistic. Cotton irrigation systems in the Westlands are border (1%), furrow (51%), sprinkler (16%), and sprinkler/furrow mix (32%), therefore we chose furrow irrigation as the dominant irrigation system in EPIC. Cotton value in $/tonne was estimated as $1413 (Agricultural Commissioner 2001).

Other Remarks & Assumptions

- The effects of Et and precipitation were not considered to affect irrigation requirements. Given the low occurrence of precipitation, this is a reasonable assumption.
- The simulation was run for 100 years in order to reduce the influence of the initial conditions, such as current nutrient content of the soils.
- There are other influxes of nitrogen into the soil through atmospheric deposition, however these effects are relatively minimal and not addressed in our study.
- Plant growth is assumed to not be limited by phosphorus, and the fertilizer applied in the EPIC simulation had sufficient levels to not be limiting for all levels of nitrogen inputs.
- Other variables in the production function are assumed fixed
- The model was not run to account for drainage practices and the Abston soil type is relatively well drained to minimize this influence.
- Lastly, numerous other agricultural practices can affect nitrogen leaching, such as tillage practices, however this study keeps tillage practices constant in the EPIC model runs.

Analysis & Results:

1. EPIC Model Results Under Various N and Irrigation Levels

Using the Abston Soil and Fresno Climate data, cotton production was simulated under varying irrigation and fertilization conditions. This was accomplished by varying irrigation inputs from 600 to 0 mm and fertilizer inputs (FN) from 60 to 0 kg/ha. Nineteen different levels of irrigation and FN were selected. **Figure 5** shows cotton yield in tonnes/ha versus irrigation

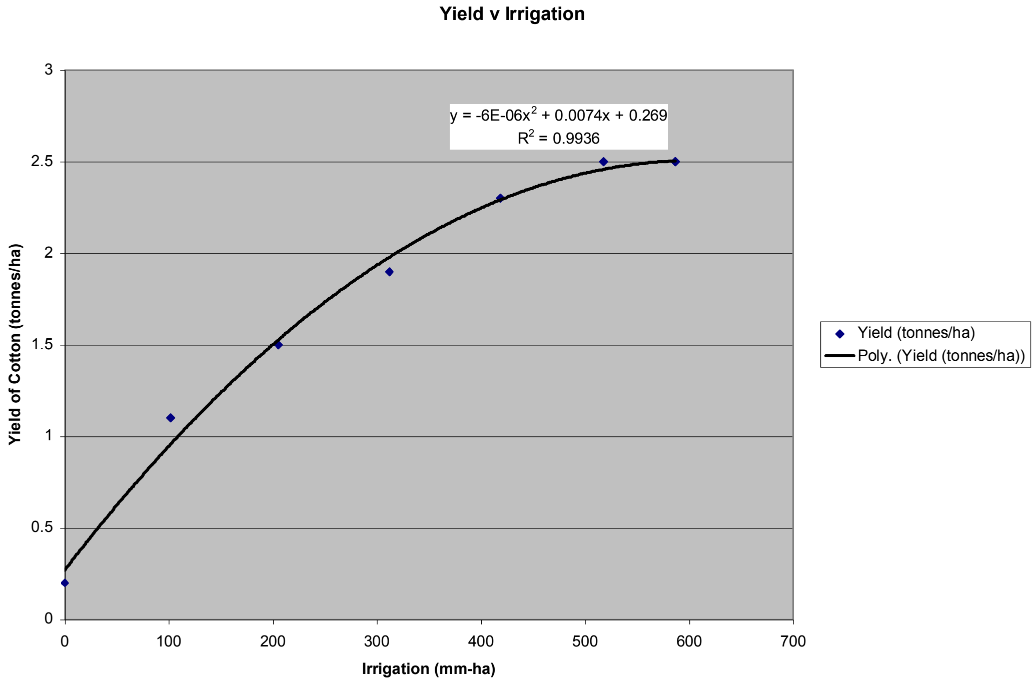


Figure 5: Cotton Yield v Applied Irrigation Water

quantity in mm. **Figure 6** shows cotton yield in tonnes/ha versus FN in kg/ha. The simulation was run for 100 years to reduce the influence of the initial conditions, such as initial nitrogen levels in the soil. Since climate data are only statistical and not actual, the long time period was necessary to calculate long term averages. **Appendix 2** shows specific output from EPIC runs. Actual EPIC output can be viewed in **Appendix 3**.

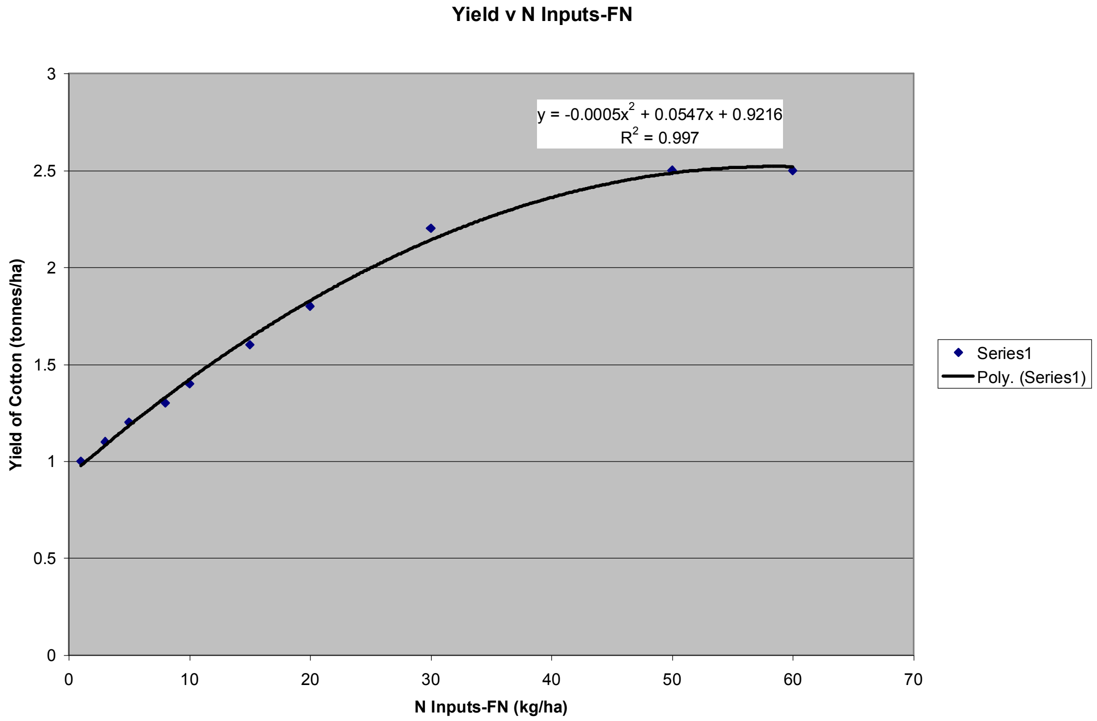


Figure 6: Cotton Yield v Nitrogen Inputs-FN

2. Determination of the Crop Production and N Runoff Functions

Using the output data from EPIC, functions for production with respect to FN and irrigation were determined, in addition to functions of NO_3 runoff (YNO3) and mineral N in percolate (PRKN) with respect to fertilization (FN). These functions and their coefficients were determined using non-linear regression in JMP Statistics and MS Excel. Non-linear functional forms for all three equations were chosen after viewing graphs of crop yield versus the inputs, YNO3 versus FN (**Figure 7**), and PRKN versus FN (**Figure 8**). (For brevity sake, all confidence limits on the parameters and other statistical data will not be presented, although the goodness of fit R^2 values on the graph indicated that the model represents the process with a high degree of certainty).

CROP PRODUCTION FUNCTION

The crop production function below relates the yield of cotton to the inputs of irrigation water and FN, holding all other variables constant.

$$\mathbf{Y_{cotp} = \alpha_0 + \alpha_1 * irrigation_{(mm)}^2 + \alpha_2 * irrigation_{(mm)} + \alpha_3 * FN_{(kg/ha)}^2 + \alpha_4 * FN_{(kg/ha)}}$$

$\alpha_0 = -1.31$,	95% Confidence Limits (-1.449, -1.173)
$\alpha_1 = -0.00000608$	95% Confidence Limits (-0.0000073, -0.00000049)
$\alpha_2 = 0.00739$	95% Confidence Limits (0.00659, 0.00818)
$\alpha_3 = -0.000468$	95% Confidence Limits (-0.000590, -0.000345)
$\alpha_4 = 0.0543$	95% Confidence Limits (0.0464, 0.0623)

Y_{cotp} ≡ Yield of cotton in (tonnes/hectare)
$irrigation_{(mm)}$ ≡ Amount of irrigation water applied (mm-ha)
$FN_{(kg/ha)}$ ≡ Amount of Nitrogen applied in fertilizer (kg/ha)

NO_3 IN SURFACE RUNOFF

Output from EPIC was also used to determine NO_3 runoff in surface water as a function of the dominant independent variable, N inputs as fertilizer. Graphing the relationship seemed to indicate a binomial function, thus the following functional form was fitted to the data, yielding the coefficients seen below.

$$\mathbf{YNO_3 = \beta_0 + \beta_1 * FN_{(kg/ha)}^2 + \beta_2 * FN_{(kg/ha)}}$$

$\beta_0 = 0.6949$
$\beta_1 = 0.0072$
$\beta_2 = -0.1581$

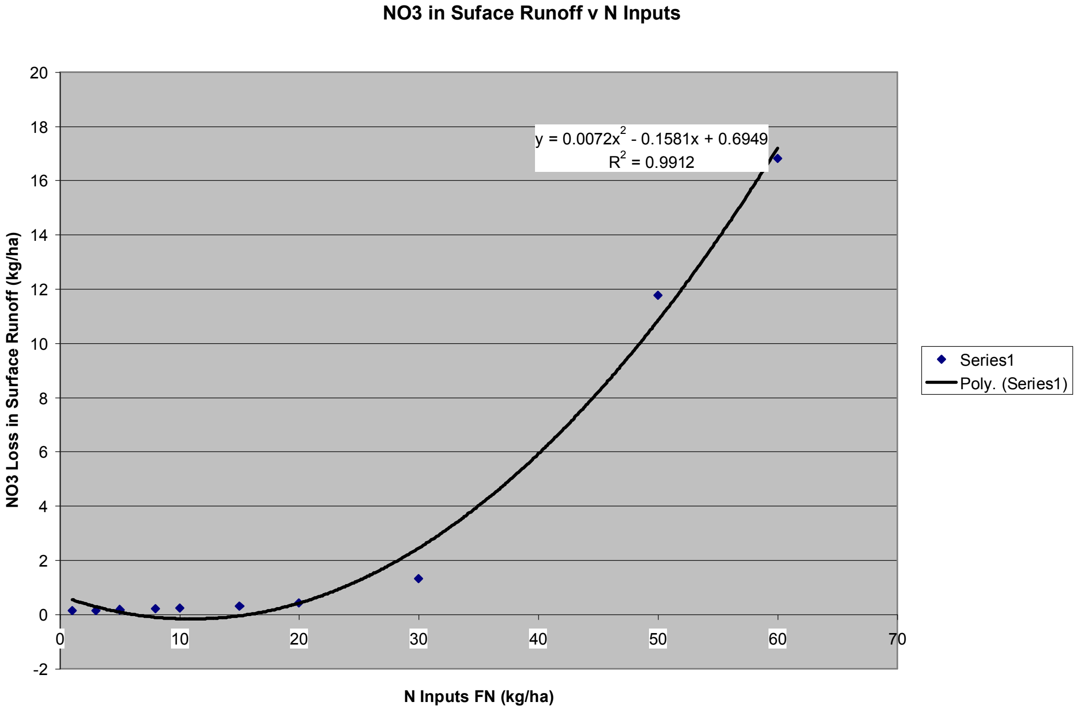


Figure 7: NO3 in Surface Runoff v Nitrogen Inputs

$YNO_3 \equiv NO_3$ Loss Runoff in Surface Water (kg/ha)

MINERAL N IN SUBSURFACE PERCOLATE

Output from EPIC was also used to determine Mineral N percolation as a function of the dominant independent variable, N inputs as fertilizer. Graphing the relationship seemed to indicate a trinomial function, thus the following functional form was fitted to the data, yielding the coefficients seen below.

$$\mathbf{PRKN = \gamma_0 + \gamma_1 * FN_{(kg/ha)}^3 + \gamma_2 * FN_{(kg/ha)}^2 + \gamma_3 * FN_{(kg/ha)}}$$

$\gamma_0 = 3.102$
$\gamma_1 = 2$ E-5
$\gamma_2 = -0.0023$
$\gamma_3 = 0.1055$

PRKN ≡ Mineral N Loss in Percolate (kg/ha)

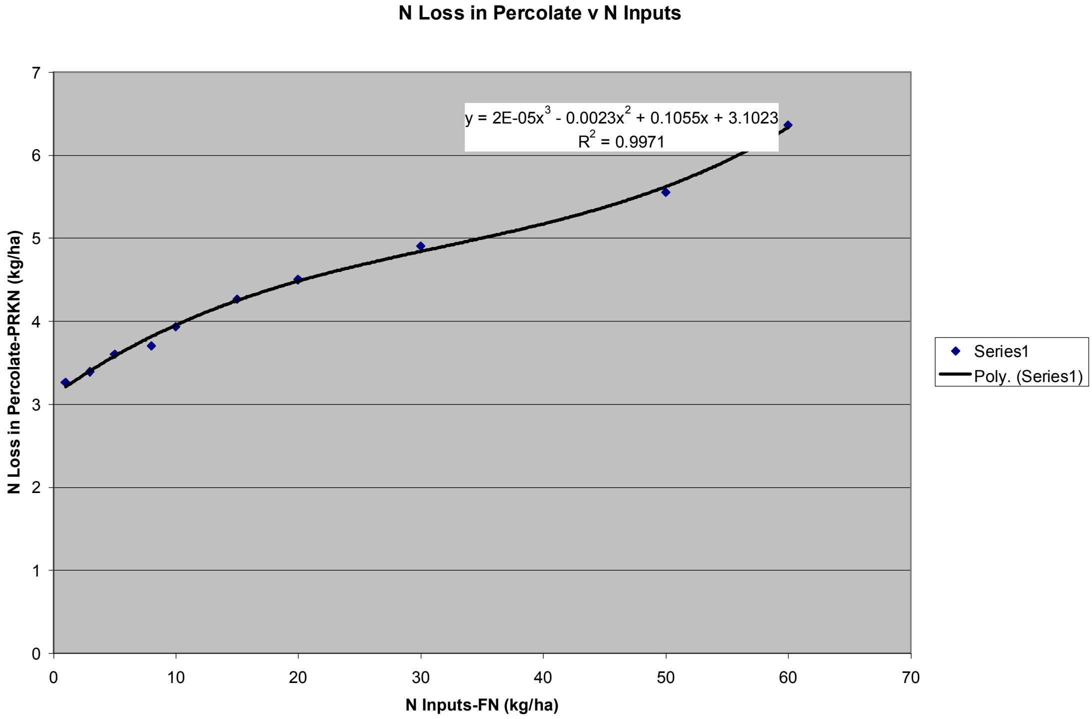


Figure 8: Nitrogen Loss in Percolate v Nitrogen Inputs

3. Determination of Revenue and Cost Functions Under "Status Quo" Farm Operation

The goal of this section is to maximize farm profit under existing conditions, thus the farm level decisions only consider the costs of the inputs irrigation water and fertilizer. For this part, certain farm costs are considered fixed at $500/ha such as labor and equipment. The water price is determined from water prices for Central Valley Project water as $0.31 per mm-ha. Fertilizer is assumed to cost $1.00 per kg which is what the EPIC documentation use as a baseline fertilizer cost.

REVENUE FUNCTION

$Y_{cotp}*A_{ha}*P_{cotp}$ = Farm Revenue (R_F)

$Y_{cotp} \equiv$ Yield of cotton (tonnes/ha)
$A_{ha} \equiv$ Area planted (ha)
$P_{cotp} \equiv$ Wholesale price ($/ton)

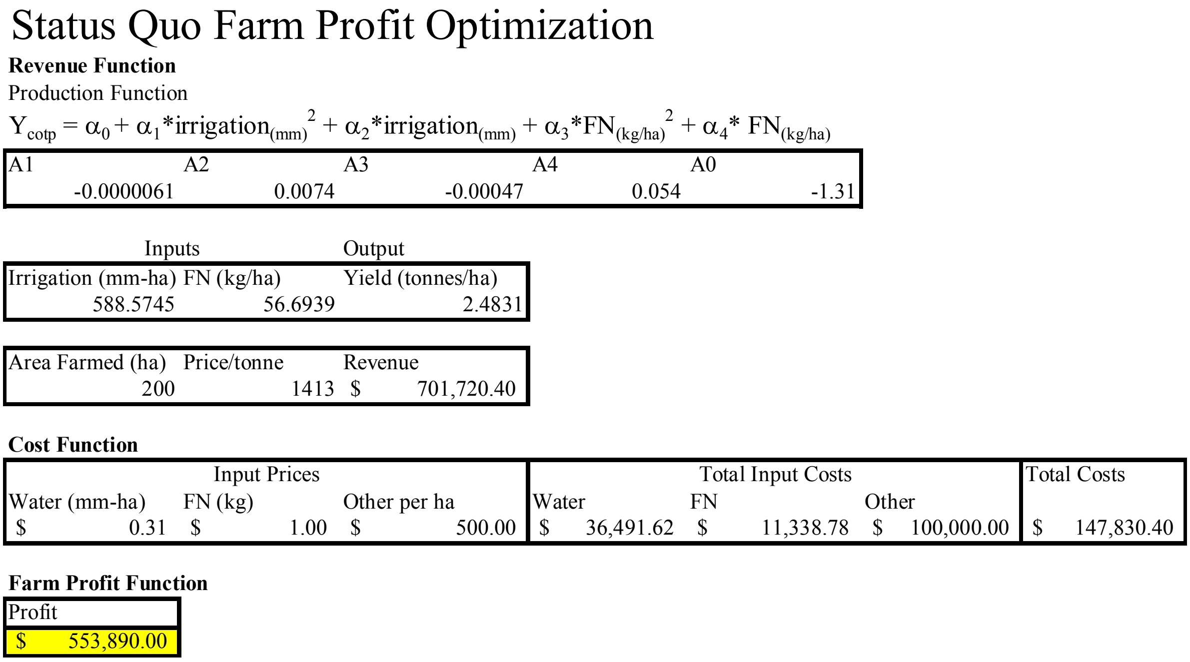
COST FUNCTION

$A_{ha}\ (P_{irr(mm\text{-}ha)} * D_{irr(mm)} + P_{FN} * FN_{kg} + P_{Fixed})$ = Farm Costs (C_F)

$P_{irr(mm\text{-}ha)} \equiv$ Price of irrigation water ($/mm-ha)
$D_{irr(mm)} \equiv$ Depth of irrigation (mm)
$A_{ha} \equiv$ Area planted (ha)
$P_{FN} \equiv$ Price of fertilizer ($/kg)
$FN_{kg} \equiv$ Quantity of fertilizer (kg/ha)
$P_{Fixed} \equiv$ Fixed Costs ($/ha)

PROFIT FUNCTION

$R_F - C_F = \pi$



Status Quo Farm Profit Optimization

Revenue Function

Production Function

$Y_{cotp} = \alpha_0 + \alpha_1 * \text{irrigation}_{(mm)}^2 + \alpha_2 * \text{irrigation}_{(mm)} + \alpha_3 * FN_{(kg/ha)}^2 + \alpha_4 * FN_{(kg/ha)}$

A1	A2	A3	A4	A0
-0.0000061	0.0074	-0.00047	0.054	-1.31

Inputs		Output
Irrigation (mm-ha)	FN (kg/ha)	Yield (tonnes/ha)
588.5745	56.6939	2.4831

Area Farmed (ha)	Price/tonne	Revenue
200	1413	$ 701,720.40

Cost Function

Input Prices			Total Input Costs			Total Costs
Water (mm-ha)	FN (kg)	Other per ha	Water	FN	Other	
$ 0.31	$ 1.00	$ 500.00	$ 36,491.62	$ 11,338.78	$ 100,000.00	$ 147,830.40

Farm Profit Function

Profit
$ 553,890.00

Figure 9: Farm Profit Optimization and Nitrogen Inputs Under Status Quo Operations

Maximization of profit was accomplished simply by setting up all of the above listed equations in MS Excel and then setting the Solver to maximize profit by changing values of irrigation and FN. **Figure 9** shows this optimization.

4. Determination of Farm-level Decision-making Under Agency Regulation

Given that there are invariably "damages" associated with N leaching into both surface water and groundwater, some drinking water agencies with regulatory power and other authorities have devised various programs such as best management practices (BMPs), land use restrictions, and taxes to help limit contamination from nonpoint agricultural sources.

Farmers receive a marginal benefit from each unit of N fertilizer applied to their fields for which they pay some cost, a cost that almost exclusively only considers the marginal cost associated with that unit of fertilizer production and application. Absent this decision-making process are costs incurred to surface water and groundwater systems, the impacts which were discussed earlier. Thus, it is quite plausible and well-documented that an agency might intervene to charge a "tax" on this damage to the groundwater and surface water resources. By charging a tax on N inputs, the regulatory agency could raise money to treat water, develop best management practices or technical assistance programs for farms, and also create an economic pressure that could encourage technological improvements on the farm to reduce leaching and runoff, such as better tillage practices.

Tax	Farm Profit	Social Benefit	FN (kg/ha)	Tax
$ -	$ 553,890.00	$ 341,130.92	56.7	$ -
$ 1.00	$ 549,884.23	$ 344,712.14	56.2	$ 1.00
$ 5.00	$ 534,539.18	$ 357,157.73	54.2	$ 5.00
$ 10.00	$ 516,716.75	$ 369,225.22	52.0	$ 10.00
$ 20.00	$ 484,767.69	$ 385,085.97	48.3	$ 20.00
$ 30.00	$ 456,680.58	$ 393,677.48	45.1	$ 30.00
$ 40.00	$ 431,552.08	$ 397,743.59	42.5	$ 40.00
$ 50.00	$ 408,753.13	$ 398,902.27	40.2	$ 50.00
$ 60.00	$ 387,828.96	$ 398,154.81	38.2	$ 60.00
$ 70.00	$ 368,440.72	$ 396,144.21	36.4	$ 70.00
$ 80.00	$ 350,329.71	$ 393,295.54	34.9	$ 80.00
$ 90.00	$ 333,294.33	$ 389,896.24	33.5	$ 90.00
$ 100.00	$ 317,174.75	$ 386,144.15	32.2	$ 100.00

Figure 10: Farm Profit and Net Social Benefit Under Various Tax Levels

This is accomplished by taxing the actual nitrogen loading (in the form of nitrate) to surface water (YNO3) and groundwater (PKRN). We also select a somewhat arbitrary cost of the damage caused by a kg of nitrogen present in groundwater. These are set at $50 per kg of YNO_3 (surface water) and $60 per kg of PKRN (groundwater). Given the costs to states and localities of complying with EPA drinking water standards and CWA Total Maximum Daily Loads (TMDLs) for impaired waters, these costs are by no means excessive. **Figure 10** displays farm profit and net social benefit at various levels of tax. To get at the social net benefit we calculated (farm revenue + tax revenue) – (farm costs + environmental damage from YNO3 and PRKN). Thus, we determined the social maximum to be generated when a tax of $58 is levied per kg of leached YNO3 and PKRN. **Figure 11** shows social net benefit as a function of fertilization. The optimization at a tax level of $58 dollars can be seen in **Figure 12.**

<u>ENVIRONMENTAL COST FUNCTION</u>

$$\mathbf{A_{ha}\ (YNO_{3(kg)} * C_{YNO3} + PRKN_{kg} * C_{PRKN}) = Total\ Environmental\ Damages\ (C_{ENV})}$$

$YNO_{3(kg)}$ ≡ Quantity of N surface runoff generated (kg/ha)
C_{YNO3} ≡ Environmental damage associated with YNO3 ($/ha)
$PRKN_{kg}$ ≡ Quantity of N in groundwater percolate (kg/ha)
C_{PRKN} ≡ Environmental damage associated with PRKN ($/ha)

TAX REVENUE FUNCTION

$$\mathbf{A_{ha} * T_N (YNO_{3(kg)} + PRKN_{kg}) = Total\ Tax\ Revenue\ (R_T)}$$

T_N ≡ Tax levied on N in runoff and percolate ($/kg)

SOCIAL BENEFIT FUNCTION

$$\mathbf{(R_F + R_T) - (C_F + C_{ENV}) = Social\ or\ Regional\ Net\ Benefit\ (\pi_{SNB})}$$

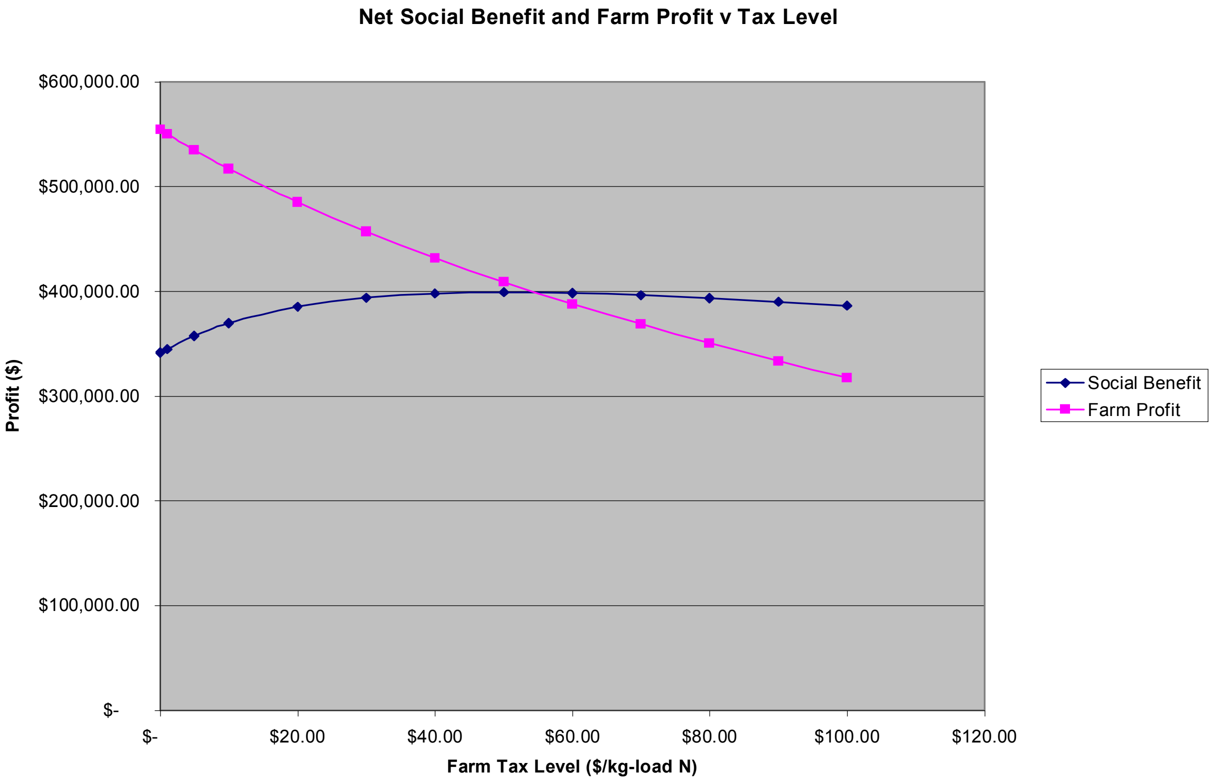
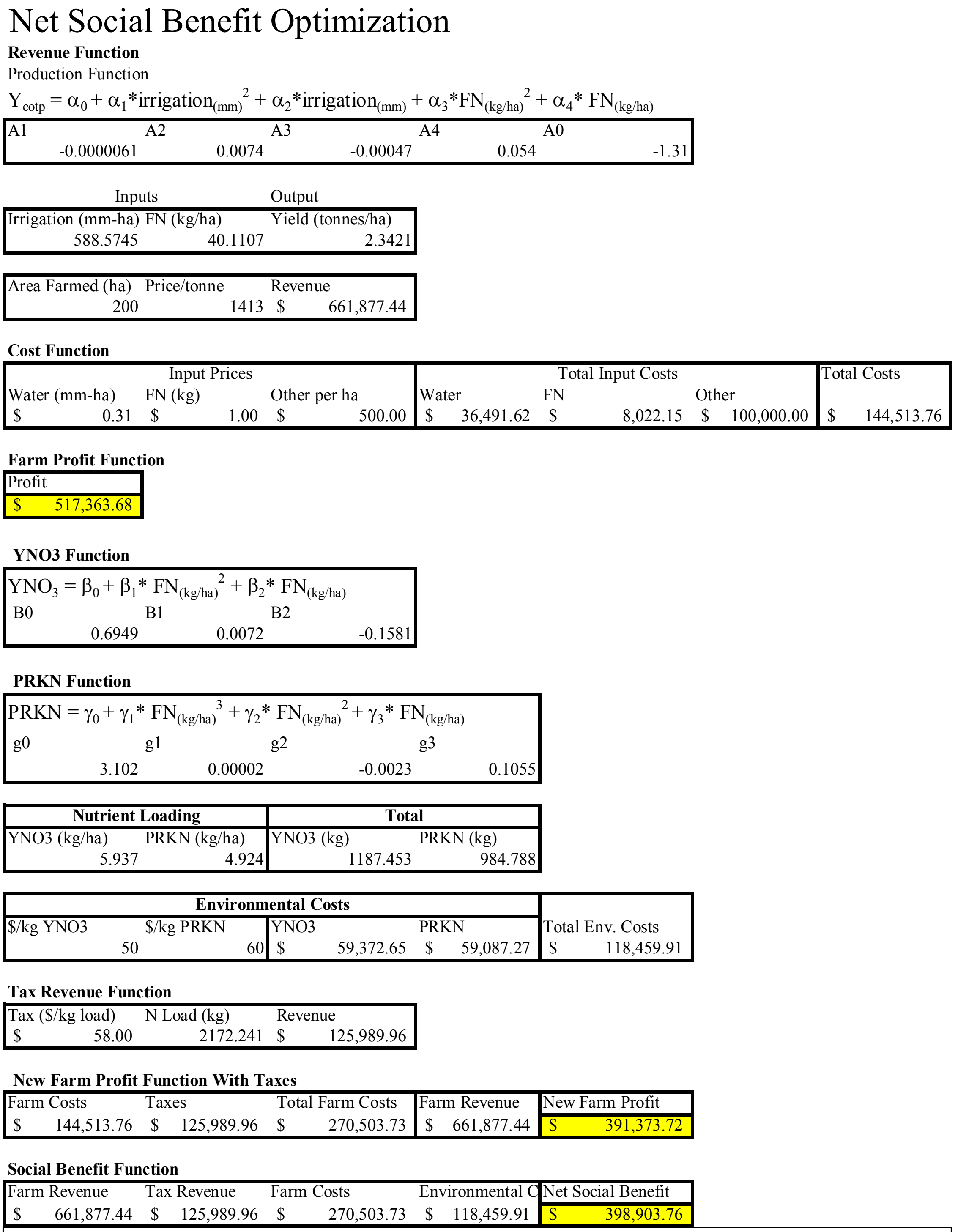


Figure 11: Net Social Benefit and Farm Profit v Tax Level



Net Social Benefit Optimization

Revenue Function

Production Function

$Y_{cotp} = \alpha_0 + \alpha_1 * irrigation_{(mm)}^2 + \alpha_2 * irrigation_{(mm)} + \alpha_3 * FN_{(kg/ha)}^2 + \alpha_4 * FN_{(kg/ha)}$

A1	A2	A3	A4	A0
-0.0000061	0.0074	-0.00047	0.054	-1.31

Inputs		Output
Irrigation (mm-ha)	FN (kg/ha)	Yield (tonnes/ha)
588.5745	40.1107	2.3421

Area Farmed (ha)	Price/tonne	Revenue
200	1413	$ 661,877.44

Cost Function

Input Prices			Total Input Costs			Total Costs
Water (mm-ha)	FN (kg)	Other per ha	Water	FN	Other	
$ 0.31	$ 1.00	$ 500.00	$ 36,491.62	$ 8,022.15	$ 100,000.00	$ 144,513.76

Farm Profit Function

Profit
$ 517,363.68

YNO3 Function

$YNO_3 = \beta_0 + \beta_1 * FN_{(kg/ha)}^2 + \beta_2 * FN_{(kg/ha)}$

B0	B1	B2
0.6949	0.0072	-0.1581

PRKN Function

$PRKN = \gamma_0 + \gamma_1 * FN_{(kg/ha)}^3 + \gamma_2 * FN_{(kg/ha)}^2 + \gamma_3 * FN_{(kg/ha)}$

g0	g1	g2	g3
3.102	0.00002	-0.0023	0.1055

Nutrient Loading		Total	
YNO3 (kg/ha)	PRKN (kg/ha)	YNO3 (kg)	PRKN (kg)
5.937	4.924	1187.453	984.788

Environmental Costs				
$/kg YNO3	$/kg PRKN	YNO3	PRKN	Total Env. Costs
50	60	$ 59,372.65	$ 59,087.27	$ 118,459.91

Tax Revenue Function

Tax ($/kg load)	N Load (kg)	Revenue
$ 58.00	2172.241	$ 125,989.96

New Farm Profit Function With Taxes

Farm Costs	Taxes	Total Farm Costs	Farm Revenue	New Farm Profit
$ 144,513.76	$ 125,989.96	$ 270,503.73	$ 661,877.44	$ 391,373.72

Social Benefit Function

Farm Revenue	Tax Revenue	Farm Costs	Environmental C	Net Social Benefit
$ 661,877.44	$ 125,989.96	$ 270,503.73	$ 118,459.91	$ 398,903.76

Figure 12: Net Social Benefit Optimization

Lastly, it is important to know what a $58 tax on YNO3 and PKRN as outputs would be on one kg of FN as an input, since one kg of input does not equal one kg of output. Thus we want to know, at what level should we tax fertilizer inputs to achieve a similar result of maximizing social net benefit? This can be done by examining how many kg of FN are used under the optimization and comparing it to the tax charged to the YNO3 and PKRN. Under the social benefit optimization, 40.1 kg/ha of FN are used and the tax assessed is $125,989.96, therefore each kg of input on the 200 ha must be taxed at $15.70 to achieve the optimized social benefit. This can also be seen by examining the marginal benefit curve of the farmer to each kg of fertilizer input as shown in **Figure 13**.

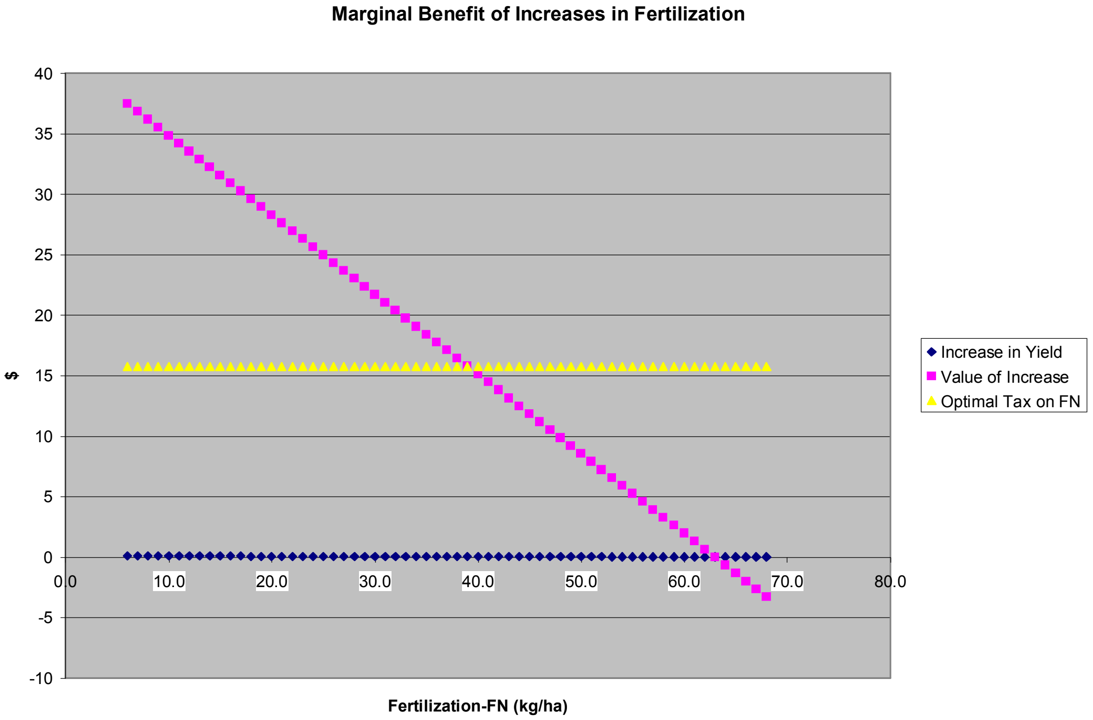


Figure 13: Marginal Benefit from Fertilizer Inputs

Discussion:

The estimation of the crop productions functions reveal several interesting things, most notably the decreasing returns from increases in fertilization. Although increasing fertilization from 0-30 kg/ha increases yield from 1 to 2.2 tonnes/ha, increasing fertilization from 30 to 60 kg/ha increases yield only an additional 0.3 tonnes/ha. At the same time YNO3 and PKRN rise from 2.4 and 4.7 kg/ha to 17.1 and 5.5 kg/ha, respectively. This demonstrates that there are large increases to nitrogen loading, particularly the surface water runoff, for relatively modest gains in agricultural productivity.

Consequentially, under the “status quo” farm operation scenario, where fertilizer costs are very low, the farmer would choose to apply 56 kg/ha, leading to a significant NPS pollution source. The cost of the fertilizer to the farmer is simply not significant in comparison with other farm operating costs, given the increase in yield that the fertilizer would produce.

Therefore, it is likely that agency intervention in form of taxes on fertilizer inputs will be required to achieve significant reductions in nutrient loads to surface water and groundwater. Under the scenario presented here, where damage from each kg of YNO3 and PRKN are assumed to do damages of $50 and $60 respectively, a regional profit optimization would reduce nutrient loads significantly. To maximize net social benefit we would need to charge a $58 tax on the nutrient output, which corresponds to a $15.70 tax on the fertilizer inputs.

The tax revenue collected under such a scenario could go back to the farms in terms of technical assistance, best management practice implementation assistance, or simple grants for technology to reduce nutrient loads.

This input-based approach to examining the effect of farm activities on NPS pollution and potential tax-based mitigation scenarios is also applicable to pesticide, sediment load, and other NPS pollution. Future studies would do well to model different tillage practices in EPIC to determine their impact on runoff concentrations. Other strategies for reducing NPS pollution might do well to tax only cropping practices that are known to lead to excessive and avoidable runoff.

While CWA and other efforts to curtail point sources of pollution impairing our Nation's waters, we are just beginning to understand the NPS processes that are currently the major source of degradation to our waters. The development of strategies that help incorporate external environmental damages into local, farm-scale decision-making, such as the approach put forward here, will be necessary to address the concerns of NPS pollution in our watersheds.

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