AJAE Appendix:

Spatial Dynamics of Water and Nitrogen Management in Irrigated Agriculture

Keith C. Knapp and Kurt A. Schwabe

September 6, 2007

Note: The material contained herein is supplementary to the article named in the title and published in the American Journal of Agricultural Economics (*AJAE*). K. Knapp and K. Schwabe are Professor and Associate Professor in the Department of Environmental Sciences, University of California, Riverside. We would like to thank the editor, anonymous reviewers, and participants at the annual meetings of the WAEA and AAEA for comments on this work. Senior authorship is shared equally.

This document provides additional information to support the analysis in Knapp and Schwabe (2007). This includes material on data and the production functions, additional explanatory material for the spatial variability results, water price literature survey, and sensitivity analysis. The organization generally follows that in the article.

Data

Yolo county at the southern end of the Sacramento valley is the location of the field experiment site for the production function data. Production costs are estimated from University of California Cooperative Extension budgets for corn in Yolo County.

Discrete Approximation to the Lognormal Distribution

As noted in the article, we assume that water infiltration coefficients are distributed according to a lognormal distribution which is discretized for the dynamic optimization model. Figure A1 shows the lognormal density function for the infiltration coefficients β and superimposed on this are the 11 discretized values, where the probability mass associated with a particular β value is computed from a corresponding interval of the continuous density function. As shown, the discretization represents well the original density function. Additional evidence is that rerunning the optimization model with a finer grid does not significantly alter the results.

Plant-level Production Functions

Conceptual background and data sources are presented in the section entitled **Economic Data and Crop-Water-Nitrogen Production Function**, and the mathematical model and results developed in the **Appendix**. While these production functions are not the focus of the article, they may be of independent interest. Here we provide additional interpretation and analysis of the estimated functions.

Figure A2 shows 3D and contour plots for the plant-level production function. The 3D plots demonstrate that yield and N-emissions are increasing in water and N applications to some maximum, but that yield can decrease at sufficiently high water levels for reasons given in the text. Nitrogen carryover generally is increasing in N and decreasing in water, although water can have the opposite effect in some circumstances. This comes from the denitrification equation (A5) where water is either reducing denitrification or enhancing mineralization; regardless, the effect is small. The contour plots demonstrate some water-nitrogen substitution; the substitution possibilities, though, can be both limited and occurring only in limited regions of the input space.

Figures A3*a* - A3*c* plot marginal products (MP) and cross-partials. It can be seen that N applications have the anticipated positive, diminishing MP. Water is more complicated. It can exhibit negative MP, and does not always satisfy concavity. The cross-partials have uniform sign for the range of conditions reported. The cross-partials are non-negative for yield and N-emissions, implying that an increase in water does not decrease –and can increase - N marginal yield product, but also enhances the N-emissions effect of N applications. The negative cross-partial for carryovers indicates that water applications diminish the positive carryover impact of additional N applications.

Remarks: (1) The plots in figures A3*a* – A3*c* are for a specific value of initial soil N and are hence not completely general. (2) These are numeric results. While the production functions are composite functions from an equation system, all functions are analytic and analytic expressions for the partial and cross-partial derivatives can be derived by hand or by a symbolic algebra system such as ***Mathematica***. The expressions are complicated and we have not attempted to evaluate them theoretically. (3) The above discussion of production function properties applies at the plant-level. The field-level production function is the integral over the field of the plant-level production functions. This could conceivably have a “convexifying” effect.

Corn Prices

Corn prices have increased in recent years due to energy prices and ethanol demand. Space does not permit a complete analysis of this issue; however, table A1 provides sensitivity analysis. We also note that fertilizer prices have also increased, thereby moderating – at least in part – input demand effects of corn price increases. We also note that corn prices could moderate in response to various long-run adjustments.

Spatial Variability and Nonlinearity

This section provides further discussion and interpretation of the model results regarding specification issues and in particular the interrelation between spatial variability and the nonlinear plant-level production functions.

Nonlinear production functions combined with spatial variability imply that the uniform model which ignores spatial variability leads to incorrect results as shown in the paper. If production functions are linear, then one would have the spatial equivalent of certainty equivalence and the plant-level production functions evaluated at the field-average water depth would yield correct results. As this does not occur, it demonstrates that the nonlinearity of the plant-level production functions – along with spatial variability – is driving the results. Put another way, the model does not exhibit what might be termed spatial certainty equivalence.

Some of the functions estimated here are not only nonlinear, they are also convex-concave. A related issue to the above is whether this nonconvexity matters or whether one can just focus on the concave portions of the function. As discussed conceptually in the text, if water infiltration were uniform, then only the concave portion would be relevant for economic analysis, thereby simplifying the modeling. However, in the spatially-variable case this is not possible and one needs the whole function for accuracy. Figure A4 shows nitrate leaching as a function of infiltrated water. Also plotted on the figure are the 11 grid cell values evaluated at optimal steady state levels of initial soil N and applied water and N. Note that infiltrated water depths fall on all 3 regions of the N-leaching function. This confirms the conceptual hypothesis in the paper that it is necessary to include the entire function for accuracy and that one cannot just concentrate on the concave portion.

To further explore the role of spatial variability, the next graph plots cumulative N-emissions $\int_0^\beta n_{et}(z) f(z) dz$ as a function of β at the optimal steady-state. As can be seen, substantial emissions occur in the middle ranges of β. Lower values imply relatively little deep percolation hence reduced N transport. High values imply substantial deep percolation; however, in the steady-state the soil N levels are reduced implying less N available to be leached. In any case, the figure provides further direct evidence of the simultaneous importance of spatial variability, nonlinearity, and threshold effects.

California Water Pricing, Transfers, and Markets

There are a variety of institutional impediments and mechanisms in place that suggest irrigated agricultural producers may not face the full opportunity cost of water, thereby implying the possibility of higher prices and/or reduced water supplies in the future. As background for the analysis of water conservation using the dynamic optimization model, we surveyed a variety of literature indicating likely water shadow values and transfer quantities from agricultural to urban and environmental sectors. Original estimates in the cited sources and all other estimates have been adjusted for inflation.

(1) Historically, water has been delivered to growers at less than full cost as part of a strategy to develop the west (Wahl 1989). Weinberg (1997) notes that full cost water prices range from three to nine times greater than the contract rates for several CVP districts in California, while Howitt (1997) indicates subsidies of 5% to 35% of water costs are typical for California agriculture.

(2) Groundwater, alternatively, is a major water source but is typically unregulated, leading to pumping cost externalities. As noted in Lund et al. (2003), groundwater is responsible for 30% to 60% of all California deliveries. Marginal user costs vary according to conditions, but estimated values for several areas in California range from \$2.35/a-f to \$30.55/a-f (Noel and Howitt 1982; Provencher 1993; Knapp and Olson 1995).

(3) Rising urban/residential/industrial water demand combined with transfer restrictions imply marginal values significantly above those in agricultural uses. Consequently, opening up water markets implies that agricultural producers would face higher water prices. Depending on the region, model assumptions, and policy scenario, estimated equilibrium water prices facing California agriculture with developed water markets range from \$51/af to \$129/af (Vaux and Howitt 1984; Berck, Robinson, and Goldman 1991; Weinberg 1997). In 2003, San Diego County Water Authority began buying water from the Imperial Irrigation District under the Quantification Settlement Agreement for \$258/af (SDCWA 2003).

On the quantity side, a survey of the literature suggests that market equilibrium in California could be achieved with transfers of approximately 5% to 15% over the next several decades. In particular, Vaux and Howitt (1984) found water transfers from agricultural to urban uses ranging from 6.3% of total agricultural supplies in 1980 to 11.5% in 2020. In a more recent analysis of Central Valley agriculture, USBR (1998) estimated that the vast majority of all water transfers would be from Tulare Basin agriculture (including Kern County) to Southern California urban users, and that 4% of the surface water in that region would be transferred, or a total of 1.2×10^6 ha cm. Weinberg (1997) calculated that water transfers from CVP water users under the CVPIA would be 4% of federal water use when voluntary water transfers were the only provision considered. Lund et al. (2003) suggest applied water demands from California agriculture from 2020-2100 will decrease by roughly 2.7%, whereas urban demands over the same time period will increase by nearly 7.2%. Even so, agriculture will remain the dominant land and water use (Lund et al. 2003).

(4) Habitat and biodiversity concerns raise the possibility of agricultural water transfers back to environmental uses. The recent CVPIA legislation implies cutbacks of 20% for CVP users and environmental fees of $7.49/af (Loomis 1994; Weinberg 1997).

(5) Finally, an additional distortion is average-cost pricing. This typically follows from zero-profit restrictions facing water districts and implies delivered water prices less than the marginal cost of the most expensive source. We do not have an estimate of this distortion but do not expect that it would exceed the various distortions noted above.

References

Berck, P., S. Robinson, and G. Goldman. 1991. “The Use of Computable General Equilibrium Models to Assess Water Policies.” In A. Dinar and D. Zilberman, eds. *The Economics and Management of Water and Drainage in Agriculture*. Norwell, MA. Kluwer Academic Publishers, pp. 599-616.

Howitt, R. 1997. “Water Market-Based Conflict Resolution.” in R.G. Sanchez, and J. Woled, eds. *Resolving Conflict in the Management of Water Resources: Proceedings of the First Biennial Rosenberg International Forum on Water Policy*. San Francisco, California. Water Resources Report No. 93, Centers for Water and Wildland Resources, University of California, Davis, September 28-30.

Knapp, K.C., and L. Olson. 1995. “The Economics of Conjunctive Groundwater Management with Stochastic Surface Supplies.” *Journal of Environmental Economics and Management* 28: 340-56.

Knapp, K.C., and K. Schwabe. 2007. “Spatial Dynamics of Water and Nitrogen Management in Irrigated Agriculture.” *American Journal of Agricultural Economics*.

Loomis, J. 1994. “Water Transfer and Major Environmental Provisions of the Central Valley Improvement Act: A Preliminary Economic Evaluation.” *Water Resources Research* 30:1865-71.

Lund, R., R. Howitt, M. Jenkins, T. Zhu, S. Tanaka, M. Pulido, M. Tauber, R. Ritzema, and I. Ferriera. 2003. “Climate Warming and California’s Water Future.” Report 03 -1, California Energy Commission, Sacramento, California.

Noel, J.E., and R.E. Howitt. 1982. “Conjunctive Multibasin Management: An Optimal Control Approach.” *Water Resources Research* 18:753-63.

Provencher, B. 1993. “A Private Property Rights Regime to Replenish a Groundwater Aquifer.” *Land Economics* 69:325-40.

San Diego County Water Authority (SDCWA). 2003. Press release August 21, 2003. http://www.sdcwa.org/news/082103QSA%20MWD%20Rejection.phtml

U.S. Bureau of Reclamation. 1998. *Central Valley Project Improvement Act: Draft Programmatic Environmental Impact Statement*. Sacramento, California.

Vaux, H. J. and R. E. Howitt. 1984. “Managing Water Scarcity: An Evaluation of Interregional Transfers.” *Water Resources Research* 20:785-92.

Wahl, R. 1989. *Markets for Federal Water: Subsidies, Property Rights, and the Bureau of Reclamation*. Washington, D.C., Resources for the Future.

Weinberg, M. 1997. “Federal Water Policy Reform: Implications for Irrigated Farms in California.” *Contemporary Economic Policy* 15:63-73.

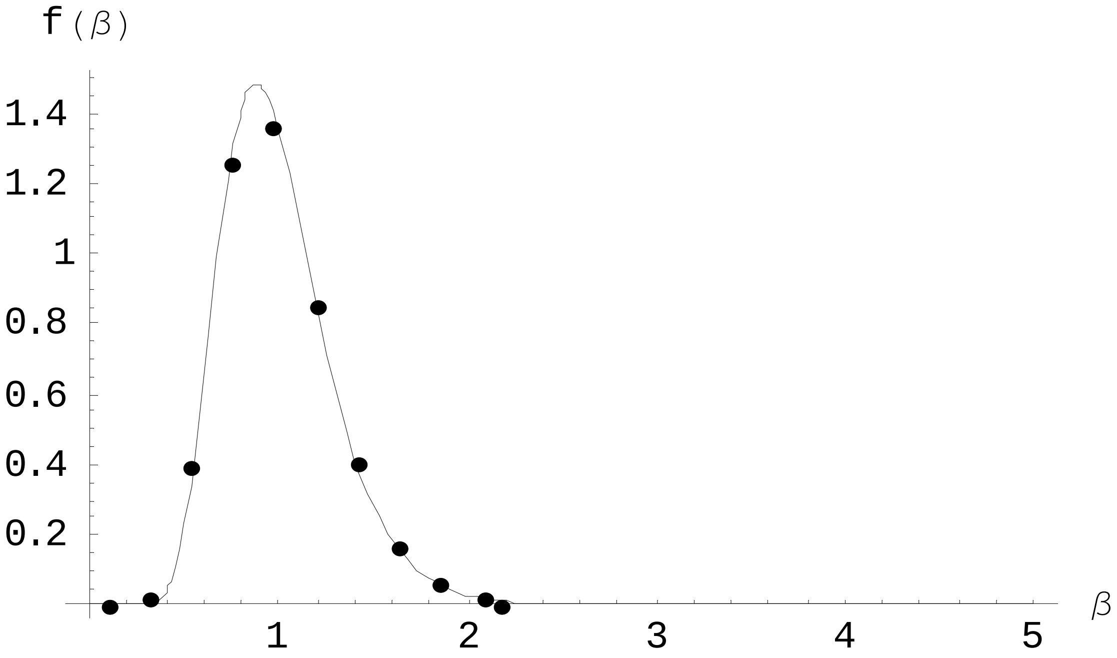

Figure A1. Lognormal density function for the water infiltration coefficients superimposed with discrete values used in the dynamic optimization model

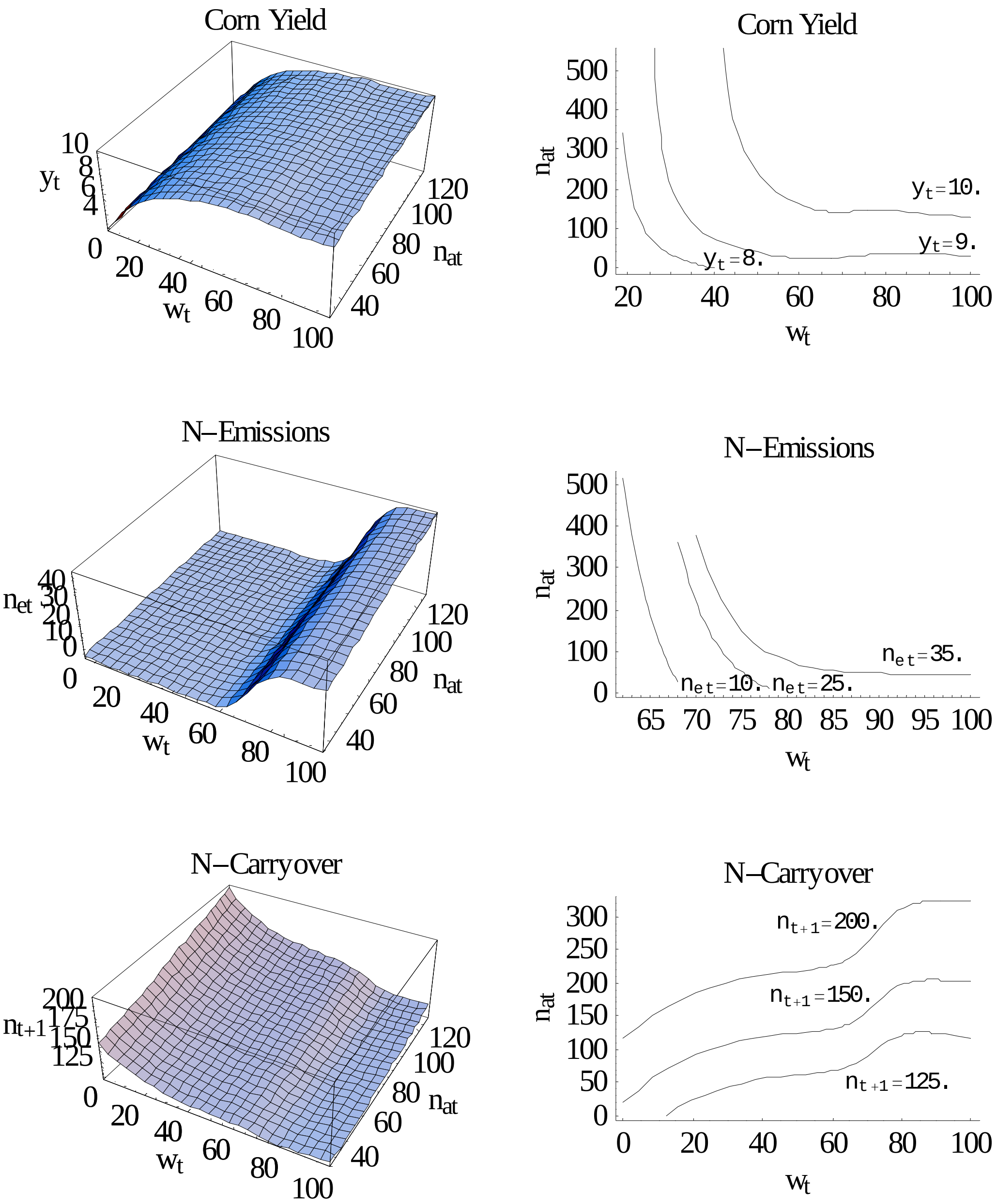

Figure A2. Plant-level production function. Corn yield y (Mg ha^{-1} yr^{-1}), nitrogen emissions n_{et} (kg ha^{-1} yr^{-1}), and nitrogen carryovers n_{t+1} (kg ha^{-1}) as functions of applied water w_t (cm yr^{-1}) and applied nitrogen n_{at} (kg ha^{-1} yr^{-1}) for initial soil nitrogen n_t = 200 kg ha^{-1} in year t.

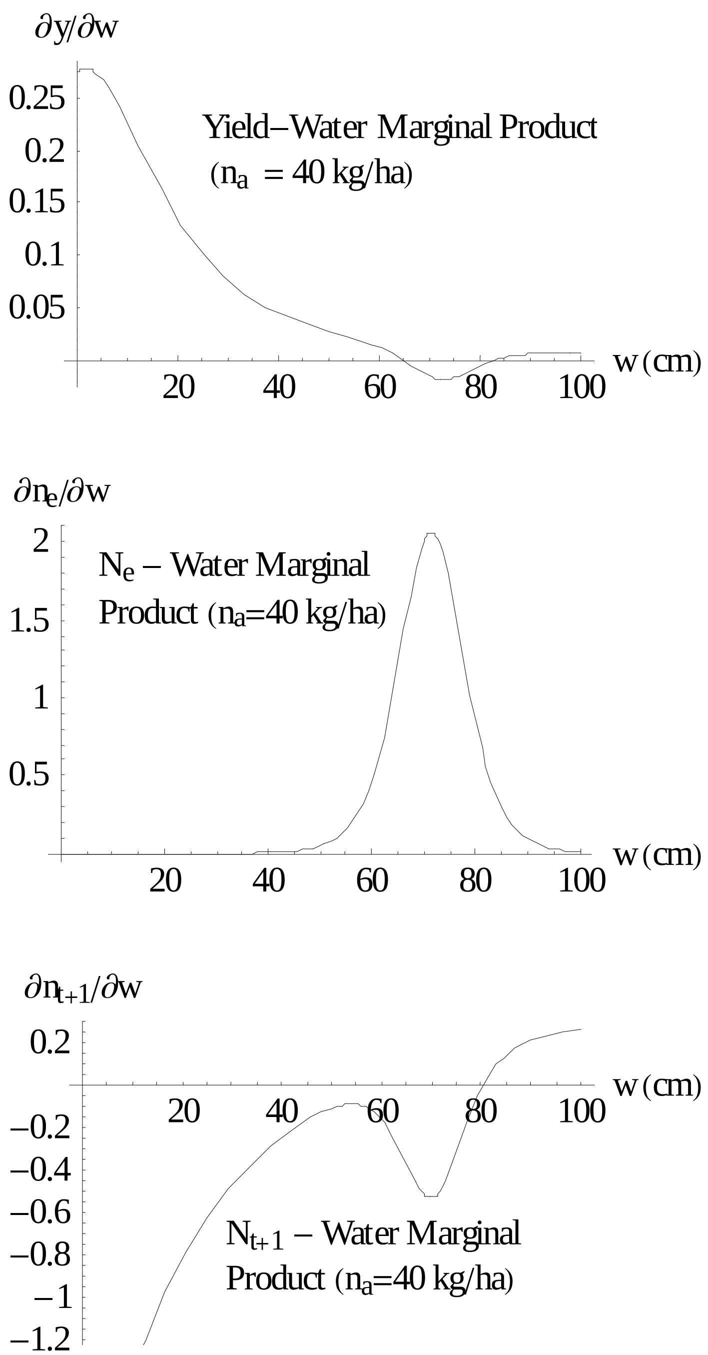

Figure A3*a*. Marginal product of water for the plant-level corn production function. Corn yield y_t (Mg ha^{-1} yr^{-1}), nitrogen emissions n_{et} (kg ha^{-1} yr^{-1}), and nitrogen carryovers n_{t+1} (kg ha^{-1}) as functions of applied water w_t (cm yr^{-1}) for initial soil nitrogen n_t = 200 kg ha^{-1} in year *t*.

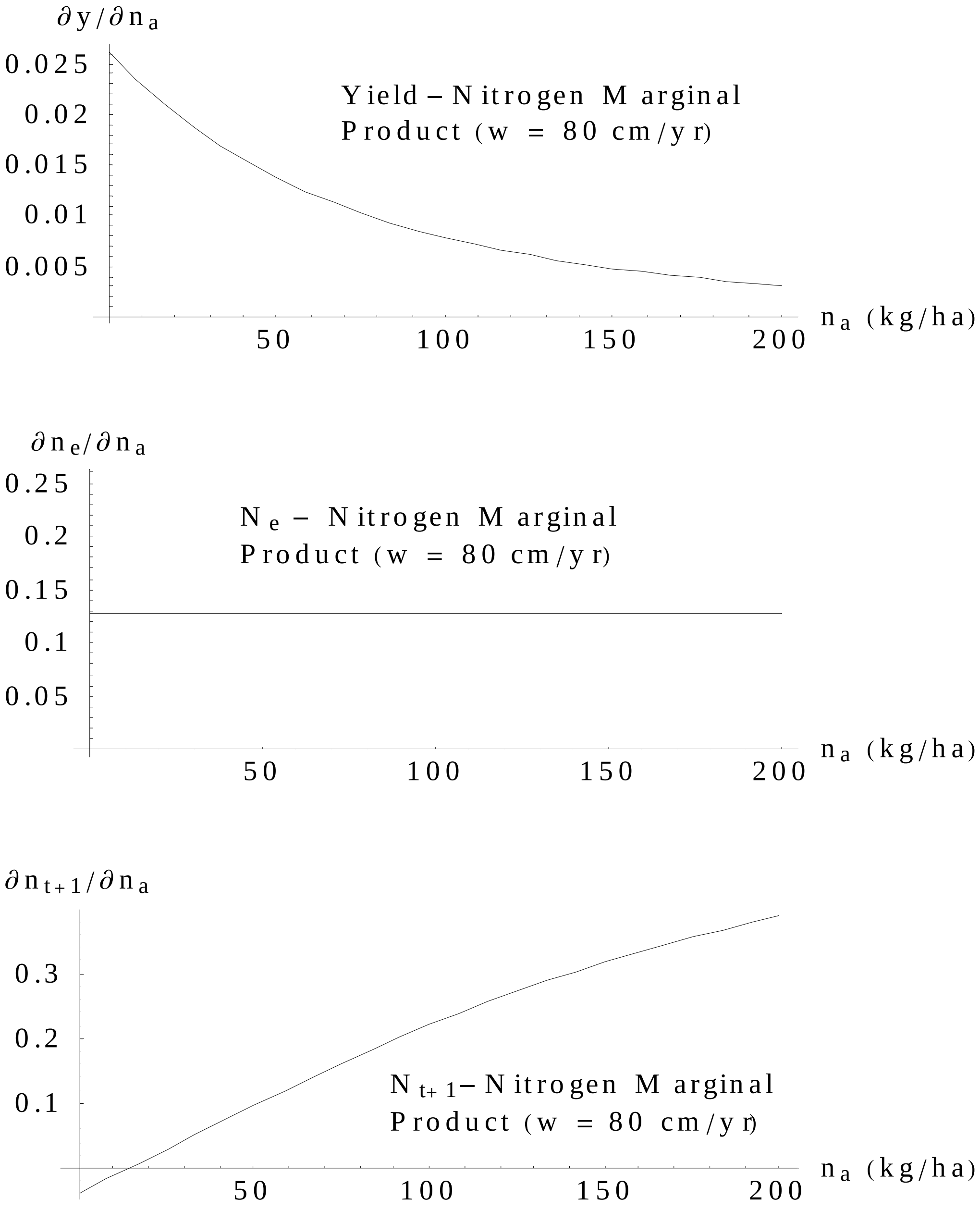

Figure A3*b*. Marginal product of applied nitrogen for the plant-level corn production function. Corn yield y_t (Mg ha^{-1} yr^{-1}), nitrogen emissions n_{et} (kg ha^{-1} yr^{-1}), and nitrogen carryovers n_{t+1} (kg ha^{-1}) as functions of applied nitrogen n_{at} (kg ha^{-1} yr^{-1}) for initial soil nitrogen n_t = 200 kg ha^{-1} in year *t*.

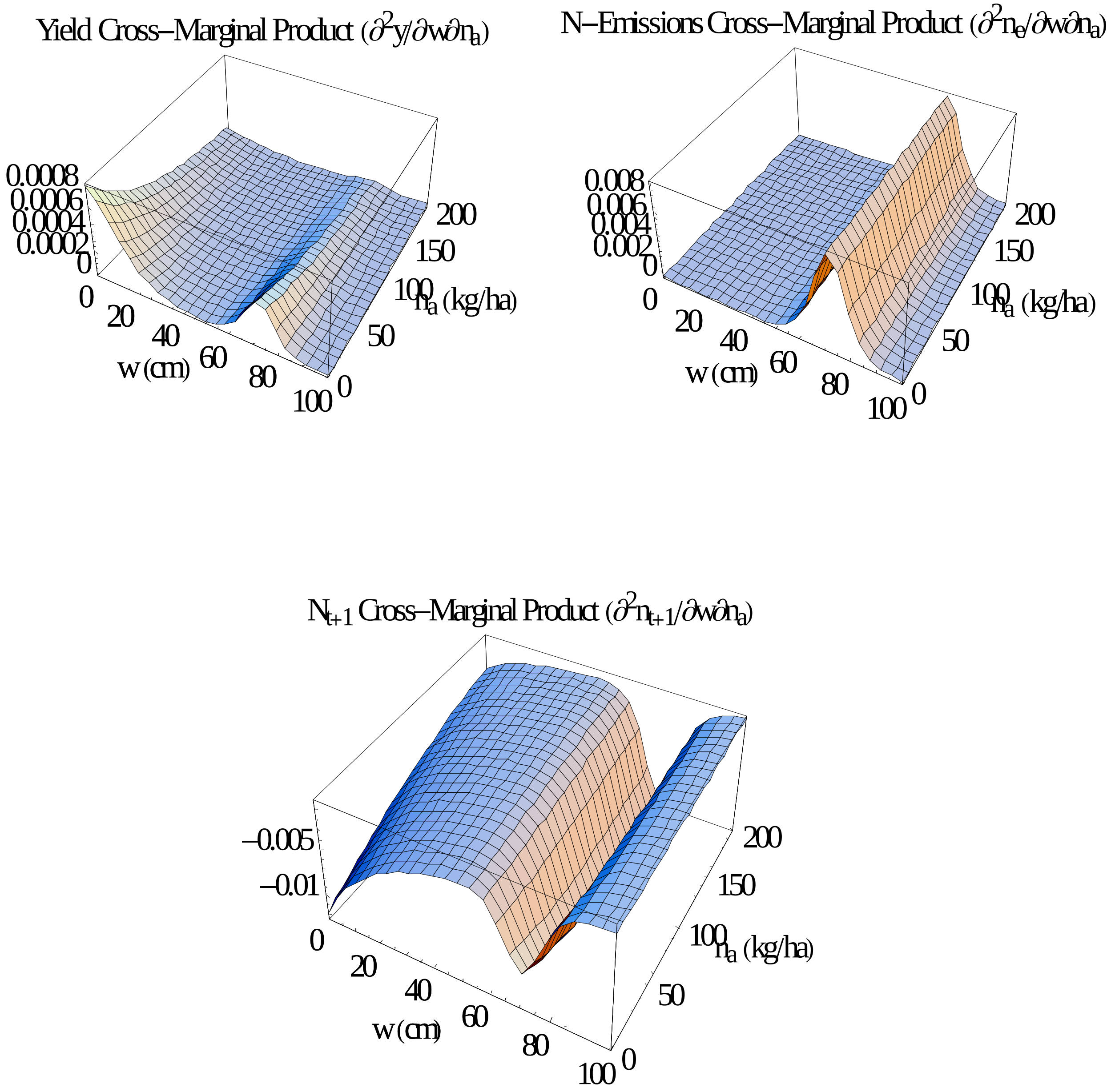

Figure A3*c*. Cross-marginal products for the plant-level production function. Corn yield y_t (Mg ha^{-1} yr^{-1}), nitrogen emissions n_{et} (kg ha^{-1} yr^{-1}), and nitrogen carryovers n_{t+1} (kg ha^{-1}) as functions of applied water w_t (cm yr^{-1}) and applied nitrogen n_{at} (kg ha^{-1} yr^{-1}) for initial soil nitrogen n_t = 200 kg ha^{-1} in year *t*.

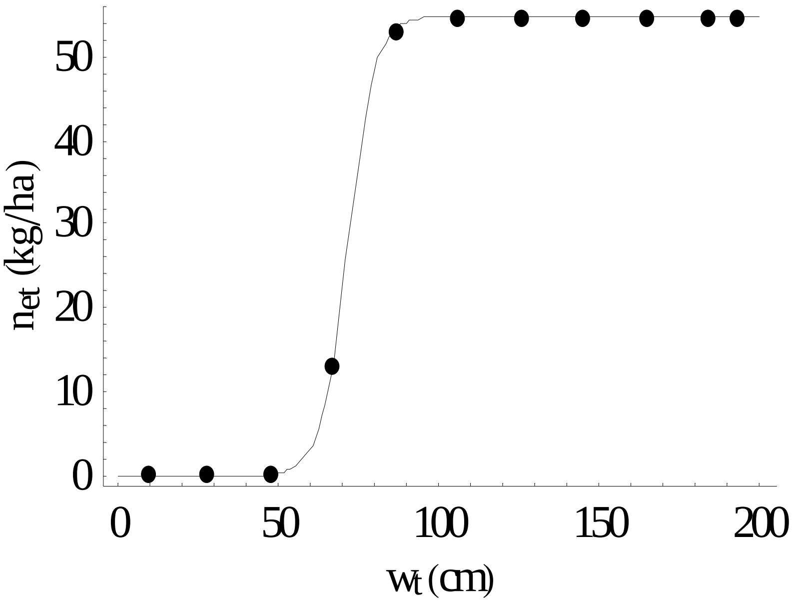

Figure A4. N-emissions as a function of applied water at steady-state levels of initial soil N and applied N and also evaluated at plot-level infiltrated water depths.

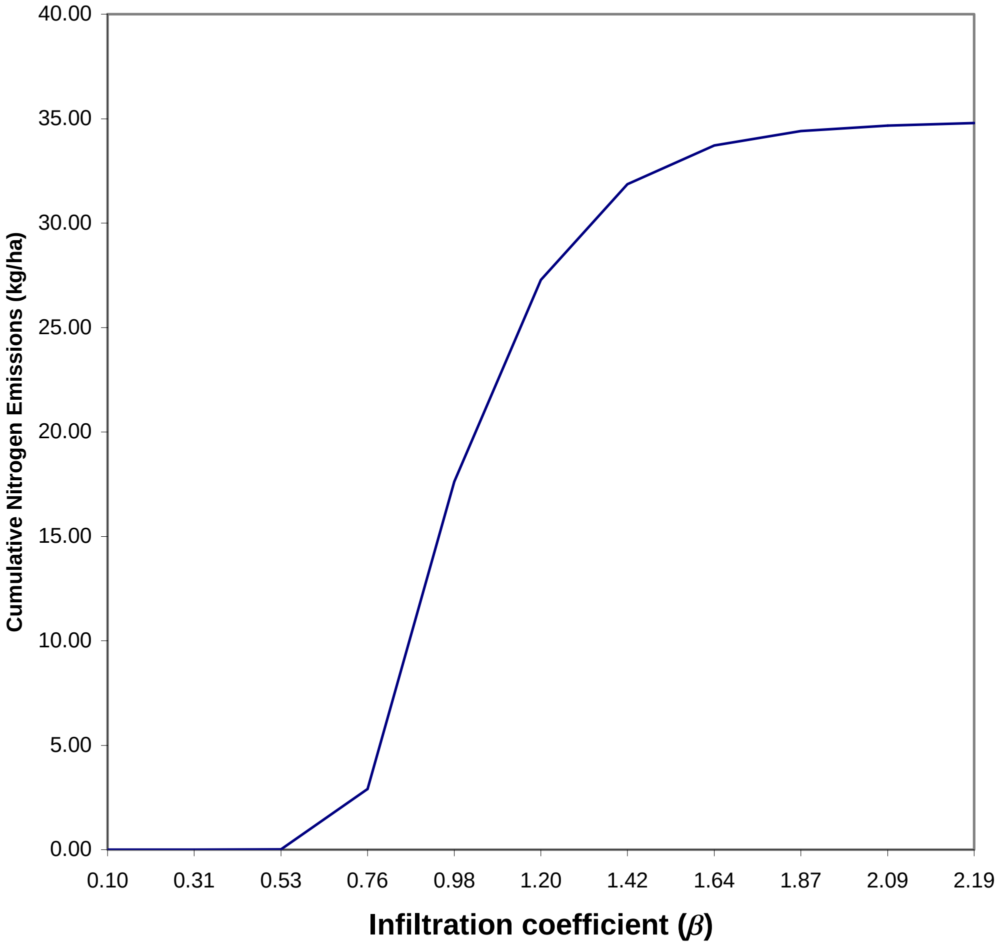

Figure A5. Cumulative N-emissions as a function of infiltration coefficients.

Table A1. Corn Price Effects on Optimal Steady-State Values

Corn Price p (\$/Mg)	Applied Water $\bar{w}_{ss}$ (cm)	Applied Nitrogen $\bar{n}_{a,ss}$ (kg/ha)	Soil Nitrogen $\bar{n}_{ss}$ (kg/ha)	Yield $\bar{y}_{ss}$ (tons/ha)	Nitrogen Emissions $\bar{n}_{e,ss}$ (kg/ha)	Annual NB (\$/ha)
102.02 (Current/Baseline)	87.9	221.4	158.8	10.07	36	168
112.02 (*10% Increase*)	89.5	230.5	164.2	10.13	38.5	269
122.64 (*20% Increase*)	91	239.4	169.7	10.18	41	377
132.86 (*30% Increase*)	92	251.1	170	10.23	43	480
143.08 (*40% Increase*)	120.5	254.9	172.5	10.39	56	588
153.30 (*50% Increase*)	122.8	261.5	177	10.42	58	693

Notes: PV-optimization with spatial variability and other parameter values at baseline values as specified in the text.