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Abstract

Agricultural nonpoint pollution is diffcult to regulate for numerous reasons, including uncertainty regarding the relationship between farm practices and pollutant levels, stochastic weather patterns that affect pollution levels and yields, and inability to monitor the flow of pollutants from individual farms. Two commonly proposed regulatory mechanisms are uniform taxes and standards. Prior research in this literature assumes producers are risk neutral. However, empirical evidence suggests farmers are risk averse. To increase the model's applicability to agricultural nonpoint pollution regulation we incorporate risk aversion into the model. An empirical application is used to illustrate how risk preferences might affect the regulatory mechanism choice.

Because many of the urban sprawl externalities are nonpoint in nature, regulatory challenges are similar to those posed by agricultural nonpoint pollution. This suggests that regulations aimed at reducing sprawl may be an indirect means of mitigating the environmental impacts of urban sprawl. An econometric model is used to analyze and predict residential land use change patterns in Albuquerque, New Mexico and surrounding areas. Results are used to assess the effectiveness of zoning restrictions in controling sprawl, and to test whether there are signifcant differences in the parameter estimates for urban and sprawl residential development patterns.

Key words: water quality, nonpoint pollution, risk aversion, agriculture, regulation, tax, standard, land use change, sprawl

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Chapter 1

Introduction

The arid southwestern United States is facing growing concerns about both water quantity and water quality. The adequacy of the available water supply is negatively impacted by increased demands that result from population growth and non-market uses. The water supply is also negatively impacted by urban development and the associated increase in impervious surfaces, which impede the absorption of rainfall into the ground and subsequent aquifer recharge (Noble, 1999). Furthermore, the pattern of urban development affects both the demand for water and water quality; water consumption is higher in low-density developments as a result of increased lawn watering (Real Estate Research Corporation, 1974), and low-density developments are particularly problematic for water quality (National Association of Regional Communities, 2005). Of the many changes in land use patterns, urbanization of agricultural and natural areas has the greatest adverse effect on water quality (Novotny and Olem, 1994).

The 1972 Clean Water Act (CWA) focused on improving surface water quality. Despite this, more than one-third of the United States' river miles, lake acres, and estuary square miles remain water quality impaired. Leading pollution problems for rivers include pathogens, siltation, habitat alterations, oxygen-depleting substances, nutrients, thermal modifications, metals, and flow alterations (U.S. Environmental Protection Agency, 2002). Pollution of water bodies takes two forms – point source pollution (which directly enters a water body through a pipe, ditch, or similar device) and nonpoint source pollution (diffuse pollution that enters a water body via runoff, run-in, or leaching). Many of the water quality improvements made during the past thirty years stem from reductions in pollution from point sources. Nonpoint source pollution is now the largest contributor to water quality impairment, which suggests that further water quality improvements will require addressing nonpoint pollution problems. Numerous sources of nonpoint pollution exist, including runoff from agricultural, silvicultural, construction, and urban areas. Regulating nonpoint source pollution is difficult, but a number of mechanisms have been proposed that focus on either standards or taxes.

According to the New Mexico Environment Department (2002), nonpoint pollution is the primary source of impairment to the quality of New Mexico water bodies. In response to the CWA requirement that states assess and address water quality impairments from nonpoint source pollution, New Mexico has identified twenty-one of its eighty-three watersheds, including portions of the Rio Grande, as Watersheds in Need of Restoration. These are defined as "watersheds that do not now meet, or face imminent threat of not meeting, clean water or other natural resource goals" (New Mexico Environment Department, 1999; U.S. Department of Agriculture and U.S. Environmental Protection Agency, 1998). Section 303(d) of the CWA requires states to develop Total Maximum Daily Load (TMDL) management plans for water bodies that do not meet relevant water quality standards. For example, the portion of the Rio Grande from the northern boundary of Isleta Pueblo to the southern boundary of Santa Ana Pueblo is included on New Mexico's 303(d) list, due to noncompliance with fecal coliform standards. Identified sources of fecal coliform bacteria include permitted discharges, periodic spills, point source permit violations, and nonpoint sources, including livestock operations, wildlife, and domestic animal waste in urban runoff (New Mexico Environment Department, 2002).[1]

Agriculture is the largest contributor to nonpoint pollution (agricultural activities contribute sediment, nutrients, pesticides, salts, and pathogens to surface waters), and is therefore the largest contributor to U.S. water quality problems (U.S. Environmental Protection Agency, 2002). For this reason agriculture has been and continues to be the focus of much of the nonpoint pollution research. However, urban areas also contribute significantly to the nonpoint pollution problem. Pollutants associated with urban areas include suspended solids, nitrogen, phosphorus, coliforms, and numerous toxic pollutants, such as oils, polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and lead. Novotny and Olem (1994) state that urbanization of natural or agricultural lands likely has the greatest adverse impact on water quality. The presence of construction sites is one way in which urban areas cause siltation and sedimentation, as construction sites can cause soil loss in excess of 50 tons/acre/year. Sediments are detrimental to water quality in and of themselves, and are also carriers of numerous pollutants, including organic components, metals, ammonium ions, phosphates, pesticides, dichloro-diphenyl-trichloroethane (DDT), and PCBs.

The increase in impervious surfaces, such as roads, parking lots, and rooftops, that results from urbanization causes flow alterations due to increased runoff and thus increased flooding. Impervious areas also increase pollutant loadings due to the flushing of accumulated pollutants (from such sources as traffic, litter, and street dust) during precipitation events. During summer months water quality is also impaired by a rapid rise in stream temperature due to runoff from roads and other surfaces warmed by the sun.[2] Additionally, because the presence of impervious surfaces impedes the absorption of rainfall into the ground, aquifer recharge can be negatively affected by urban development (Noble, 1999). Urban land uses are clearly detrimental to the available water supply and its quality. Future water quality will be impacted not only by the degree of development but also by the pattern of development.

[1] Although other New Mexico water quality standards are not exceeded along this stretch of the Rio Grande, the applicable standards do not reflect nutrient criteria set forth by the EPA in accordance with section 304(a) of the CWA. The EPA nutrient criteria are specific to geographic areas (termed 'ecoregions') and waterbody types and are intended to serve as a guide to states in the development of their water quality standards. Although the EPA recommends a total nitrogen criteria of 0.22 mg/L for the subecoregion that contains the Middle Rio Grande (U.S. Environmental Protection Agency, 2000), New Mexico has not set a total nitrogen standard for this stretch of river (New Mexico Water Quality Control Commission, 2002). Data collected between 1993 and 1995 indicate a median nitrogen concentration at Otowi of 0.06 mg/L, but that wastewater treatment plant inflows and agricultural return flows cause the median concentration to increase to 0.66 mg/L at Isleta (Moore and Anderholm, 2002).

[2] Novotny and Olem (1994) and Brooks et al. (1991) provide useful information pertaining to relationships between land use and water quality.

This research focuses on two aspects of nonpoint source pollution. First, using a theoretical model we examine the impact of regulatory mechanisms directed at agricultural nonpoint contributions. Under what conditions are taxes preferred over standards when farmers are assumed to be risk-averse? Second, we use a southwestern case study to empirically assess the effectiveness of using minimum lot sizes to curb urban sprawl and encourage infill development. The two papers are tied by the idea that regulating agricultural nonpoint source pollution may impact land use change. That is, regulation of agricultural nonpoint pollution may ultimately result in decreased farm profits and thus an increased incentive for farmers to sell their land to developers. If sales and urbanization of agricultural land occur as a result of regulations imposed to reduce agricultural nonpoint pollution, society will in essence trade agricultural nonpoint pollution for urban nonpoint pollution. Such potential tradeoffs need to be acknowledged and considered when forming regulations aimed at reducing agricultural nonpoint pollution. The research presented herein assesses optimal agricultural nonpoint pollution regulation given farmers' risk preferences as well as the effect of smaller minimum lot sizes on urban development patterns. Although this research uses two distinct models to assess questions regarding the design and effectiveness of regulatory mechanisms aimed at mitigating agricultural and urban nonpoint pollution, future work should strive to link the two research questions in an integrated model capable of linking and estimating the effects of regulating agricultural nonpoint pollution on urban development and its patterns.

1.1 Addressing Nonpoint Pollution with Standards and Regulations

Nonpoint pollution concerns can be addressed using either voluntary approaches (such as education, financial assistance, and technical assistance) and/or regulatory mechanisms (such as permits, taxes, and standards). Although the use of regulatory mechanisms to regulate nonpoint pollution is certainly feasible, nonpoint pollution poses difficulties for the formulation of efficient regulatory policies. As an example, the diffuse nature of nonpoint sources makes monitoring either technologically infeasible or prohibitively expensive, resulting in uncertainty regarding the relationship between firm practices and emissions. Additionally, nonpoint pollution is stochastic – the level of nonpoint pollution is frequently driven by weather, topography, and land use. These and other complexities associated with nonpoint pollution suggest that many of the policy implications that stem from the pollution externalities literature, while applicable to the regulation of point source pollution, do not easily extend to nonpoint pollution regulation.[3] Effective nonpoint regulation requires either the revision of policies to account for nonpoint complexities or the design of policies specifically geared to nonpoint pollution mitigation.

Taxes and standards are the two commonly used and analyzed regulatory approaches. Within the economics literature there exists a significant body of research devoted to assessing the circumstances under which taxes or standards are the preferred regulatory mech-

[3] An externality is a side effect resulting from an activity, the benefits and costs of which are not reflected in market prices. Externalities may be either positive (benefits result) or negative (costs result). Pollution externalities are a particular kind of negative externality.

anism. Weitzman (1974) wrote the seminal paper comparing taxes and standards, and researchers have since extended his model to make it more realistic. However, most of the existing literature is applicable to point source pollution; the literature has only recently been applicable to nonpoint pollution (see Wu and Babcock (2001)). Wu and Babcock (WB) incorporate spatial heterogeneity in the form of various soil types, thereby making the model applicable to nonpoint pollution stemming from agricultural production.

We incorporate risk preferences in the WB model. Because agricultural producers have been shown to be risk averse, our extension makes the model more realistic for assessing the regulation of agricultural nonpoint pollution. Our model predicts that the overall impact of producers' (farmers') risk averse behavior on whether a tax or standard is the preferred regulatory mechanism is uncertain; it must be assessed on a case by case basis, as the impact will depend on site- and case-specific factors (such as soils, slopes, and the degree of farmers' risk aversion). Although we are unable to determine with certainty the effect of risk aversion on regulatory mechanism choice, we demonstrate that risk averse behavior affects mechanism choice, as it can either amplify or dampen the impacts of the classic results derived by Weitzman (1974), Malcomson (1978), and Stavins (1996). We also demonstrate that although Wu and Babcock (2001) showed that the presence of lands for which the uniform tax is prohibitive favors the uniform tax, this in not necessarily the case in the presence of risk aversion; under certain conditions, risk aversion may reinforce, weaken, or reverse the WB result. Not only does risk aversion alter previous results derived under the assumption of risk neutrality, risk aversion also results in the addition of several new terms to the net benefits equation. Overall the effect of risk averse behavior on the preferability of standards versus taxes is ambiguous. For this reason, site-specific empirical analysis is necessary to determine whether a uniform tax or uniform standard is preferable. We present a simple simulation model, which serves to demonstrate how risk aversion can affect the choice of regulatory mechanism.

1.2 Land Use Change and Nonpoint Pollution

The growth of Albuquerque and other urbanized areas poses a threat to the quality and availability of New Mexico's water supply. Albuquerque's geographic area doubled between 1970 and 1990 as a result of a 67% growth in population and an 18% increase in per capita land consumption (Kolankiewicz and Beck, 2001). A Natural Resources Defense Council (2003) report gave Albuquerque a grade of 'poor' for water quality and compliance. Primary water quality concerns were arsenic and radon levels, although numerous other contaminants (including *E. coli* and total coliform bacteria) were found in Albuquerque's tap water. Two disinfection byproducts (total trihalomethanes and haloacetic acids) also occur in Albuquerque's tap water, indicating that an effort to address microbial pollutants may itself be creating water quality concerns (microbial pollutants such as *E. coli* can be treated using a chlorine disinfection process, though the process results in disinfection byproducts (DBPs) that may themselves pose health risks[4]). Because urban runoff is a source of microbial pollutants, a positive relationship exists between urban areas, microbial pollutants, and chlorine DBPs. Population growth and the accompanying expansion in Albuquerque's geographic

[4]The health effects of DBPs have not been studied sufficiently enough to define the relevant health risks.

area, replacement of porous surfaces with impervious surfaces, and increased vehicular traffic are likely to cause a rise in the region's water quality concerns.

Current and future Albuquerque area water quality concerns are amplified by water supply concerns. The New Mexico Office of the State Engineer has declared the Middle Rio Grande Basin a "critical basin" — a groundwater basin experiencing rapid economic and population growth for which there is insufficient information pertaining to the available water supply (Bartolino et al., 2002). A growing population and the associated increase in impervious surfaces result in altered streamflows, an increased incidence of flooding, and decreased aquifer recharge (Noble, 1999). Population growth and development patterns affect an area's water supply not only via implications for impervious surfaces and aquifer recharge, but also through impacts on demands placed upon the area's water supply. A study by the Real Estate Research Corporation demonstrated that water consumption is higher in low-density developments as a result of increased lawn watering (Real Estate Research Corporation, 1974).

The existence of water supply and water quality concerns in the Albuquerque area, links between land use and water quality and use, and projections of positive population growth for Albuquerque suggest the need for models capable of predicting the rate and pattern of land use change.[5] To address this need, we develop an econometric model of residential land use change for a 528 square mile area encompassing Albuquerque and outlying regions within Bernalillo County, New Mexico. The model enables us to determine the variables that are most important in explaining the current pattern of residential land use. Because differences in development patterns may exist for urban and sprawl areas, we examine each separately.

Our results indicate that both natural geographic characteristics (such as slopes and soils) and man-made characteristics (such as surrounding land uses) are statistically significant covariates. We estimate three separate statistical models: one for urban areas only, one for sprawl areas only, and one for the two combined. Numerous covariates have consistent statistical significance in the three models, including income, the soil's capacity to serve as a septic absorption field, nearby residential development densities, and proximity to jobs, parks, and open space areas. However, differences do exist between the three models; parameter estimates vary in their signs, magnitudes, and statistical significance. On the basis of a chi-squared test, we conclude that it is preferable to model urban and sprawl development patterns separately. This finding has potentially important implications for land use modeling efforts in other geographic areas; it indicates that applying one statistical model to a diverse region that contains both urban and sprawl areas may yield inaccurate results and have adverse effects on land development management efforts.

[5]The Mid-Region Council of Governments (MRCOG) has developed a model for the purposes of developing alternative land use scenarios, although their model differs from ours in a number of important ways, including the unit of analysis and explanatory variables. In addition, whereas the MRCOG model segments residential development into low-, medium-, and high-priced single family and multifamily residential developments, we segment the study area into urban and sprawl areas.

Chapter 2

Regulation of Agricultural Nonpoint Pollution Using Standards and Taxes: How Does Risk Aversion Affect Choice of Regulatory Mechanism?

We incorporate farmers' risk preferences into a theoretical model used to assess the relative efficiency of input standards and taxes for the purpose of regulating agricultural nonpoint pollution. The analysis enables us to assess whether producers' risk preferences are an important consideration in the choice of regulatory mechanisms.

2.1 Literature Review

2.1.1 Relevance of Risk Aversion

A risk-averse individual is one who will not accept a fair bet; that is, given the choice between a bet or gamble with an expected value of $\$X$ and a sure payment of $\$X$, the individual will choose the sure payment. In contrast, a risk-neutral individual is indifferent between the sure payment and the gamble, and a risk-seeking individual would choose the gamble. Depending upon the degree of risk aversion, if given a choice between a gamble with an expected value of $\$X$ and a sure payment of less than $\$X$, a risk-averse individual might opt in favor of the sure payment. Two measures exist that may be used to quantify the intensity of an individual's risk aversion: the Arrow-Pratt measure of absolute risk aversion $\left(-\frac{U''(W)}{U'(w)}\right)$ and the Arrow-Pratt measure of relative risk aversion $\left(-\frac{WU''(W)}{U'(w)}\right)$, where $U(W)$ denotes utility (U) as a function of wealth (W), and $U'(W)$ and $U''(W)$ denote $\frac{\partial U}{\partial W}$ and $\frac{\partial^2 U}{\partial W^2}$, respectively. The values of both risk aversion measures will be positive for risk-averse individuals, zero for risk-neutral individuals, and negative for risk-seeking individuals. The Arrow-Pratt relative risk aversion measure allows for the possibility that an individual is risk averse in a certain range of wealth, but may be risk neutral or even risk seeking in other ranges of wealth.

Absolute risk aversion can be either increasing (IARA), constant (CARA), or decreasing

(DARA). DARA (CARA, IARA) indicates that the individual's degree of risk aversion is lower (constant, higher) at higher levels of wealth. Thus a DARA individual's willingness to pay to avoid a given bet will decline as their wealth increases. To illustrate, suppose utility as a function of wealth takes the form $U(W) = ln(W)$. The Arrow-Pratt absolute risk aversion measure is given by

$$\lambda = -\frac{U''(W)}{U'(W)} = \frac{1}{W},$$

which indicates that as W increases, absolute risk aversion (λ) will decrease. Because risk aversion declines as wealth increases, the DARA individual will be willing to pay less to avoid the same given bet as their wealth level increases.[1]

The relevance of risk preferences to agricultural production and the regulation of agricultural production has been demonstrated by a variety of authors. Leathers and Quiggin (1991) demonstrate that the effect on input use of an input price increase (tax) depends upon whether the input is risk-increasing or risk-decreasing and whether risk-aversion takes the form of increasing, constant, or decreasing absolute risk aversion.[2] Their results show that a Pigouvian tax may cause DARA producers to move farther away from the social optimum and that obtaining unambiguous and "normal" (expected) results requires the assumption that producers have constant absolute risk aversion (CARA). Conclusions about policy effects and optimal incentives require empirical knowledge of the production function, the environmental impacts of input use, and the risk attitudes of producers.

To reassess some of the ambiguities reported by Leathers and Quiggin regarding farmers with DARA risk preferences, Karagiannis (1998) extends their theoretical framework by incorporating increasing relative risk aversion (IRRA). IRRA has become a popular assumption due to its intuitive appeal – IRRA implies that a proportional increase in risk results in a more-than-proportional increase in aversion to risk and thus that the disutility of risk is positively related to profit. Karagiannis finds that an input tax will cause a risk-averse farmer facing production uncertainty to reduce the use of a risk-increasing (risk-reducing) input if absolute risk aversion is non-increasing (absolute risk aversion is decreasing and relative risk aversion is less than one). If production uncertainty is multiplicative, a risk-averse farmer will reduce input use in response to an input tax if absolute risk aversion is non-increasing. If production uncertainty is additive, a risk-averse farmer will reduce input use in response to an input tax regardless of the type of risk aversion.[3]

Feinerman and Choi (1993) provide a theoretical model of the welfare effects for farmers of regulating nitrogen using action equivalent taxes and quotas, that is, taxes and quotas that yield the same expected nitrogen application. They find that a risk-neutral farmer will

[1] Similar concepts of increasing, decreasing, and constant risk aversion apply to the Arrow-Pratt relative risk aversion measure.

[2] Whether particular inputs, such as fertilizers and pesticides, are risk-increasing or risk-decreasing is still an unresolved question, as existing empirical evidence is mixed (Pannell et al., 2000; Isik, 2002; Jaenicke et al., 2003). For the region of interest, an increase in the application of an input will result in an increase in the expected profit. However, an increase in the application of a risk-increasing input is also associated with an increase in the variance of yields and profits, whereas an increase in the application of a risk-decreasing input is associated with a decrease in the variance of yields and profits.

[3] Throughout our discussion and analysis we focus on farmers' *income* risk preferences. Because environmental quality is likely a variable in a farmer's utility function, an interesting extension to the work presented herein would be the incorporation of environmental risk preferences.

prefer the tax, as expected profits are higher under the tax than under the quota, but that the preferred policy is ambiguous for a risk-averse farmer. A numerical example confirmed the theoretical findings.

Lambert (1990) uses a single crop empirical model to demonstrate that risk aversion affects input levels and proportions and an extended multi-crop model to illustrate that the ability to switch crops mitigates the impacts of taxes and standards on the certainty equivalent of returns. Lambert also shows that analysis of pollution control policies may over- or underestimate costs, depending upon the direction of the marginal contribution of the input on the riskiness of returns.

Peterson and Boisvert (2001) develop a self-selecting program that incorporates asymmetric information about technology and risk preferences. The authors assume government knows that technology and risk attitudes differ, but does not know the distribution of types. An empirical application of their model illustrates that information about risk is valuable to government, as program payments could be reduced if information pertaining to risk preferences were known, but that such information is less valuable than information regarding soils (which the authors use as a proxy for technology).

Isik (2002) expands on previous research by simultaneously considering both production and price uncertainty (prior studies have considered only one source of uncertainty). Isik derives theoretical results, examines impacts of various policies, and uses a numerical simulation to illustrate policy results. His research ultimately demonstrates that policy impacts on the level of input use will depend upon the form of production uncertainty (additive or multiplicative), the degrees of price and production uncertainty, the risk-input relationship, and risk preferences.

Empirical applications of theoretical tests presented by Roosen and Hennessy (2003) strongly suggest that risk-averse producers use less nitrogen than risk-neutral producers, but provide weaker evidence that nitrogen application rates decline as risk aversion increases.

2.1.2 Comparative Advantage of Taxes and Standards

Regulation of nonpoint pollution can take a number of different forms. Policy instruments can be applied to emissions proxies, inputs, practices, or ambient concentrations of pollutants and can take the form of standards, taxes, tradeable permits, subsidies, or contracts. However, regulating nonpoint pollution presents several difficulties. Using emissions as the regulatory base is difficult, as measuring and monitoring emissions is expensive and complex. Regulation of estimated pollution emissions is difficult, as pollution production functions generally do not exist. Regulating ambient pollution levels is problematic for a variety of reasons, including monitoring costs, multiple sources, and time lags between polluting activities and water quality impacts. Much of the nonpoint pollution (NPP) literature has therefore focused on regulating inputs through either taxes or standards. First-best taxes and quantity standards must be defined for each firm and input. However, the complexity of such a system makes it infeasible. Thus second-best uniform taxes and standards have been of interest. An area of research has been the relative efficiency of these second-best policy instruments.

Weitzman (1974) examines the comparative advantage of uniform taxes and standards in the presence of both certainty and uncertainty regarding the cost and benefit functions. He shows that in the presence of complete and perfect information the two policy instruments are equivalent. When uncertainties pertaining to crop yields and environmental damages are introduced (and a single producer assumed) this equivalence no longer holds. Examining the comparative advantage of prices over quantities requires imposing a structure on the benefit and cost functions; Weitzman imposes a quadratic form on both. Uncertainty regarding the benefit function does not affect the comparative advantage (although subsequent work by Stavins (1996) illustrates that this result was due to Weitzman's assumption that cost uncertainty and benefit uncertainty were uncorrelated). Standards are preferred when the benefit function is more sharply curved and when the cost function is closer to being linear. A price instrument is preferred when the benefit function is closer to being linear. If the cost function is highly curved, the instruments near equivalency.[4]

Weitzman then extends the uncertainty model to incorporate either multiple products or multiple producers of the same product. Under the assumption that different producers have different cost functions but the same impact on benefits, Weitzman (1974) shows that the relative advantage of prices to quantities increases as the number of producers increases. As the correlation between producers' cost functions diminishes, the comparative advantage of prices increases; this effect is more pronounced the greater the number of producers.

In his analysis Weitzman imposes the assumption that the amount of uncertainty in marginal cost is sufficiently small to justify second-order approximations of the total benefit and total cost functions around $\hat{q}$, where $\hat{q}$ is the quantity that maximizes expected net benefits when quantity instruments are used. In doing so, Weitzman treats the marginal cost and marginal benefit functions as linear and assumes their slopes are known with certainty. Malcomson (1978) examines the effect of relaxing this assumption – he assesses the case of uncertainty affecting not only the intercepts of the marginal cost and marginal benefit functions, but also their slopes. Malcomson shows that if uncertainty affects both slopes and intercepts and if only the uncertainty pertaining to the intercept is considered, the wrong policy choice may be made and the resulting loss may be significant.

Stavins (1996) follows Weitzman in assuming linear marginal cost and marginal benefit functions, but relaxes Weitzman's assumption that the cost and benefit functions are uncorrelated.[5] Stavins' results show that positive (negative) correlation between costs and benefits tends to favor quantities (taxes). Stavins also shows that this correlation effect can reverse the identification of the price instrument as the optimal instrument, but is less likely to reverse the identification of the quantity instrument as the optimal instrument.

Wu and Babcock (2001) extend Weitzman's work by incorporating spatial heterogeneity. In light of Malcomson's results, WB allow both slope and intercept of the marginal benefit (MB) and marginal cost (MC) functions to vary across firms. They also incorporate Stavins' results, in that they allow for correlation between the MC and MB functions. Results suggest that increases in the slope of MC, the correlation between MC and MB, and the variance in farmers' responses to the tax all decrease the relative advantage of the tax. Variance in MC reduces the relative advantage of the tax if the MB and MC are positively correlated. Incorporating spatial heterogeneity brings up the issue of corner solutions, which occur when

[4]Weitzman also notes that in some instances disastrous consequences may result if a price instrument is applied when a quantity instrument is in fact preferred. For this reason quantity policies may be preferable.

[5]Relaxing this assumption is realistic for agricultural NPP, as benefits (farm profits) and costs (environmental damages) are both affected by stochastic weather, which implies correlation between benefits and costs.

MB are so low that chemical use is unprofitable under the tax or when MB decline so rapidly that the standard is nonbinding. WB show empirically that the presence of corner solutions can reverse the conventional finding of standard or tax superiority.

Weitzman's 1974 seminal paper and all subsequent extensions have assumed farmers are risk-neutral. However, it is well known that farmers face price and yield uncertainty. It has been repeatedly shown that many farmers are risk-averse (Lin et al., 1974; King and Robison, 1984; Saha et al., 1994) and the relevance of risk preferences to farmers' decisions and responsiveness to policies has been a topic of considerable research.

As mentioned previously, our contribution to this rather extensive literature involves incorporating risk preferences into the extended Weitzman model provided by Wu and Babcock (2001). Because it has been demonstrated that farmers are risk averse, extending the model in this manner will serve to increase the applicability of the model to the regulation of agricultural nonpoint pollution. Our research provides a greater understanding of how risk averse behavior affects when taxes may be the preferred mechanism for regulating agricultural nonpoint pollution, and when standards may be preferred.

2.2 Theoretical Model

The theoretical development presented herein builds upon the theory presented in Wu and Babcock (2001), which extends Weitzman's (1974) seminal work by incorporating spatial heterogeneity as well as other complexities developed by Malcomson (1978) and Stavins (1996). We extend Weitzman (1974) further by incorporating risk aversion. Following Wu and Babcock (2001), spatial heterogeneity (denoted by μ) affects both agricultural production and nonpoint pollution production, and is characterized by landscape features (such as slope and soil type) that may affect agricultural production. We incorporate risk in the production function for μ-type land by using the Just-Pope production function $y = f(q,\mu,\theta) + g(q,\mu,\theta)^{\frac{1}{2}}\varepsilon$, where y = yield, $f(\cdot)$ is the mean or deterministic portion of the production function, $g(\cdot)$ is the variance or risk portion of the production function, q is the amount of input used (q may be either a risk-increasing or risk-decreasing input), θ is a random variable that represents stochastic weather (Just and Pope, 1978, 1979), and ϵ is a random error that is distributed $N(0,1)$.[6] The profits on μ-type land are defined as $\Pi(q,\mu,\theta) = p[f(q,\mu,\theta) + g(q,\mu,\theta)^{\frac{1}{2}}\varepsilon] - wq$, where p is output price, w is input price, and $\pi_{qq} \leq 0$. Expected profits are thus $E[\Pi(q,\mu,\theta)] = \pi(q,\mu) = pf(q,\mu,\theta) - wq$, and the variance of profits is $V[pg(q,\mu,\theta)^{\frac{1}{2}}\varepsilon] = \sigma^2(q,\mu) = p^2 g(q,\mu,\theta)\sigma_\varepsilon^2$. Previous extensions to Weitzman's 1974 seminal paper have assumed risk-neutrality and have thus assumed producers maximize expected profits. In contrast, we incorporate risk aversion and assume producers maximize the certainty equivalence of profits.[7] The function that denotes environmental damages resulting from use of input q on μ-type land is $D(q,\mu,\theta)$. We assume $D_q(q,\mu,\theta) \geq 0$ and

[6]The Just-Pope production function is sufficiently general to accommodate both risk-increasing and -decreasing inputs. If we assume $\varepsilon \sim N(0,\sigma_\varepsilon^2)$, expected yields are $E(y) = E[f(q,\mu,\theta) + g(q,\mu,\theta)^{\frac{1}{2}}\varepsilon] = f(q,\mu,\theta)$, and the variance of crop yields is $V(y) = V[f(q,\mu,\theta) + g(q,\mu,\theta)^{\frac{1}{2}}\varepsilon] = V[g(q,\mu,\theta)^{\frac{1}{2}}\varepsilon] = E[g(q,\mu,\theta)^{\frac{1}{2}}\varepsilon - E(g(q,\mu,\theta)^{\frac{1}{2}}\varepsilon)]^2 = g(q,\mu,\theta)\sigma_\varepsilon^2$.

[7]Certainty equivalence of profits is equal to expected profits minus $\frac{1}{2}$ the product of the Arrow-Pratt coefficient of absolute risk aversion and the variance of profits, that is, $CE(\pi) = \pi(q,\mu) - \frac{1}{2}\lambda\sigma^2(q,\mu)$.

$D_{qq}(q, \mu, \theta) \geq 0$ and denote $E[D(q, \mu, \theta)]$ as $D(q, \mu)$.

The regulatory agency and farmers are assumed to have symmetric information regarding θ and are assumed to make their regulatory and production decisions prior to realization of actual weather patterns. Farmers are assumed to know the landscape (μ) relevant to their farm, whereas the regulator only has knowledge regarding the probability distribution of landscape characteristics, $h(\mu)$. A similar assumption is made regarding risk preferences; farmers are assumed to know their own Arrow-Pratt absolute risk aversion coefficient (λ), but the agency only knows the probability distribution of risk preferences, $h(\lambda)$.

2.2.1 Producer and Agency Decisions under an Input Tax

Given that a uniform tax τ is imposed on input q, the risk-averse producer will choose the application rate q that maximizes after-tax certainty equivalent profits:[8]

$$\begin{aligned} \max_{q} \quad & \pi(q, \mu) - \frac{1}{2}\lambda\sigma^2(q, \mu) - \tau q \\ s.t. \quad & q \geq 0. \end{aligned} \tag{2.1}$$

Solving the first-order condition of (2.1) yields

$$\tau = \pi_q(q(\tau, \mu), \mu) - \frac{1}{2}\lambda\sigma_q^2(q(\tau, \mu), \mu).^9 \tag{2.2}$$

From (2.2) we can conclude that if $\tau \geq \pi_q(0, \mu) - \frac{1}{2}\lambda\sigma_q^2(0, \mu)$ then $q(\tau, \mu) = 0$, or else the application rate will be that which satisfies (2.2). For simplicity we assume μ is a scalar, normalized such that $0 \leq \mu \leq 1$. An assessment of how chemical application rates change as μ changes requires assumptions regarding the signs of $\pi_{q\mu}$ and $\sigma_{q\mu}^2$. We assume $\sigma_{q\mu}^2 > 0$ and $\pi_{q\mu} > 0$.[10] The assumption that $\pi_{q\mu} > 0$ implies that chemical application rates are higher on land with a higher μ. The effect of the assumption that $\sigma_{q\mu}^2 > 0$ on application rates will depend upon the values of λ and σ_q^2. If $\lambda = 0$ (i.e., farmer is risk neutral), $\sigma_{q\mu}^2$ has no effect on application rates and thus the effect of μ on application rates depends solely on π_{qu} and application rates will increase with μ. If $\lambda > 0$ and $\sigma_q^2 > 0$ (farmer is risk averse and chemical is risk-increasing), then $\sigma_{q\mu}^2$ has the effect of decreasing application rates. Thus in this case the overall effect of μ on application rates is ambiguous. Lastly, if $\lambda > 0$ and $\sigma_q^2 < 0$ (i.e., farmer is risk averse and input is risk-decreasing), $\sigma_{q\mu}^2$ has the effect of increasing application rates. Thus an increase in μ will result in an increase in application rates when $\lambda > 0$ and $\sigma_q^2 < 0$.

Let $\mu(\tau)$ be the solution to $\tau = \pi_q(0, \mu) - \frac{1}{2}\lambda\sigma_q^2(0, \mu)$. Given the previous discussion regarding the effect of a change in μ on chemical application rates, we can conclude that no

[8] Maximizing certainty equivalent profits is equivalent to maximizing expected utility.

[9] For risk-increasing (risk-decreasing) inputs, $\sigma_q^2 \geq 0$ ($\sigma_q^2 \leq 0$).

[10] Our reasoning for assuming $\sigma_{q\mu}^2 > 0$ is as follows. Wu and Babcock (2001) assume $\pi_{q\mu} > 0$, that is, the marginal profit of an increase in chemical use increases as μ increases. This suggests that a higher μ implies higher quality land. It is reasonable to assume that π will be low on low-quality land and that additional applications of q will not result in significant changes in π (i.e., σ_q^2 is low when μ is low), regardless of whether q is risk-increasing or risk-decreasing. Similarly, we can assume that for high-quality land π will be high and increasing q *will* significantly change π (i.e., σ_q^2 is high when μ is high), again regardless of whether q is risk-increasing or risk-decreasing. From this line of reasoning we can conclude that $\sigma_{q\mu}^2 > 0$.

chemical is applied to land with $\mu \leq \mu(\tau)$ if $\lambda = 0$ or if $\lambda > 0$ and $\sigma_q^2 < 0$. However it is unclear whether chemicals will be applied to land with $\mu \leq \mu(\tau)$ when $\lambda > 0$ and $\sigma_q^2 > 0$.

The agency seeks to set a tax rate that maximizes expected social surplus:

$$\max_{\tau} E_\lambda E_\mu[\pi(q(\tau,\mu),\mu) - 0.5\lambda\sigma^2(q(\tau,\mu),\mu) - D(q(\tau,\mu),\mu)] = \int_0^\lambda \left\{ \int_0^{\mu(\tau)} [\pi(0,\mu) - 0.5\lambda\sigma^2(0,\mu) - D(0,\mu)]h(\mu)d\mu + \int_{\mu(\tau)}^1 [\pi(q(\tau,\mu),\mu) - 0.5\lambda\sigma^2(q(\tau,\mu),\mu) - D(q(\tau,\mu),\mu)]h(\mu)d\mu \right\} h(\lambda)d\lambda \quad s.t. \quad \tau \geq 0, \quad (2.3)$$

which can be re-written as

$$\begin{aligned} \max_{\tau} \quad & \int_0^\lambda \int_0^{\mu(\tau)} [\pi(0,\mu) - 0.5\lambda\sigma^2(0,\mu) - D(0,\mu)]h(\mu)d\mu\, h(\lambda)d\lambda \\ & + \int_0^\lambda \int_{\mu(\tau)}^1 [\pi(q(\tau,\mu),\mu) - 0.5\lambda\sigma^2(q(\tau,\mu),\mu) - D(q(\tau,\mu),\mu)]h(\mu)d\mu\, h(\lambda)d\lambda \\ s.t. \quad & \tau \geq 0. \end{aligned} \quad (2.4)$$

The first order condition is

$$\begin{aligned} \int_0^\lambda \Big\{ & [\pi(0,\mu) - 0.5\lambda\sigma^2(0,\mu) - D(0,\mu)]h(\mu(\tau))\mu'(\tau) \\ & - [\pi(q(\tau,\mu(\tau)),\mu(\tau)) - 0.5\lambda\sigma^2(q(\tau,\mu(\tau)),\mu(\tau)) - D(q(\tau,\mu(\tau)),\mu(\tau))]h(\mu(\tau))\mu'(\tau) \\ & + \int_{\mu(\tau)}^1 [\pi_q(q(\tau,\mu),\mu) - 0.5\lambda\sigma_q^2(q(\tau,\mu),\mu) - D_q(q(\tau,\mu),\mu)]q_\tau(\tau,\mu)h(\mu)d\mu \Big\} h(\lambda)d\lambda \\ & = 0. \end{aligned} \quad (2.5)$$

Because $q(\tau,\mu(\tau)) = 0$ the first and second terms cancel one another, and we are left with

$$\int_0^\lambda \int_{\mu(\tau)}^1 [\pi_q(q(\tau,\mu),\mu) - 0.5\lambda\sigma_q^2(q(\tau,\mu),\mu) - D_q(q(\tau,\mu),\mu)]q_\tau(\tau,\mu)h(\mu)d\mu\, h(\lambda)d\lambda = 0, \quad (2.6)$$

which indicates that the optimal tax, τ^*, must satisfy

$$E_\lambda E_\mu\{[\pi_q(q(\tau^*,\mu),\mu) - 0.5\lambda\sigma_q^2(q(\tau^*,\mu),\mu)]q_\tau(\tau^*,\mu) \mid \tau^* < \pi_q(0,\mu)\} = E_\lambda E_\mu\{D_q(q(\tau^*,\mu),\mu)q_\tau(\tau^*,\mu) \mid \tau^* < \pi_q(0,\mu)\}. \quad (2.7)$$

That is, the optimal tax should be set such that mean marginal certainty equivalent equals mean marginal pollution damage on land where the chemical is applied (land for which $q(\tau^*,\mu) > 0$).

2.2.2 Producer and Agency Decisions under an Input Standard

Given that the regulatory agency sets a chemical-use standard L, the farmer's objective is to maximize the certainty equivalent profits subject to the standard:

$$\begin{aligned} \max_{q} \quad & \pi(q,\mu) - \frac{1}{2}\lambda\sigma^2(q,\mu) \\ s.t. \quad & q \le L. \end{aligned} \tag{2.8}$$

The initial application rate (the application rate set prior to the imposition of the standard) is denoted by $q^0(\mu)$ and is set by the producer such that the marginal certainty equivalent is equal to zero:

$$\pi_q(q,\mu) - \frac{1}{2}\lambda\sigma_q^2(q,\mu) = 0. \tag{2.9}$$

If $q^0(\mu) < L$, then the application rate is not affected by the standard. If $q^0(\mu) > L$, then the application rate must be reduced to the standard L. Defining $\mu(L)$ as the solution to $q^0(\mu) = L$ implies that the standard does not affect application rates on land for which $\mu < \mu(L)$.

The agency seeks to set a standard that will maximize expected social welfare:

$$\begin{aligned} \max_{L} \quad & \int_0^{\lambda}\int_0^{\mu(L)} [\pi(q^0(\mu),\mu) - 0.5\lambda\sigma^2(q^0(\mu),\mu) - D(q^0(\mu),\mu)]h(\mu)d\mu\, h(\lambda)d\lambda \\ & + \int_0^{\lambda}\int_{\mu(L)}^{1} [\pi(L,\mu) - 0.5\lambda\sigma^2(L,\mu) - D(L,\mu)]h(\mu)d\mu\, h(\lambda)d\lambda \\ s.t. \quad & L \ge 0, \end{aligned} \tag{2.10}$$

which yields the first order condition

$$\begin{aligned} & \int_0^{\lambda} [\pi(q^0(\mu(L)),\mu(L)) - 0.5\lambda\sigma^2(q^0(\mu(L)),\mu(L)) - D(q^0(\mu(L)),\mu(L))]h(\mu(L))\mu'(L)\, h(\lambda)d\lambda \\ & - \int_0^{\lambda} [\pi(L,\mu(L)) - 0.5\lambda\sigma^2(L,\mu(L)) - D(L,\mu(L))]h(\mu(L))\mu'(L)\, h(\lambda)d\lambda \\ & + \int_0^{\lambda}\int_{\mu(L)}^{1} [\pi_q(L,\mu) - 0.5\lambda\sigma_q^2(L,\mu) - D_q(L,\mu)]h(\mu)d\mu\, h(\lambda)d\lambda = 0. \end{aligned} \tag{2.11}$$

Because $q^0(\mu(L)) = L$, the first and second terms of the first order condition cancel each other, and we are left with

$$\int_0^{\lambda}\int_{\mu(L)}^{1} [\pi_q(L,\mu) - 0.5\lambda\sigma_q^2(L,\mu) - D_q(L,\mu)]h(\mu)d\mu\, h(\lambda)d\lambda = 0. \tag{2.12}$$

This indicates that the optimal standard, L^*, satisfies

$$E_\lambda E_\mu\{[\pi_q(L^*,\mu) - \frac{1}{2}\lambda\sigma_q^2(L^*,\mu)] \mid q^0(\mu) \ge L^*\} = E_\lambda E_\mu\{D_q(L^*,\mu) \mid q^0(\mu) \ge L^*\}. \tag{2.13}$$

That is, the optimal standard equates the mean marginal certainty equivalent and the mean marginal pollution damage on land where the standard is binding. Assume the optimal standard is imposed and let $q^r(\mu)$ be the application rate on μ-type land under L^*. Then

$$q^r(\mu) = \begin{cases} q^0(\mu) & \text{if } q^0(\mu) \leq L^* \\ L^* & \text{if } q^0(\mu) > L^*. \end{cases} \tag{2.14}$$

2.2.3 Relative Efficiency of Second-Best Tax and Standard

As discussed previously, neither a uniform tax nor a uniform standard is first-best. Thus the question of ultimate interest is which of these two second-best policy instruments is relatively more efficient. To address this question we must consider the difference in the expected social surplus derived under the two policies (Weitzman, 1974):

$$\begin{aligned} \Delta \equiv\ & E_\lambda E_\mu\{[\pi(q(\tau^*,\mu),\mu) - 0.5\lambda\sigma^2(q(\tau^*,\mu),\mu) - D(q(\tau^*,\mu),\mu)] \\ & -[\pi(q^r(\mu),\mu) - 0.5\lambda\sigma^2(q^r(\mu),\mu) - D(q^r(\mu),\mu)]\}. \end{aligned} \tag{2.15}$$

Assessing this difference requires that we place additional structure on the expected profits, variance of profits, and damage functions:

$$\pi(q,\mu) = b_0(\mu) + b_1\beta_1(\mu)(q - q^r(\mu)) + \frac{1}{2}b_2\beta_2(\mu)(q - q^r(\mu))^2 \tag{2.16}$$

$$\sigma^2(q,\mu) = p^2\sigma_\varepsilon^2[g_0(\mu) + g_1\gamma_1(\mu)(q - q^r(\mu)) + \frac{1}{2}g_2\gamma_2(\mu)(q - q^r(\mu))^2] \tag{2.17}$$

$$D(q,\mu) = c_0(\mu) + c_1\alpha_1(\mu)(q - q^r(\mu)) + \frac{1}{2}c_2\alpha_2(\mu)(q - q^r(\mu))^2 \tag{2.18}$$

where b_1, b_2, c_1, c_2, g_1, and g_2 are fixed coefficients and $\alpha_1(\mu), \alpha_2(\mu), \beta_1(\mu), \beta_2(\mu), \gamma_1(\mu)$, and $\gamma_2(\mu)$ are functions of the land's physical characteristics. The mean of λ is assumed to be $\bar{\lambda} > 0$, while the means of $\alpha_1(\mu), \alpha_2(\mu), \beta_1(\mu), \beta_2(\mu), \gamma_1(\mu)$, and $\gamma_2(\mu)$ are assumed to be 1. Following Just and Pope (1978, 1979) and Love and Buccola (1991), we assume $\sigma_\varepsilon^2 = 1$.

To derive an expression for equation (2.15) we must first derive the amount of chemical applied under the optimal tax ($q(\tau^*,\mu)$) by substituting π_q and σ_q^2 (calculated using equations (2.16) and (2.17)) into equation (2.2) and solving for q:

$$q(\tau^*,\mu) = \frac{\tau - b_1\beta_1(\mu) + \frac{1}{2}\lambda p^2 g_1\gamma_1(\mu)}{b_2\beta_2(\mu) - \frac{1}{2}\lambda p^2 g_2\gamma_2(\mu)} + q^r(\mu). \tag{2.19}$$

Also useful in deriving an expression for equation (2.15) are expressions for the variance and covariance of marginal profit, marginal damage, and marginal variance of profits under the optimal standard:

$$\sigma_{mb}^2 = b_1^2E(\beta_1^2) - b_1^2 \tag{2.20}$$
$$\sigma_{mc}^2 = c_1^2E(\alpha_1^2) - c_1^2 \tag{2.21}$$
$$\sigma_{mv}^2 = p^4g_1^2E(\gamma_1^2) - p^4g_1^2 \tag{2.22}$$
$$v_{bc} = b_1c_1E(\alpha_1\beta_1) - b_1c_1 \tag{2.23}$$
$$v_{bv} = p^2b_1g_1E(\beta_1\gamma_1) - p^2b_1g_1 \tag{2.24}$$
$$v_{cv} = p^2c_1g_1E(\alpha_1\gamma_1) - p^2c_1g_1, \tag{2.25}$$

where σ^2_{mb}, σ^2_{mc}, and σ^2_{mv} denote variances of marginal profit, marginal damage, and marginal variance of profits, and v_{bc}, v_{bv}, and v_{cv} denote the relevant covariances.[11] Also useful is an expression for the variance of the marginal effect of the tax on chemical use:

$$\sigma^2_{sb} = \frac{1}{b_2^2 E(\beta_2^2) + \frac{1}{4}\lambda^2 p^4 g_2^2 E(\gamma_2^2) - \lambda p^2 b_2 g_2} - \frac{1}{(b_2 + \frac{1}{2}\lambda p^2 g_2)^2}. \tag{2.26}$$

Substituting equations (2.19), (2.16), (2.17), and (2.18) into (2.15) yields

$$\begin{aligned}
\Delta \;=\; & S \cdot E_\lambda E_\mu \Bigg\{ \Bigg[b_1\beta_1 \left(\frac{\tau - b_1\beta_1 + \frac{1}{2}\lambda p^2 g_1\gamma_1}{b_2\beta_2 - \frac{1}{2}\lambda p^2 g_2\gamma_2} \right) + \frac{1}{2} b_2\beta_2 \left(\frac{\tau - b_1\beta_1 + \frac{1}{2}\lambda p^2 g_1\gamma_1}{b_2\beta_2 - \frac{1}{2}\lambda p^2 g_2\gamma_2} \right)^2 \\
& -\frac{1}{2}\lambda p^2 [g_1\gamma_1 \left(\frac{\tau - b_1\beta_1 + \frac{1}{2}\lambda p^2 g_1\gamma_1}{b_2\beta_2 - \frac{1}{2}\lambda p^2 g_2\gamma_2} \right) + \frac{1}{2} g_2\gamma_2 \left(\frac{\tau - b_1\beta_1 + \frac{1}{2}\lambda p^2 g_1\gamma_1}{b_2\beta_2 - \frac{1}{2}\lambda p^2 g_2\gamma_2} \right)^2] \\
& -c_1\alpha_1 \left(\frac{\tau - b_1\beta_1 + \frac{1}{2}\lambda p^2 g_1\gamma_1}{b_2\beta_2 - \frac{1}{2}\lambda p^2 g_2\gamma_2} \right) - \frac{1}{2} c_2\alpha_2 \left(\frac{\tau - b_1\beta_1 + \frac{1}{2}\lambda p^2 g_1\gamma_1}{b_2\beta_2 - \frac{1}{2}\lambda p^2 g_2\gamma_2} \right)^2 \Bigg] \mid \tau^* < \pi_1(0,\mu) \Bigg\} + \\
& (1-S) \cdot E_\lambda E_\mu \big\{ \big[-b_1\beta_1 q^r + 0.5 b_2\beta_2 (q^r)^2 - 0.5\lambda p^2 \big(-g_1\gamma_1 q^r + 0.5 g_2\gamma_2 (q^r)^2 \big) + c_1\alpha_1 q^r \\
& -0.5 c_2\alpha_2 (q^r)^2 \big] \mid \tau^* \geq \pi_q(0,\mu) \big\},
\end{aligned} \tag{2.27}$$

where S is the portion of land on which the tax is non-prohibitive. Applying the expectation operators, making use of equations (2.20) - (2.26), and combining and rearranging terms yields

$$\begin{aligned}
\Delta \;=\; & S \Bigg\{ \frac{b_1 - c_1 - \frac{1}{2}\bar{\lambda} p^2 g_1}{b_2 - \frac{1}{2}\bar{\lambda} p^2 g_2} \left(\tau^* - b_1 + \frac{1}{2}\bar{\lambda} p^2 g_1 \right) + \frac{1}{b_2 - \frac{1}{2}\bar{\lambda} p^2 g_2} \left(v_{bc} - \sigma^2_{mb} + \frac{1}{2}\bar{\lambda} v_{bv} \right) + \\
& \frac{\frac{1}{2}\bar{\lambda}}{b_2 - \frac{1}{2}\bar{\lambda} p^2 g_2} \left(v_{bv} - v_{cv} - \frac{1}{2}\bar{\lambda}\sigma^2_{mv} \right) + \frac{(b_2 - c_2 - \frac{1}{2}\bar{\lambda} p^2 g_2) \left[\sigma^2_{sb} (b_2 - \frac{1}{2}\bar{\lambda} p^2 g_2)^2 + 1 \right]}{2(b_2 - \frac{1}{2}\bar{\lambda} p^2 g_2)^2} * \\
& \left[\left(\tau^* - (b_1 - \frac{1}{2}\bar{\lambda} p^2 g_1) \right)^2 + \sigma^2_{mb} + \frac{1}{4}\bar{\lambda}^2 \sigma^2_{mv} - \bar{\lambda} v_{bv} \right] \Bigg\} + \\
& (1-S) \cdot E_\lambda E_\mu \big\{ \big[-b_1\beta_1 q^r + 0.5 b_2\beta_2 (q^r)^2 - 0.5\lambda p^2 \big(-g_1\gamma_1 q^r + 0.5 g_2\gamma_2 (q^r)^2 \big) \\
& +c_1\alpha_1 q^r - 0.5 c_2\alpha_2 (q^r)^2 \big] \mid \tau^* \geq \pi_q(0,\mu) \big\},
\end{aligned} \tag{2.28}$$

where $\bar{\lambda}$ denotes the mean of λ. Substitute the optimal tax into equation (2.28) to further simplify the expression for Δ. To determine the optimal tax, substitute expressions for π_q, D_q, σ^2_q, and $q_\tau(\tau^*, \mu)$ into equation (2.7) and solve for τ^*:

$$\tau^* = \frac{(b_2 - \frac{1}{2}\bar{\lambda} p^2 g_2)(c_1 - b_1 + \frac{1}{2}\bar{\lambda} a p^2 g_1)}{(b_2 - c_2 - \frac{1}{2}\bar{\lambda} p^2 g_2)[\sigma^2_{sb}(b_2 - \frac{1}{2}\bar{\lambda} p^2 g_2)^2 + 1]} + b_1 - \frac{1}{2}\bar{\lambda} p^2 g_1. \tag{2.29}$$

[11]That is, v_{bc} denotes the covariance between marginal profits and marginal damages, v_{bv} denotes the covariance between marginal profits and marginal variance of profits, and v_{cv} denotes the covariance between marginal damages and marginal variance of profits.

Substituting equation (2.29) into (2.28) and rearranging terms yields the final form of the equation that specifies the factors that influence the relative efficiency of standards and taxes in regulating nonpoint pollution given risk-averse producers:

$$
\begin{aligned}
\Delta = S\Bigg\{ & \underbrace{\frac{-\sigma_{mb}^2(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 + c_2)}{2(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2)^2}}_{A} + \underbrace{\frac{v_{bc}}{b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2}}_{B} + \underbrace{\frac{(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 - c_2)\sigma_{sb}^2\sigma_{mb}^2}{2}}_{C} \\
& - \underbrace{\frac{(b_1 - \frac{1}{2}\bar{\lambda}p^2 g_1 - c_1)^2}{2(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 - c_2)[\sigma_{sb}^2(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2)^2 + 1]}}_{D} - \underbrace{\frac{\frac{1}{2}\bar{\lambda}v_{cv}}{b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2}}_{E} \\
& + \underbrace{\frac{\bar{\lambda}v_{bv}}{b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2}\left[1 - \frac{(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 - c_2)[\sigma_{sb}^2(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2)^2 + 1]}{2(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2)}\right]}_{F} \\
& - \underbrace{\frac{\frac{1}{4}\bar{\lambda}^2\sigma_{mv}^2}{b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2}\left[1 - \frac{(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 - c_2)[\sigma_{sb}^2(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2)^2 + 1]}{2(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2)}\right]\Bigg\}}_{G} \\
& + (1 - S) \cdot \underbrace{E_\lambda E_\mu\{q^r\left[D_q(\frac{1}{2}q^r, \mu) - \pi_q(\frac{1}{2}q^r, \mu) - \frac{1}{2}\lambda\sigma_q^2(\frac{1}{2}q^r, \mu)\right] \mid \tau^* \geq}_{H} \\
& \underbrace{\pi_q(0, \mu) - \frac{1}{2}\lambda\sigma_q^2(0, \mu)\}}_{H} .
\end{aligned}
\tag{2.30}
$$

If Δ is positive, the uniform tax is preferred to the uniform standard, whereas if Δ is negative, the uniform standard is preferred. The first three terms of equation (2.30) are analogous to results derived by Weitzman (1974), Malcomson (1978), and Stavins (1996). The fourth term of the S portion of the equation and the first two terms of the $(1-S)$ portion of the equation are analogous to results derived by Wu and Babcock (2001). The remaining terms result from the incorporation of risk aversion.

To assess the impacts of the various terms in equation (2.30) on the relative advantage of a uniform tax versus a uniform standard, we assume the marginal certainty-equivalent profit function, which we denote by MCE(π), is downward-sloping (i.e., $b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 < 0$).[12] The first term of equation (2.30) is similar to the classic Weitzman (1974) result that stipulates that whether a tax or standard is preferable depends upon the relative slopes of the marginal profit (b_2) and marginal damage (c_2) functions. In the presence of risk aversion, the advantage of a tax over a standard depends upon the relative slopes of the marginal certainty-equivalent profit ($b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2$) and marginal damage ($c_2$) functions. If the variance of profit function is linear ($g_2 = 0$), the term reduces to that presented by WB: $\frac{-\sigma_{mb}^2(b_2+c_2)}{2b_2^2}$; only in the presence of a non-linear variance function does the incorporation of risk affect the first term of equation

[12] Although the MCE(π) function could theoretically have a positive, negative, or constant slope, we impose an assumption for tractability. We assume a negative slope, as this is analogous to the more common assumption of a negatively sloped marginal profit function.

(2.30). The analysis provided by WB for marginal profit and marginal damage functions holds for the present context of marginal certainty-equivalent profit and marginal damage functions – when the marginal damage function is steeper than the marginal certainty-equivalent profit function, the uniform standard is preferable, as it yields a smaller deadweight loss than the uniform tax. In contrast, when the marginal certainty-equivalent profit function is steeper than the marginal damage function, the uniform tax is preferable, as the uniform standard yields a larger deadweight loss. The presence of risk aversion may result in a marginal certainty-equivalent profit $[MCE(\pi)]$ function that is more or less steep than the marginal profit function. For this reason, choosing a regulatory mechanism based upon the relative slopes of the marginal profit and marginal damage functions may or may not result in the appropriate mechanism choice.

The second term of equation (2.30) is analogous to Stavins's result, and reflects how the covariance between marginal certainty-equivalent profits and environmental damages affects regulatory mechanism choice. Stavins (1996) showed that an analogous term resulted in an advantage for the standard when the covariance term was positive, and an advantage for the tax when the covariance was negative. The result holds in the presence of risk-aversion. Recall that under a tax, a greater quantity of chemicals will be applied to land with higher marginal certainty-equivalent profits than to land with lower marginal certainty-equivalent profits (*ceteris paribus*), as illustrated by equation (2.2). But if marginal certainty-equivalent profits and marginal environmental damages are positively correlated ($v_{bc} > 0$), the producer's response to the tax implies that more chemicals are being applied to land that yields high marginal environmental damages. Thus in the case of $v_{bc} > 0$, producers' responses to the tax reduce society's preference for the tax and favor the standard. In contrast, if marginal certainty-equivalent profits and marginal environmental damages are negatively correlated ($v_{bc} < 0$), producers' responses to the tax imply that more chemicals are being applied to lands that yield low marginal environmental damages. Thus in the case of $v_{bc} < 0$, producers' responses to the tax increase society's preference for the tax. A positive g_2 will amplify the importance of v_{bc} in determining the preferred regulatory mechanism, whereas a negative g_2 will diminish the importance of v_{bc} in determining the preferred regulatory mechanism.[13] Stavins (1996) demonstrated that if a tax is the mechanism of choice according to Weitzman's relative slope rule, the presence of v_{bc} is likely to reverse this finding. Stavins also showed that the presence of v_{bc} may also reverse a finding of standard superiority based upon the relative slope rule, although this is less likely.

The third term of equation (2.30) depicts the effect on the relative advantage of taxes and standards of the variance of q_τ, denoted by σ^2_{sb}.[14] The equivalent term as presented in WB is $\frac{-c_2\sigma^2_{sb}\sigma^2_{mb}}{2}$. Because $(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 - c_2) < -c_2 < 0$, we can conclude that the third term reduces the value of Δ and thus favors the standard, and that incorporating risk aversion amplifies the impact of σ^2_{sb} on mechanism choice. It is reasonable that the variations in chemical applications that result from farmers' responses to the tax will pose a relative advantage for the standard. Furthermore, the magnitude of the effect of σ^2_{sb} on mechanism choice is

[13]Note that although we have assumed a negatively-sloped certainty-equivalent profit function (i.e., $b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 < 0$), g_2 may still be either negative or positive.

[14]Although σ^2_{sb} also appears in the sixth term of the Δ equation, the sixth term is a new term that arises due to the presence of risk aversion and is thus addressed separately below. Here we focus on how the presence of risk aversion alters the classic results.

amplified by variation in marginal profits (σ^2_{mb}); the larger the variation in marginal profits, the larger the effect on mechanism choice of the variation in farmers' responses to the tax. The effect on mechanism choice of variation in farmers' chemical-use responses to the tax is amplified by a steeper marginal damage function (a larger, more positive c_2) and/or a steeper marginal certainty-equivalent profit function (a larger, more negative b_2).

Corner solutions (first introduced by WB) result from spatial heterogeneity and are reflected in the $(1 - S)$ portion and the fourth term of the S portion of equation (2.30). As discussed by WB, the fourth term of the S portion of the Δ equation is nonnegative. The term is positive if $b_1 - \frac{1}{2}\bar{\lambda}p^2 g_1 \neq c_1$.[15] To assess the circumstances under which $b_1 - \frac{1}{2}\bar{\lambda}p^2 g_1$ does and does not equal c_1, it is helpful to gain an intuitive understanding of the meanings of $b_1 - \frac{1}{2}\bar{\lambda}p^2 g_1$ and c_1. Note that the marginal damage function is $D_q = c_1\alpha_1(\mu) + c_2\alpha_2(\mu)(q - q^r)$. Under the optimal standard this reduces to $D_q = c_1\alpha_1(\mu)$ (refer to equation (2.14)), which means that the expected marginal damage under the optimal standard on lands for which the tax is nonprohibitive is equal to c_1. Similarly, the marginal certainty-equivalent profit function is $\pi_q - \frac{1}{2}\lambda\sigma^2_q = b_1\beta_1(\mu) + b_2\beta_2(\mu)(q - q^r) - \frac{1}{2}\lambda p^2[g_1\gamma_1(\mu) + g_2\gamma_2(\mu)(q - q^r)]$. Under the optimal standard this reduces to $\pi_q - \frac{1}{2}\lambda\sigma^2_q = b_1\beta_1(\mu) - \frac{1}{2}\lambda p^2 g_1\gamma_1(\mu)$, and thus the expected marginal certainty-equivalent profit under the optimal standard on lands for which the tax is nonprohibitive is equal to $b_1 - \frac{1}{2}\lambda p^2 g_1$. We are now able to state that $b_1 - \frac{1}{2}\lambda p^2 g_1 = c_1$ indicates equivalence between the expected marginal damage function and the expected marginal certainty-equivalent profit function under the optimal standard on land where tax is nonprohibitive. Equivalence of $b_1 - \frac{1}{2}\lambda p^2 g_1$ and c_1 only occurs when the standard is binding for land where the tax is nonprohibitive. Nonequivalence of $b_1 - \frac{1}{2}\lambda p^2 g_1$ and c_1 occurs when the standard is nonbinding on land where the tax is nonprohibitive, which is most likely to occur when low levels of chemical use yield a large marginal certainty-equivalent profit (implying that chemical use will be profitable under the tax), but marginal certainty-equivalent profits decline rapidly (implying the standard will be nonbinding).

The $(1 - S)$ portion of the equation represents the difference in the mechanisms' efficiencies that results from the presence of corner solutions (lands for which the uniform tax is prohibitive). The first two terms in this portion of the equation were first introduced by WB, whereas the third term in this portion of the equation results from the presence of risk aversion. Recall that Weitzman's classic relative slope rule (the first term of the Δ equation) indicates that for lands where the tax is nonprohibitive, a tax (standard) is preferred when the marginal damage function is less (more) steep than the marginal certainty-equivalent profit function. As is depicted in Figure 2.1, this relationship does not hold for lands where the tax is prohibitive. Figure 2.1 is drawn to represent a parcel of land on which the tax is prohibitive; the tax is prohibitive since it is set at a level such that $\tau^* > \pi_q(q = 0)$. The top panel presents the case of relatively low marginal damages that are less sensitive to the input level (relative to marginal profits). Deadweight loss is less under the standard than under the tax.[16] That is, when the tax is prohibitive and the marginal damage function is

[15] The term is nonnegative due to the assumptions of a non-positively sloped marginal certainty-equivalent profit function (i.e., $b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 \leq 0$) and a non-negatively sloped marginal damage function (i.e., $c_2 \geq 0$).

[16] In both panels the deadweight loss under a tax is denoted by area A, the deadweight loss under the standard is denoted by area B, and the advantage of a tax (the area denoted by the $(1-S)$ portion of the Δ equation) is given by area $(B - A)$. To see that in the top panel area $(B - A)$ denotes the $(1 - S)$ portion of equation (2.30) in the absence of risk aversion, note that the area of triangle $(B + C)$ is given by $q^r D_q(\frac{1}{2}q^r)$

relatively low and flat in comparison to the marginal profit function, spatial heterogeneity tends to favor the standard and may reverse the Weitzman result. Conversely, the bottom panel presents the case of relatively high marginal damages that are more sensitive to the input level. Deadweight loss is greater under the standard than under the tax. Thus when the tax is prohibitive and the marginal damage function is relatively high and steep in comparison to the marginal profit function, spatial heterogeneity tends to favor the tax and may reverse the Weitzman result.

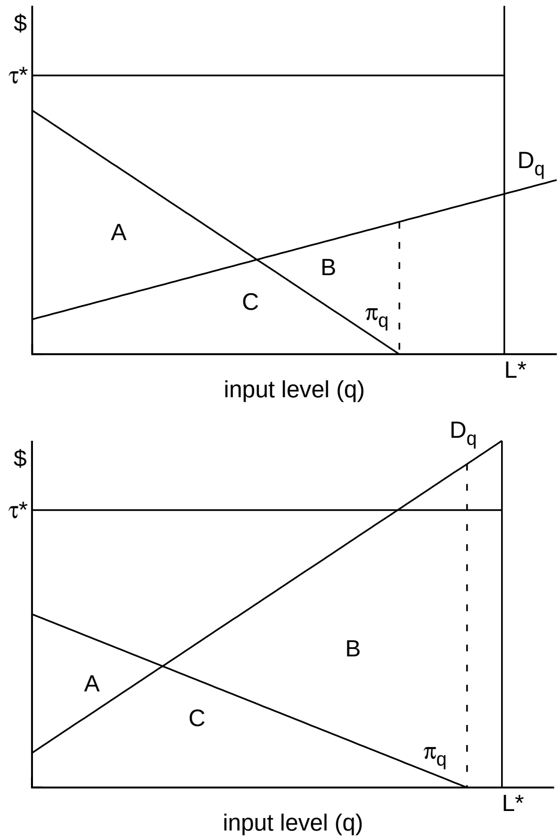


Figure 2.1. The Effect of Corner Solutions on Mechanism Choice

The presence of risk aversion may affect the intercept and/or slope of the marginal certainty-equivalent profit function, and therefore influences the relative efficiency of taxes and standards. For the case of a prohibitive tax and relatively low marginal damages that are less sensitive to the input level, if the incorporation of risk causes the intercept and/or slope of the marginal certainty-equivalent profit function to be greater than those of the marginal profit function then risk-averse behavior increases the preference for the standard caused by spatial heterogeneity. Similarly, for the case of a prohibitive tax and relatively high marginal damages that are more sensitive to the input level, if the incorporation of risk causes the intercept and/or slope of the marginal certainty-equivalent profit function to be less than

and the area of triangle $(A + C)$ is given by $q^r \pi_q(\frac{1}{2}q^r)$, and thus the difference between the two areas is $(B - A) = (B + C) - (A + C) = q^r[D_q(\frac{1}{2}q^r) - \pi_q(\frac{1}{2}q^r)]$. A similar argument holds for the bottom panel.

those of the marginal profit function then risk-averse behavior increases the preference for the tax caused by spatial heterogeneity. Otherwise risk aversion will diminish the potential of spatial heterogeneity to cause a reversal of the Weitzman result.

We now turn to discussing terms in the Δ equation that are specific to the current specification, i.e., terms that arise due to the incorporation of risk aversion:

$$-\frac{\frac{1}{2}\bar{\lambda}v_{cv}}{b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2}, \tag{2.31}$$

$$\frac{\bar{\lambda}v_{bv}}{b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2}\left[1 - \frac{(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 - c_2)[\sigma_{sb}^2(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2)^2 + 1]}{2(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2)}\right], \text{and} \tag{2.32}$$

$$-\frac{\frac{1}{4}\bar{\lambda}^2\sigma_{mv}^2}{b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2}\left[1 - \frac{(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 - c_2)[\sigma_{sb}^2(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2)^2 + 1]}{2(b_2 - \frac{1}{2}\bar{\lambda}p^2 g_2)}\right]. \tag{2.33}$$

The sign of equation (2.31) depends upon the sign of v_{cv}, the covariance between marginal environmental damages (D_q) and marginal variance of profits (σ_q^2). A negative covariance between D_q and σ_q^2 favors the standard, whereas a positive covariance favors the tax. Assuming $D_q > 0$, v_{cv} will be positive for risk-increasing inputs but negative for risk-decreasing inputs. To gain an intuitive understanding of this result, recall from equation (2.2) that producers will use more chemicals on land with a high marginal certainty-equivalent profit, i.e., a low marginal variance of profits, *ceteris paribus*. If the marginal variance of profits and marginal environmental damage functions are positively correlated, land with a low marginal variance of profits will tend to have lower marginal pollution costs. Thus with $v_{cv} > 0$, farmers' responses to the tax make the tax more efficient. However, if marginal variance of profits and marginal damages are negatively correlated, land with a low marginal variance of profits will tend to have high marginal pollution costs. Thus in the case of $v_{cv} < 0$, farmers' responses to the tax make the tax less efficient and therefore favor the standard.

Assessing the impacts of the terms depicted in equations (2.32) and (2.33) is complicated by the fact that the sign of the term in large square brackets is ambiguous. Let us first address the term presented in equation (2.32), which presents how the covariance of marginal profits and the marginal variance of profits (v_{bv}) affects mechanism choice. The ability to determine the effect of this term on mechanism choice is also hindered by ambiguity pertaining to the sign of v_{bv}. In order to sign v_{bv} we must impose assumptions regarding whether q is a risk-increasing or risk-decreasing input. Suppose we are moving in the direction of an increase in q, which implies $\pi_q > 0$. If q is a risk-increasing (-decreasing) input, as more q is applied the variance in production and therefore profits increases (decreases), i.e., $\sigma_q^2 > 0$ ($\sigma_q^2 < 0$). Therefore, for risk-increasing (-decreasing) inputs $v_{bv} > 0$ ($v_{bv} < 0$). Although we have imposed assumptions that enable us to sign the left portion of equation (2.32), we are not able to determine whether the term represented in equation (2.32) will be positive or negative, as the sign of the term in large square brackets is ambiguous. Therefore, the effect on mechanism choice of the covariance of marginal profits and marginal variance of profits is indeterminate. Similarly, the effect on mechanism choice of the term presented by equation (2.33) is indeterminate; although clearly the variance of the marginal variance of profits is nonnegative ($\sigma_{mv}^2 > 0$), the sign of the term in large square brackets is again ambiguous.

To summarize, we are able to determine with certainty the effect of including risk aversion on the sign of some of the risk-related terms in equation (2.30), but are not able to do so for other terms. The overall effect of risk aversion on the relative efficiency of a uniform standard versus a uniform tax is therefore uncertain and must be assessed on a case-by-case basis. To demonstrate how risk aversion might affect regulatory mechanism choice, in the next section we present an expanded version of a numerical example presented by WB.

Table 2.1: Summary of Theoretical Model Results

Term[a]	Favored mechanism	Condition/Comment
A	standard	if $\lvert c_2\rvert > \lvert b_2 - \frac{1}{2}\bar{\lambda}p^2g_2^2\rvert$ (marginal damage function is steeper than marginal certainty equivalent profit function)
	tax	if $\lvert c_2\rvert < \lvert b_2 - \frac{1}{2}\bar{\lambda}p^2g_2^2\rvert$ (marginal damage function is flatter than marginal certainty equivalent profit function)
B	tax	if $v_{bc} > 0$ (marginal profits and marginal environmental damages are positively correlated)
	standard	if $v_{bc} < 0$ (marginal profits and marginal environmental damages are negatively correlated)
C	standard	
D	tax	
E	tax	if $v_{vc} > 0$ (marginal variance of profits and marginal environmental damage functions are positively correlated; i.e., risk-increasing inputs)
	standard	if $v_{vc} < 0$ (marginal variance of profits and marginal environmental damage functions are negatively correlated; i.e., risk-decreasing inputs)
F	ambiguous	sign of term in square brackets is indeterminate
G	ambiguous	sign of term in square brackets is indeterminate
H	tax	if $\lvert c_2\rvert > \lvert b_2 - \frac{1}{2}\bar{\lambda}p^2g_2^2\rvert$ (marginal damage function is steeper than marginal certainty equivalent profit function)
	standard	if $\lvert c_2\rvert < \lvert b_2 - \frac{1}{2}\bar{\lambda}p^2g_2^2\rvert$ (marginal damage function is flatter than marginal certainty equivalent profit function)

[a] Refer to underbraces in equation (2.30) on page 16.

2.3 Numerical Example of the Importance of Risk Aversion

The numerical example presented below (an extension of the model used by WB) simulates corn production in the Oklahoma high plains where nonpoint pollution in the form of nitrogen runoff from agricultural fields is of concern. WB demonstrate that corner solutions, which arise as a result of spatial heterogeneity, can reverse a mechanism choice made using Weitzman's relative slope rule.[17] We demonstrate that risk aversion can reverse a mechanism choice made based upon the assumption of risk neutrality. The example presented below is based on information provided in WB and Wu et al. (1994).

Spatial heterogeneity is incorporated by modeling production on the region's two dominant soil types – Richfield clay loam and Dalhart fine sandy loam. The expected marginal products of corn on the Richfield and Dalhart soils are $MP^R = 9.63 - 0.44q$ and $MP^D = 5.85 - 0.2q$, respectively, where q denotes effective water (water utilized by the corn crop) and superscripts R and D denote the Richfield and Dalhart soil types. If we assume the price of corn is \$2 per bushel and the price of effective water is \$8 per acre foot, this results in the following marginal profit functions: $\pi_q^R = 11.26 - 0.88q$ and $\pi_q^D = 3.70 - 0.40q$. In the absence of regulations water applications will occur where $\pi_q = 0$; 12.8 acre feet of water will be applied to Richfield soils and 9.25 acre feet of water will be applied to Dalhart soils, i.e., $q_0^R = 12.8$ and $q_0^D = 9.25$. The expected marginal runoff functions on the two soil types are $MR^R = -0.73 + 0.11q$ and $MR^D = 1.62 - 0.05q$. Using parameter estimates reported in Wu et al. (1994), WB calculate the variance of marginal profits to be 6.61 on the Richfield soil when $q = 0$, and assume σ_{mb}^{R2} takes this value ($\sigma_{mb}^{R2} = 6.61$). Altough growing conditions are such that nitrogen leaching and runoff are highly correlated with irrigation and thus regulations to control nonpoint pollution could be imposed on either nitrogen applications or irrigation, we assume taxes and standards are imposed on the use of irrigation water. (Assumed values are summarized in Table 2.2.)

Table 2.2: Summary of Values Used in Empirical Analysis

Term	Value(s)
marginal product of corn on Richfield soils	$MP^R = 9.63 - 0.44q$
marginal product of corn on Dalhart soils	$MP^D = 5.85 - 0.2q$
marginal runoff on Richfield soils	$MR^R = -0.73 + 0.11q$
marginal runoff on Dalhart soils	$MR^D = 1.62 - 0.05q$
price of corn	$p = \$2/\text{bushel}$
price of effective water	$p_w = \$8/\text{acre foot}$
variance of marginal profits on Richfield soils	$\sigma_{mb}^{R2} = 6.61$
mean Arrow-Pratt absolute risk aversion coefficients	$\bar{\lambda} = 0.538,\ 3.272$
slope of the marginal variance of profits	$g_2 = 0, 0.4, 1, -0.1, -0.4, -0.6$

[17]Corner solutions refer to the possibility that the uniform tax is prohibitive for some lands and thus $q(\tau, \mu)$ is set equal to zero for those lands (refer to discussion pertaining to equation (2.2) on page 11).

Table 2.2 (continued)

Term	Value(s)
covariance between marginal environmental damages and marginal variance of profits	v_{cv} = 0, 10, 30, -10, -30

WB impose assumptions that eliminate all but the Weitzman result from the S portion of the equation, thereby enabling them to focus on how the presence of corner solutions (represented by the $(1-S)$ portion of the Δ equation) might reverse a regulation decision made based upon Weitzman's relative slope rule. We impose these same assumptions. Assume marginal profit (π_q) and marginal nitrogen runoff (D_q) are uncorrelated, i.e., $v_{bc} = 0$, and thereby eliminate the second term of equation (2.30). Assume the marginal pollution cost of nitrogen runoff is so high that farms located on Dalhart soils will not irrigate under the tax (recall that as the marginal pollution cost increases, τ^* increases – see equation (2.29)). As a result of this assumption the S portion of equation (2.30) is applicable only to Richfield soils while the $(1-S)$ portion is applicable only to Dalhart soils. The presence of the fourth term in the Δ equation stems from the fact that while expected marginal certainty-equivalent profit equals expected marginal pollution damages $[E(MCE(\pi)) = E(D_q)]$ on land for which the tax is nonprohibitive, this equivalence is not guaranteed under the standard. The fourth term disappears when land for which the standard is binding is the same as that for which the tax is nonprohibitive. As a result of WB's assumption that the tax is nonprohibitive and the standard is binding on Richfield soils, the fourth term of the Δ equation disappears.[18] The corollary to this assumption is that the standard is nonbinding on Dalhart soils. We can therefore replace $q^r(\mu)$ in the $(1-S)$ portion of the equation with the value $q_0^D = 9.25$. Recall that σ_{sb}^2 denotes the marginal effect of the tax on the application rate of q. The assumption made by WB that the tax is nonprohibitive on only one type of soil (Richfield soils) implies that there is no variation in the marginal effect of the tax on the application rate of q and thus $\sigma_{sb}^{R2} = 0$. As a result, the third term of the Δ equation disappears and the sixth and

[18]This can be demonstrated mathematically as follows. Recall from equation (2.13) that the optimal standard equates the expected marginal certainty-equivalent profit and the mean marginal pollution damage on land where the standard is binding:

$$E_\lambda E_\mu\{[\pi_q(L^*,\mu) - \frac{1}{2}\lambda\sigma_q^2(L^*,\mu)] \mid q^0(\mu) \geq L^*\} = E_\lambda E_\mu\{D_q(L^*,\mu) \mid q^0(\mu) \geq L^*\}.$$

Because the standard is binding and the tax is nonprohibitive on the same land (Richfield soils), we can rewrite this as

$$E_\lambda E_\mu\{[\pi_q(q^r(\mu),\mu) - \frac{1}{2}\lambda\sigma_q^2(q^r(\mu),\mu)] \mid \tau^* < \pi_q(0,\mu)\} = E_\lambda E_\mu\{D_q(q^r(\mu),\mu) \mid \tau^* < \pi_q(0,\mu)\}.$$

Taking first order partial derivatives of equations (2.16), (2.17), and (2.18) with respect to q, evaluating at $(q^r(\mu),\mu)$, and substituting into this equation yields $E_\lambda E_\mu\{b_1\beta_1(\mu) - \frac{1}{2}\lambda p^2 g_1\gamma_1(\mu)\} = E_\lambda E_\mu\{c_1\alpha_1(\mu)\}$, which simplifies to $b_1 - \frac{1}{2}\bar{\lambda}p^2 g_1 - c_1 = 0$.

seventh terms simplify to[19]

$$\frac{\bar{\lambda}v^R_{bv}}{b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g_2}\left[1 - \frac{(b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 - c^R_2)}{2(b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g_2)}\right], \text{and} \tag{2.34}$$

$$-\frac{\frac{1}{4}\bar{\lambda}^2\sigma^{R2}_{mv}}{b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g_2}\left[1 - \frac{(b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g_2 - c^R_2)}{2(b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g_2)}\right]. \tag{2.35}$$

Imposing the same assumptions as those imposed by WB simplifies equation (2.30) to

$$\begin{aligned}\Delta \;=\; & S\Bigg\{\frac{-\sigma^{R2}_{mb}(b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g^R_2 + \psi r^R_2)}{2(b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g^R_2)^2} - \frac{\frac{1}{2}\bar{\lambda}v^R_{cv}}{b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g^R_2} + \frac{\bar{\lambda}v^R_{bv}}{b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g^R_2} * \\ & \left[1 - \frac{(b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g^R_2 - \psi r^R_2)}{2(b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g^R_2)}\right] - \frac{\frac{1}{4}\bar{\lambda}^2\sigma^{R2}_{mv}}{b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g^R_2}\left[1 - \frac{(b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g^R_2 - \psi r^R_2)}{2(b^R_2 - \frac{1}{2}\bar{\lambda}p^2 g^R_2)}\right]\Bigg\} \\ & +(1-S)\cdot E_\lambda E_\mu q^D_0\big\{\psi MR^D(\frac{1}{2}q^D_0) - \pi^D_q(\frac{1}{2}q^D_0) - \sigma^{D2}_q(\frac{1}{2}q^D_0)\big\},\end{aligned} \tag{2.36}$$

whereas the Δ equation as presented by WB takes the form

$$\begin{aligned}\Delta \;=\; & S\left\{\frac{-\sigma^{R2}_{mb}(b^R_2 + \psi r^R_2)}{2b^{R2}_2}\right\} + (1-S)\cdot E_\lambda E_\mu q^D_0\big\{\psi MR^D(\frac{1}{2}q^D_0) - \pi^D_q(\frac{1}{2}q^D_0) \mid \\ & \tau^* \geq \pi_q(0,\mu) - \frac{1}{2}\lambda\sigma^2_q(0,\mu)\big\}.\end{aligned} \tag{2.37}$$

Note that in equations (2.36) and (2.37) c_2 has been rewritten as $r_2\psi$, where r_2 denotes the slope of the marginal runoff function and ψ is the marginal cost of runoff. In this initial analysis of the effects of risk preferences on mechanism choice we wish to only consider how the presence of risk aversion affects those terms previously derived in the literature. We therefore assume the marginal variance of profits and marginal nitrogen runoff are uncorrelated ($v_{cv} = 0$) and thereby eliminate the second term of equation (2.36). This assumption seems a reasonable extension to the WB assumption that marginal profit and marginal nitrogen runoff are uncorrelated. We eliminate the third term of equation (2.36) by assuming the covariance of marginal profits and marginal variance of profits is zero ($v_{bv} = 0$), and the fourth term by assuming the variance of the marginal variance of profits is zero ($\sigma^2_{mv} = 0$). The $(1-S)$ portion of equation (2.36) is simplified by assuming the marginal variance of profits evaluated at $\frac{1}{2}q_0$ is equal to zero for the Dalhart soils ($\sigma^{D2}_q(\frac{1}{2}q^D_0) = 0$).

Derivation of the Weitzman result requires that we impose two additional assumptions: risk neutrality ($\bar{\lambda} = 0$) and the absence of corner solutions ($(1-S)$=0). The Weitzman form of the Δ equation is thus

$$\Delta = -\{0.47\psi - 3.76\}. \tag{2.38}$$

Setting $\Delta = 0$ and solving for ψ (the marginal cost of runoff) yields the value of ψ for which the uniform tax and uniform standard are equally efficient and neither has a comparative

[19] Note that although the terms are now in a simpler form, their signs are still indeterminate and thus we cannot determine whether the terms favor the uniform tax or standard.

advantage, which in the Weitzman case occurs at $\psi = 8.0$. The classic Weitzman result is that the preferred regulatory mechanism depends upon the relative slopes of the marginal damage and marginal profit functions. When the marginal damage function is steeper than the marginal benefit (profit) function, it is preferable to use a standard, whereas a tax is preferred when the marginal benefit function is steeper than the marginal damage function. Therefore, to the left of $\psi = 8.0$ the marginal benefit function is steeper and a tax is preferred; to the right of $\psi = 8.0$ the marginal damage function is steeper and a standard is preferred.[20]

The WB result is derived by relaxing the assumption of no corner solutions (spatial heterogeneity), and setting the resulting Δ equation,

$$\Delta = -S\{0.47\psi - 3.76\} + (1 - S)\{12.84\psi - 17.09\}, \tag{2.39}$$

equal to zero and solving for ψ as a function of $(1-S)$.[21] WB assess when spatial heterogeneity would reverse a regulatory mechanism recommendation arrived at using Weitzman's classic relative slope rule. As noted previously, spatial heterogeneity introduces the possibility of corner solutions — the possibility that on certain lands $q(\tau, \mu)$ will be set equal to zero under the uniform tax. The S portion of equation (2.39) represents Weitzman's relative slope rule, whereas the $(1 - S)$ portion represents the impact of corner solutions. With spatial heterogeneity incorporated, WB demonstrate that if $\psi < 1.33$ and if corner solutions occur on a large portion of land, the Weitzman recommendation is reversed — a standard should be used rather than a tax (Figure 2.2).[22] (In the figures used to illustrate the results, areas colored red indicate that a tax is preferred, whereas areas colored blue indicate that a standard is preferred.) For example, if $\psi = 0.25$ and corner solutions occur on at least 20% of the regulated farmland, then rather than the tax (as recommended by the Weitzman result) the WB result suggests use of a standard. WB also demonstrate that reversal of the Weitzman result is almost certain when $\psi > 8$; the presence of corner solutions on less than 1% of land is sufficient to reverse the Weitzman recommendation, implying that a tax is preferred rather than a standard.

For an explanation of how the inclusion of corner solutions may reverse the Weitzman result, refer to the discussion regarding Figure 2.1 on page 19. In brief, at low (high) values of ψ, marginal profits tend to be higher (lower) and more (less) sensitive to q than marginal damages. As a result, on lands where the tax is prohibitive the deadweight loss associated with the tax is larger (smaller) than that associated with the standard. The standard (tax) is thus preferred when ψ is sufficiently low (high) and the tax is prohibitive on a sufficiently large quantity of land.

We now turn to assessing the impact of risk aversion on mechanism choice. We begin by

[20]Recall that the slope of the marginal damage function is $c_2 = r_2\psi$, and thus the slope of the marginal damage function increases as ψ increases.

[21]Equation (2.39) differs from equation (21) provided in WB due to a calculation error made in WB.

[22]Note that the Weitzman result, which does not account for corner solutions and thus is represented along the x-axis where $(1 - S) = 0$, is also depicted in Figure 2.2. The value of Δ is positive and thus the graph is red when $(1 - S) = 0$ and $\psi < 8.0$, implying the tax is preferred. Alternately, when $(1 - S) = 0$ and $\psi > 8.0$, Δ is negative and the graph is blue, indicating the standard is preferred.

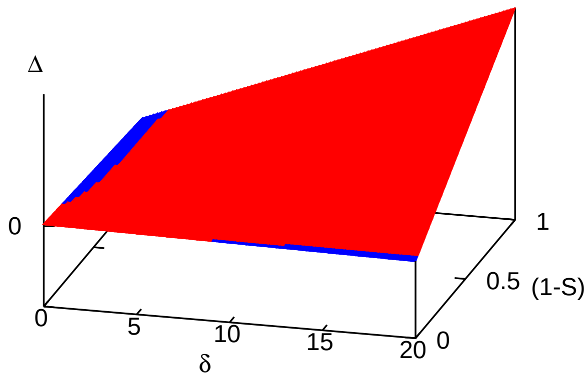


Figure 2.2. Wu and Babcock Result

assessing the impact of risk aversion in its simplest form:

$$\begin{aligned}\Delta \;=\; & S\left\{\frac{-\sigma_{mb}^{R2}(b_2^R - \frac{1}{2}\bar{\lambda}p^2 g_2^R + \psi r_2^R)}{2(b_2^R - \frac{1}{2}\bar{\lambda}p^2 g_2^R)^2}\right\} + \\ & (1-S)\cdot E_\lambda E_\mu q_0^D\{\psi MR^D(\frac{1}{2}q_0^D) - \pi_q^D(\frac{1}{2}q_0^D)\},\end{aligned} \tag{2.40}$$

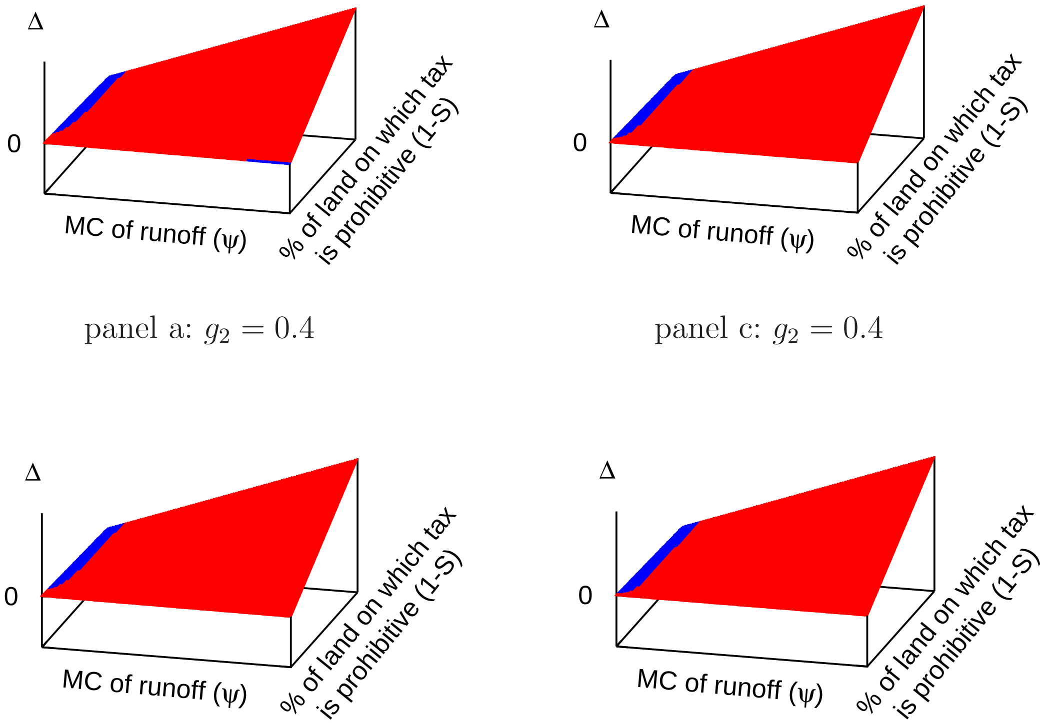
which requires assuming non-zero values for both $\bar{\lambda}$ and g_2. The empirical risk aversion literature provides a wide range of estimated λ values; in the literature reviewed above estimated values range from 0.0045 for small Kansas wheat farmers (Saha et al., 1994) to 15.922 for US corn and soybean producers (Chavas and Holt, 1996). To illustrate how varying degrees of absolute risk aversion can impact optimal regulatory mechanism choice, we assume two different values for $\bar{\lambda}$: 0.538 and 3.272 (Love and Buccola, 1991; Antle, 1987).[23]

In the presence of risk aversion the MCE(π) function will be steeper than the π_q function and g_2 will be positive if the input in question is risk-increasing. Conversely, if the input is risk-decreasing the MCE(π) function will be flatter than the π_q function and g_2 will be negative. In the analysis below we therefore use positive g_2 values to assess the impacts of risk-increasing inputs and negative g_2 values to assess the impacts of risk-decreasing inputs. Although for the risk-increasing case there are no restrictions on how large g_2 may be (the slope of the MCE(π) function simply approaches negative infinity as $g_2 \to \infty$), there are restrictions on the value of g_2. For risk-decreasing inputs, the more negative g_2 becomes the flatter the MCE(π) function becomes, and at sufficiently large negative values of g_2 the MCE(π) could become positively sloped. To avoid such an eventuality, for the case of risk-decreasing inputs we place the following restrictions on g_2 when $\bar{\lambda} = 0.538$ and $\bar{\lambda} = 3.272$: $-0.80 < g_2 < 0$ and $-0.1 < g_2 < 0$.

[23]The $\bar{\lambda}$ values are intended to reflect moderate and more severe risk aversion, although given the broad range of estimated values available in the literature it is difficult to assess what values indeed do represent moderate and high risk aversion.

We initially allow risk aversion to affect only Weitzman's relative slope term. Figure 2.3 illustrates results for a risk-increasing input. Panels a and b present results for moderate risk aversion; panels c and d present results for high risk aversion. Accounting for risk-averse behavior in the presence of risk-increasing inputs causes two effects in Weitzman's relative-slope term: (1) the slopes of the marginal benefit function changes (π_q becomes $MCE(\pi)$) and (2) the denominator of the relative slope term changes. The values assumed for this numerical example, the second effect dominates. That is, for case of risk-increasing inputs, the denominator of the Weitzman term becomes larger than for the risk-neutrality case, and thereby diminishes the impact of the Weitzman term on the regulatory mechanism choice. Corner solutions thus dominate the regulatory mechanism choice.

moderate risk aversion ($\bar{\lambda} = 0.538$) **high risk aversion** ($\bar{\lambda} = 3.272$)



panel a: $g_2 = 0.4$

panel c: $g_2 = 0.4$

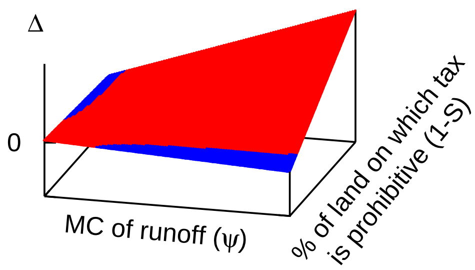
panel b: $g_2 = 1$

panel d: $g_2 = 1$

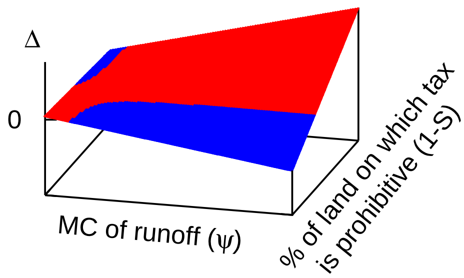
Figure 2.3. Effect of Risk Aversion (in Simplest Form) with Risk-Increasing Inputs

For the values used in our analysis, the effect of risk aversion on mechanism choice is more dramatic when we assume a risk-decreasing input (see Figure 2.4). Panels a and b present results for moderate risk aversion; panel c presents results for high risk aversion. As with risk-increasing inputs, accounting for risk-averse behavior in response to risk-decreasing inputs causes two effects in the relative-slope term: (1) the slope of the marginal benefit function changes and (2) the denominator of the relative slope term changes. Let us first examine the effect on relative slopes. For the case of risk-averse behavior and risk-decreasing inputs, the MCE(π) function is flatter than the π_q function. This changes the relative slopes of the marginal damage function and marginal benefit function (where the marginal benefit function is π_q for the case of risk-neutrality and $MCE(\pi)$ for the case of risk aversion). If the marginal cost of runoff (ψ) is high, implying that D_q is steep relative to the marginal benefit function, then the inclusion of risk aversion increases the relative steepness of the marginal damage function, and thereby increases the preference for the standard. This is precisely the result depicted in Figure 2.4; preference for the standard increases at high values of ψ. In contrast, if the marginal cost of runoff is low (i.e., D_q is flat relative to the marginal benefit function), the inclusion of risk aversion decreases the relative flatness of the D_q function and therefore decreases the preference for the tax. However, this is *not* the result depicted in Figure 2.4. Rather, for low values of ψ the preference for the tax is *greater* than that which occurs under the assumption of risk-neutrality. The reason for the discrepancy stems from the effect of risk aversion on the denominator of the relative-slope term. When g_2 is negative, the denominator of the relative slope term becomes less than one (although still positive), which serves to amplify the importance of the Weitzman term in determining the preferred regulatory mechanism.

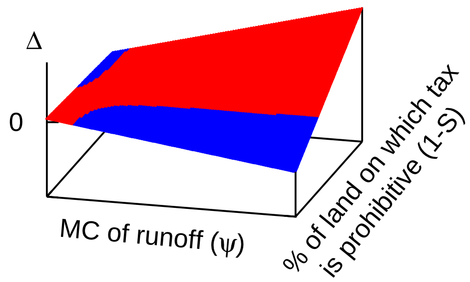
moderate risk aversion ($\bar{\lambda} = 0.538$) **high risk aversion** ($\bar{\lambda} = 3.272$)



panel a: $g_2 = -0.4$



panel c: $g_2 = -0.1$



panel b: $g_2 = -0.6$

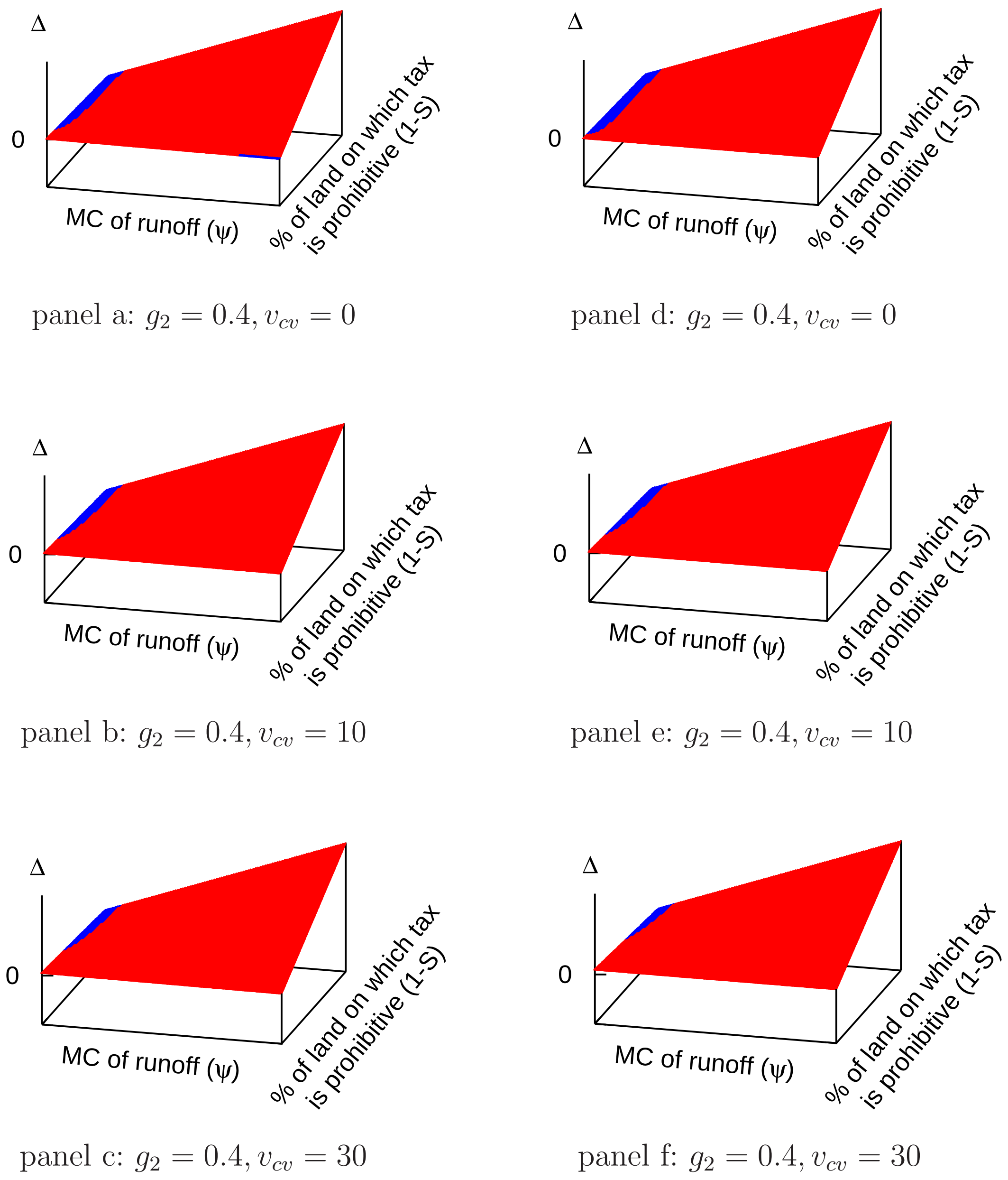
Figure 2.4. Effect of Risk Aversion (in Simplest Form) with Risk-Decreasing Inputs

We next include risk aversion in a slightly more complex form by allowing for non-zero v_{cv} values. The relevant Δ equation is thus of the form

$$\begin{aligned}\Delta &= S\Bigg\{\frac{-\sigma_{mb}^{R2}(b_2^R - \frac{1}{2}\bar{\lambda}p^2 g_2^R + \psi r_2^R)}{2(b_2^R - \frac{1}{2}\bar{\lambda}p^2 g_2^R)^2} - \frac{\frac{1}{2}\bar{\lambda}v_{cv}^R}{b_2^R - \frac{1}{2}\bar{\lambda}p^2 g_2^R}\Bigg\} \\ &\quad +(1-S)\cdot E_\lambda E_\mu q_0^D\big\{\psi MR^D(\frac{1}{2}q_0^D) - \pi_q^D(\frac{1}{2}q_0^D)\big\}. \end{aligned} \tag{2.41}$$

Recall from our discussion of the theoretical model that v_{cv} denotes the covariance of the marginal damages (D_q) and marginal variance of profits (σ_q^2), and thus positive v_{cv} values are associated with risk-increasing inputs, while negative v_{cv} values are associated with risk-decreasing inputs. As illustrated in Figure 2.5, a positive covariance between D_q and π_q favors the tax. In contrast, a negative covariance favors the standard (see Figure 2.6). As expected, the effect of v_{cv} on the choice of regulatory mechanism is larger when producers are more risk-averse. Table 2.3 provides a summary of the empirical results.

moderate risk aversion ($\bar{\lambda} = 0.538$) **high risk aversion** ($\bar{\lambda} = 3.272$)



panel a: $g_2 = 0.4, v_{cv} = 0$

panel d: $g_2 = 0.4, v_{cv} = 0$

panel b: $g_2 = 0.4, v_{cv} = 10$

panel e: $g_2 = 0.4, v_{cv} = 10$

panel c: $g_2 = 0.4, v_{cv} = 30$

panel f: $g_2 = 0.4, v_{cv} = 30$

Figure 2.5. Effect of Risk Aversion with Risk-Increasing Inputs and Non-Zero v_{cv}

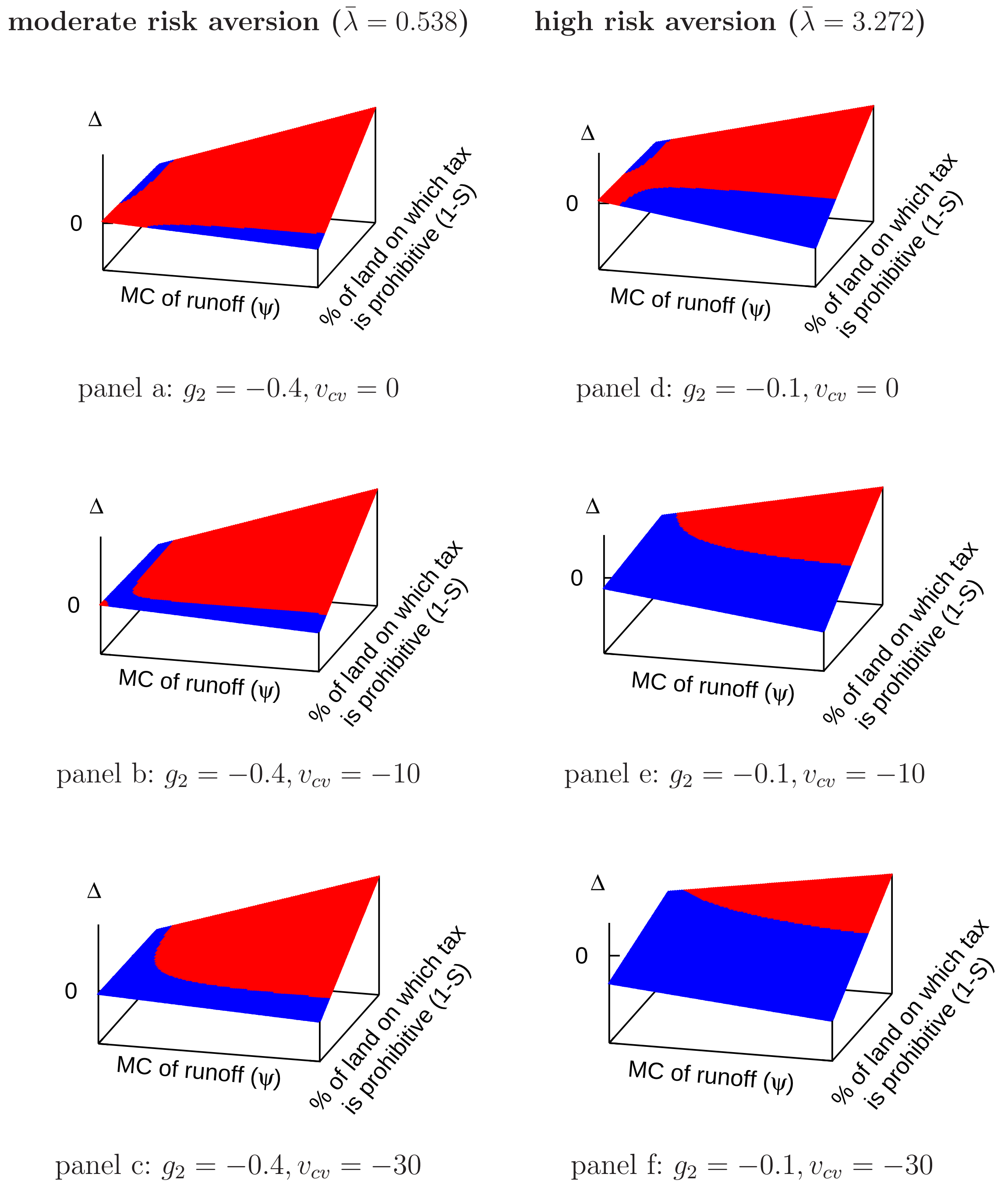


Figure 2.6. Effect of Risk Aversion with Risk-Decreasing Inputs and Non-Zero v_{cv}

Table 2.3: Summary of Empirical Results

Δ Equation Term	Preferred Regulatory Mechanism
Risk neutrality results	
Weitzman's relative slope	Tax preferred if $\psi < 8$. Standard preferred if $\psi > 8$.
WB's corner solutions	Corner solutions are likely to reverse Weitzman result & create preference for standard if $\psi < 1.33$. Weitzman result holds (tax preferred) if $1.33 < \psi < 8$. Corner solutions are almost certain to reverse Weitzman result & create preference for tax if $\psi > 8$.
Risk aversion affects Weitzman term only[a]	
Risk-increasing input	Corner solutions are more likely to reverse Weitzman result
Risk-decreasing input	Corner solutions are less likely to reverse Weitzman result
Risk aversion affects Weitzman term & $v_{cv} \neq 0$	
Risk-increasing input	Increases preference for tax.
Risk-decreasing input	Increases preference for standard.

2.4 Discussion and Conclusions

Our theoretical model illustrates that risk aversion affects terms previously derived in this line of literature and also introduces new terms. Although some terms clearly favor use of either a tax or standard under certain conditions, the effect of other terms on the relative efficiency of taxes and standards is ambiguous. More specifically, results from the theoretical model show that incorporating risk aversion affects the magnitude and relative magnitude of terms previously derived in the literature, but does not change the basic results previously derived. For example, from the theoretical model we are able to determine that although risk aversion does affect the Weitzman (1974) relative slope term, the basic result remains — a standard (tax) is preferred when the marginal damage function is steeper (flatter) than the marginal certainty-equivalent profit function. Similarly, incorporating risk aversion does not alter the basic result derived by Stavins (1996) — a negative (positive) covariance between marginal certainty-equivalent profits and marginal damages favors the tax (standard). The basic results derived by Wu and Babcock (2001) regarding the effect of spatial heterogeneity on mechanism preference are also unchanged: (1) variance in q_τ creates a preference for the standard, and (2) for lands where the tax is prohibitive, the mechanism preference that arises from the relative slopes of the MCE(π) and D_q functions is opposite of that for lands where the tax is nonprohibitive. Several new terms arise as a result of risk aversion — terms pertaining to the influence on mechanism choice of the covariance between D_q and σ_q^2 (which favors the tax if positive and favors the standard if negative), the covariance of π_q and σ_q^2

(the effect of which is ambiguous), and the variance of the marginal variance of profits (which also has an ambiguous effect).

We are unable to state with certainty the effect of risk aversion on regulatory mechanism choice: the overall impact of producers' (farmers') risk-averse behavior on the choice of regulatory mechanism depends upon site- and case-specific factors (such as soils, slopes, the type of input (risk-increasing or -decreasing), and the degree of farmers' risk aversion) and must therefore be assessed on a case by case basis. Through use of an empirical application we demonstrate that even without the introduction of new terms to the Δ equation, risk-averse behavior does affect mechanism choice. The model we use is an extension to the model presented by Wu and Babcock (2001). Results derived by WB indicate that spatial heterogeneity may reverse the Weitzman result when marginal damages are relatively low and insensitive to input use, and is likely to reverse the Weitzman result when marginal damages are relatively high and sensitive to the level of input use. Our results demonstrate that if we allow risk aversion to only affect Weitzman's relative slope term, risk aversion increases the influence of relative slopes on mechanism choice thereby reducing the influence of corner solutions on mechanism choice. The opposite holds true for risk-decreasing inputs. We also simulate the impacts of non-zero values for the covariance of marginal damages and marginal variance of profits (v_{cv}). Figures 2.5 and 2.6 in Section 2.3 demonstrate the kinds of effects that v_{cv} can have on mechanism choice — for the case of risk-increasing inputs large v_{cv} values create a strong preference for the tax (a standard is rarely the preferred mechanism), whereas for the case of risk-decreasing inputs the v_{cv} term leads to a much broader range of conditions under which the standard is preferred.

To provide an example of the intuition behind some of our results, consider the case of a negative v_{cv} term and risk-decreasing inputs. Recall from solving the first order necessary conditions derived from the farmers objective function under the tax that the farmer will use more chemicals on land with a higher marginal certainty-equivalent profit function, i.e., a low marginal variance of profits, *ceteris paribus*. If σ_q^2 and D_q are negatively correlated, this implies that land with a low marginal variance of profits (σ_q^2) will tend to have high marginal pollution costs (D_q). Thus as a result of the farmer's reponse to the tax (using more chemicals on land with a higher marginal certainty-equivalent profit and low marginal variance of profits), more chemicals are used on land with a high marginal pollution cost. The farmer's response to the tax therefore favors the standard.

Although we do not simulate results for all terms that stem from incorporating risk aversion, our results illustrate and re-iterate the importance of considering risk preferences when determining which regulatory mechanism (uniform tax or uniform standard) to use for agricultural nonpoint pollution abatement. We demonstrate that risk aversion of a magnitude well within the boundaries of empirically estimated risk aversion parameter values can have significant impacts on the levels of social surplus associated with taxes and standards.

Regulatory approaches, including taxes and standards, can be efficient ways to abate negative externalities resulting from production processes. However, whether taxes or standards are more efficient depends upon various factors and has been a subject of much research. Weitzman and others have analyzed various aspects of the tax versus standard decision. WB include spatial heterogeneity in the model, making the literature applicable to the issue of regulating agricultural nonpoint pollution. We further extend the literature to include risk-averse producers and demonstrate that risk can be an important component in determining which regulatory mechanism is more efficient. This suggests that if risk preferences are not considered when regulatory decisions are made, inefficient outcomes may result. As an example, if regulatory decisions regarding agricultural nonpoint pollution are made without considering farmers' risk preferences, the choice of mechanism may cause farm profits to decline such that farmers opt to subdivide and sell farmlands, rather than continue farming. In such a scenario the regulatory process will indeed reduce agricultural nonpoint pollution, but will also increase pollution from urban sources, which may or may not be optimal.

Chapter 3

Predicting the Spatial Pattern of Residential Development

We develop an econometric model of residential land use change for a 528 square mile area encompassing Albuquerque and outlying regions within Bernalillo County, New Mexico. The model enables us to determine the variables that are most important in explaining the current pattern of residential land use.

3.1 Literature Review

Prior to the late 1980s, much of the urban sprawl literature focused on explaining urban fringe land values rather than land use patterns. Recent research has turned to addressing the determinants of land use and the pattern of land use. One of the early studies of land use patterns (McMillen, 1989) uses a multinomial logit model to examine the determinants of residential, agricultural, and vacant land uses in Chicago's urban fringe. McMillen finds that lot size, the presence of railroads, distance to nearby towns, and the proportion of surrounding land that is either vacant, forested, or agricultural affect the likelihood that a lot is used for residential purposes.[1]

Bockstael (1996) uses a hedonic model to estimate the value of land in residential use. These values are then used in conjunction with an estimated agricultural land value to estimate a probit model of land conversions from undeveloped to residential use. The study area is the Patuxent River watershed (located in the Chesapeake Bay watershed), which consists of both highly urban areas and rural counties in various stages of development. Land conversion is modeled as a function of residential and agricultural land values, slopes, soil quality, and forestation; all variables are statistically significant and have the expected sign. Model estimates are used to predict land use patterns under alternative policy scenarios. The predicted land use patterns are then combined with nitrogen load indices to estimate nutrient loading changes that would result from the predicted land use changes.

[1] In this paper, we focus on research that has used spatially explicit parcel-level models of land use change. However, the land-use-change literature also contains models of land use change at a larger scale (such as at the county level) as well as considerable theoretical research. See, for example, Wu and Plantinga (2003), Cho et al. (2005), Hascic and Wu (2006), and Wu and Cho (2007).

Bockstael and Bell (1998) focus on a portion of the Patuxent River watershed and use predicted land values (in agricultural and residential use) in a logit model to estimate the likelihood of land use conversion. The value of land in agricultural use is predicted primarily as a function of soil type. The value of land in residential use is predicted using a hedonic model of newly built homes; home sales prices are modeled as a function of landscape features (e.g., distance to coastline), man-made features (e.g., distance to city center, surrounding residential and commercial densities, etc.), and regulatory policies (density policies). Statistically significant variables include residential land value and dummy variables that denote whether the land is forested, has steep slopes, and if water and sewer services are available. Results from the logit model are used to develop a map of low, medium, and high probabilities of development under various density (zoning) policies. Effects on water quality (specifically, nitrogen loading) of alternate zoning policies are subsequently estimated using rules of thumb that relate nitrogen loadings to land use and soil type.

Irwin and Bockstael (2002), whose work also focuses on the Patuxent River watershed, provide an empirical test of the idea that interactions among spatially distributed agents affect the urban land use pattern, an idea that has been well-developed theoretically within the economics literature.[2] They include surrounding residential development densities as explanatory variables in a proportional hazards model of landowners' decisions to convert land from an undeveloped state to residential use. Their results provide evidence that (1) exogenous factors (such as provision of public utilities and landscape characteristics) do not fully explain the urban spatial structure, and (2) agent interactions have a negative impact on the conversion of buildable land to residential use, which may help explain urban sprawl.

Proportional hazard modeling, used by Irwin and Bockstael (2002) and Irwin et al. (2003) enables analysis of not only the *pattern* but also the *timing* of the land use changes. Irwin et al. (2003) apply a proportional hazards model to parcel-level data for an exurban Maryland county and provide further evidence to support the interacting agents hypothesis first empirically tested by Irwin and Bockstael (2002). Irwin et al. also provide insight into the effectiveness of various growth management efforts, including zoning regulations, open space requirements, and state-level programs initiated to encourage development in some areas and discourage development in other areas. Results indicate that larger lots and a greater number of allowable lots accelerate the development of a parcel, while open space requirements do not impact the timing of a parcel's development. The effectiveness of various state-level programs is mixed. The results suggest that patterns of land use change may be more readily affected through the provision of utility services than through conservation easement programs.

To incorporate development densities into land use change analysis, Cho and Newman (2005) expand the model used by Bockstael and Bell (1998) to a three-stage model: the first stage is a hedonic model of land values; the second stage is a probit model of the land development decision, and the third stage is a probit model of the development density decision. The study area is rural Macon County, located in the Blue Ridge Mountains of North Carolina. Results indicate that a parcel is more likely to be developed if it is close to a previously developed parcel. This result differs from that of Irwin and Bockstael (2002), who found evidence of negative spillover effects. Cho and Newman's results also indicate positive

[2]For example, see Papageorgiou and Smith (1983), Arthur (1988), Fujita (1988), Krugman (1991), Krugman (1996), Anas (1992), Anas and Kim (1996), and Page (1999).

spatial correlation for development densities. Most of the land development decision results derived by Cho and Newman are intuitive (e.g., a positive coefficient on road densities and negative coefficients on parcel size and distance to city center), although a negative coefficient on elevation is seemingly counterintuitive. The authors surmise that although houses at higher elevations have better views and are thus more desirable, there is less available land at higher elevations and thus such houses are less affordable.

Residential development densities are also assessed by Newburn and Berck (2006) using a random-parameter logit model. The random-parameter logit model is used to capture the effects of non-uniformly applied and enforced maximum-density restrictions. Newburn and Berck analyze differences in the effect of regulations on the density of suburban and rural-residential development in Sonoma County, California. Their findings indicate that maximum-density zoning restrictions and the provision of sewer and water services have significant impacts on the pattern and density of residential development in both suburban and rural areas. The authors note that minimum lot size restrictions may increase low-density sprawl by requiring homeowners to consume more land.

Much of the previous research addressing residential land use change focuses on areas of the eastern and midwestern US. In contrast, our analysis focuses on a region of the southwestern US, where development patterns and pressures may differ. The southwest's temperate climate and vast array of outdoor amenities are unique and have caused a large migration to the region over the past several decades. Specifically, we examine residential development patterns in a 528 square mile portion of Bernalillo County, New Mexico, an area that includes the City of Albuquerque and surrounding rural areas.

Several earlier studies also include rural and urban landscapes and therefore analyze both urban and sprawl-type developments (e.g., Bockstael (1996), Bockstael and Bell (1998), Irwin and Bockstael (2002), and Newburn and Berck (2006)), yet none assess whether it is appropriate to analyze urban and sprawl areas using a single model.[3] We estimate econometric models for the entire study area and the disaggregated urban and sprawl areas. Doing so enables us to address an unanswered question that remains in the literature — whether it is appropriate to model land use change within urban and sprawl areas using a single model, or if doing so might result in inaccurate development predictions and inappropriate regulatory policies.

The second issue we address is the effectiveness of using zoning regulations to curb Albuquerque-area sprawl. Previous research (Bockstael and Bell, 1998; Irwin et al., 2003) has demonstrated that minimum lot size (i.e., maximum allowable density) can be an effective means of altering development patterns. If reductions in minimum lot size decrease (increase) the number of parcels predicted to undergo future residential development in sprawl (urban)

[3]Although Newburn and Berck (2006) allude to this issue, they do not directly address it. They use separate models to estimate the relationships between covariates and various development densities. Their model uses four development densities as well as a fifth category for parcels that remain undeveloped. The two highest densities (which both have more than house per acre) are assumed to represent suburban development, while the two lower densities (which have less than one house per acre) are considered to represent rural development. The definitions of suburban and rural development are therefore not based upon where the developments occur spatially, but are based solely upon development densities. Although the appropriateness of their definitions of suburban and rural areas might be questioned, they find differences in the parameter estimates' magnitudes, significance, and signs between the various models.

areas, this suggests that minimum lot size can be an effective means of reducing sprawl and the associated environmental externalities. We therefore provide an assessment of the implications of smaller minimum lot sizes for Albuquerque-area sprawl.

3.2 Model and Data

3.2.1 Theoretical Model

We assume that a rational, profit-motivated landowner will convert a parcel from an undeveloped state (vacant or agricultural) to residential use if the value of the land (W) in residential use exceeds the value of the land in an undeveloped state. That is, parcel i is developed if $W_{ir} \geq W_{iu}$, where r denotes residential use and u denotes an undeveloped state. Numerous physical characteristics (e.g., slopes, soils), amenity access characteristics (e.g., distances to activity centers and open space), and other observable characteristics (e.g., surrounding land uses and sociodemographics) affect W_{ir} and W_{iu}. The value of a parcel in residential use will also be affected by the costs associated with converting the parcel to residential use from an undeveloped state.

The probability of residential development is thus modeled as

$$\Pr(\text{develop}) = \Pr(W_{ir} \geq W_{iu}). \tag{3.1}$$

Rewriting W as the summation of a systematic portion V, which is a function of the observable parcel characteristics, and an error term η that captures both a random component and unobservable parcel characteristics that affect development activity yields

$$\begin{aligned} \Pr(\text{develop}) &= \Pr(V_{ir} + \eta_{ir} \geq V_{iu} + \eta_{iu}) \\ &= \Pr(V_{ir} - V_{iu} \geq \eta_{iu} - \eta_{ir}). \end{aligned} \tag{3.2}$$

By imposing the assumption that $\eta_{iu} - \eta_{ir}$ follows a logistic distribution we are able to use a logit model to estimate the probability of development.[4] The probability of development is thus given by

$$\begin{aligned} \Pr(\text{develop}) &= \Lambda(\boldsymbol{\beta}' X) \\ &= \frac{1}{1 + e^{-\boldsymbol{\beta}' X}} \end{aligned} \tag{3.3}$$

where X is a matrix of explanatory variables (observable parcel characteristics) and $\boldsymbol{\beta}$ is a vector of coefficients. The joint likelihood of observing a given pattern of development for $i = 1, \ldots, N$ parcels is

$$\begin{aligned} L &= \prod_{y_i=1} \Lambda(\boldsymbol{\beta}' X_i) \prod_{y_i=0} [1 - \Lambda(\boldsymbol{\beta}' X_i)] \\ &= \prod_i [\Lambda(\boldsymbol{\beta}' X_i)]^{y_i} [1 - \Lambda(\boldsymbol{\beta}' X_i)]^{1-y_i}, \end{aligned} \tag{3.4}$$

[4] A probit model could also be used to estimate the probability of development, and would likely yield results similar to those of the logit model.

where $y_i = 1$ if parcel i is developed and 0 otherwise. Applying maximum likelihood estimation to the log-likelihood function,

$$\begin{aligned}\max_{\boldsymbol{\beta}} \ln L &= \sum_{i}^{n} \big[y_i \ln(\Lambda(\boldsymbol{\beta}' X_i)) + (1 - y_i) \ln(\Lambda(\boldsymbol{\beta}' X_i)\big] \quad (3.5)\\ &= \sum_{i}^{n} \big[y_i \ln\big(\frac{1}{1 + e^{-\boldsymbol{\beta}' X_i}}\big) + (1 - y_i) \ln\big(\frac{e^{-\boldsymbol{\beta}' X_i}}{1 + e^{-\boldsymbol{\beta}' X_i}}\big)\big]\end{aligned}$$

produces the parameter estimates ($\hat{\beta}$s) that maximize the likelihood that make the data "most likely." The effect of a variable on the probability of land development can be calculated using the model results; for example, the marginal effect of variable X_j on the probability of development is

$$\frac{\partial \Pr(y = 1)}{\partial j} = \lambda(\boldsymbol{\beta}' X)\beta_j, \quad (3.6)$$

where β_j is the coefficient associated with variable X_j and λ is the logistic density function.[5]

3.2.2 Study Area and Data

The study area is located within Bernalillo County in central New Mexico and consists of land east of the Rio Puerco, west of the Sandia Mountains, north of Isleta Reservation and the Bernalillo County line, and south of Sandia Reservation and the Bernalillo County line. The City of Albuquerque and surrounding communities and rural areas are located within the study area.[6] As discussed previously, we hypothesize that the parameters' magnitudes and signs may differ for urban and sprawl areas. We therefore segment the study area into urban and sprawl areas such that sprawl areas are characterized by rapid and relatively recent development.

We estimate the statistical model using 1999 and 2007 parcel-level data obtained from the Bernalillo County Assessor's Office. Included in the data set are all parcels within Bernalillo County used primarily for agricultural production (identified through their enrollment in the New Mexico agricultural tax exemption program) and those classified by the assessor as vacant. We use 1999 parcel data because this is the first year for which information pertaining to the agricultural tax exemption is available. We use 2007 parcel data to account for growing awareness of the agricultural tax exemption program — as awareness of the agricultural tax exemption program grows, more agricultural lands become enrolled in the

[5]The approach taken herein is similar to that used by others (e.g., Irwin and Bockstael (2002)). However, as pointed out by an anonymous reviewer, there is a two-way causality between land value and land development that we have not modeled here. Although two-way causality is certainly a valid issue, incorporating endogenous land values in our model is problematic due to the fact that New Mexico is a non-disclosure state (home sales price data is not publicly available).

[6]For future comparison purposes, we limit our study area so that it coincides with that used in the Planned Growth Strategy (City of Albuquerque and County of Bernalillo, 2000). The Planned Growth Strategy is a joint effort undertaken by City of Albuquerque and Bernalillo County employees to develop, adopt, and achieve an image of place (including transportation networks, urban services provision, and major centers of commercial enterprise) for the greater Albuquerque area.

program. By using the Assessor's 2007 parcel data we are able to identify parcels used for agricultural production in 2007 that did not claim the agriculture tax exemption in 1999. By doing so, we implicitly assume parcels have not been converted from a developed use to agricultural use.[7]

Several criteria are used to eliminate parcels from this preliminary data set of 40,014 parcels. We exclude parcels located either outside the Planned Growth Strategy boundary, within the Village of Corrales (as this area is now part of Sandoval County), or within the Village of Los Ranchos (due to the fact that information pertaining to the dependent variables is not available for the area until 2005). We also eliminate parcels that for one reason or another are not suitable for residential development. Zoning designation and description information is used to omit parcels not zoned for residential use. Zoning restrictions are also used to delete parcels that are too small for residential development. We omit parcels with a zero land value, as these are typically easements or ponding areas, as well as parcels located within tribal lands, parks, open space, national forests, or Kirtland Air Force Base. Parcels owned by public entities such as the US Postal Service and the New Mexico State Highway and Transportation Department are also excluded. This selection process results in a data set comprised of 21,814 parcels. We extract a random sample of 1,000 parcels for use in testing the predictive power of our statistical model, leaving 20,814 observations for use in the regression analysis.

Conversion from an undeveloped state to residential use is proxied using Bernalillo County and City of Albuquerque residential building permits; we code the dependent variable *building permit* as a 1 if one or more residential building permits were filed for a parcel between 1999 and 2007 and as a 0 otherwise. Figure 3.1 provides a map of the parcels included in our data set. The map delineates whether a parcel is vacant or agricultural land and whether a building permit was filed for the parcel between 1999 and 2007. Building permits were filed on 5,385 of the 20,814 (26%) parcels in our data set. (Definitions for the dependent and explanatory variables are provided in Table 3.1).

Table 3.1: Variable Definitions

Variable	Definition
Dependent Variable	
Building permit	Residential building permit filed between 1999 and 2007
Independent Variables	
Physical Characteristic Variables	
LimSeptic	Parcel located outside WWSA and in sprawl area, and soils are rated as somewhat limited for septic absorption fields
VeryLimSeptic	Parcel located outside WWSA and in sprawl area, and soils are rated as very limited for septic absorption fields
Slope	Parcel has areas with slopes greater than 10%

[7] There is no effect on our analysis if agricultural parcels identified through the use of 2007 data were in fact vacant in 1999, but were subsequently converted to agricultural use.

Table 3.1 (continued)

Variable	Definition
PrimeFarm	Parcel is located in MRGCD, has productive soils, and its primary use is agricultural
OtherAg	Parcel's primary use is agricultural
Sociodemographic Variables	
Income	Median income for census blockgroup ($1000s)
Amenity Access Variables	
BaseD	Distance to Kirtland Air Force Base (miles)
BosqueD	Distance to bosque (miles)
Neighboring Land Use Variables	
Res800	% of land in residential use within 800m ($\approx$ 0.5 miles) of parcel centroid
Comm400	% of land in commercial, office, manufacturing, or warehouse use within 400m ($\approx$ 0.25 miles) of parcel centroid
Comm4001600	% of land in commercial, office, manufacturing, or warehouse use within 400-1600m ($\approx$ 0.25-1 mile) of parcel centroid
OS400	% of land in open space or parks within 400m ($\approx$ 0.25 miles) of parcel centroid
OS4001600	% of land in open space or parks within 400-1600m ($\approx$ 0.25-1 mile) of parcel centroid
Zoning Variables	
CABQR1	Parcel zoned by City of Albuquerque as R1
CABQR2R3	Parcel zoned by City of Albuquerque as R-G, R-2, or R-3
CABQRORA	Parcel zoned by City of Albuquerque as RO-1, RO-20, RA-1, or RA-2
CABQSU	Parcel zoned by City of Albuquerque as SU-1, SU-2, SU-3, H-1, or PC
CNTYOffComm	Parcel zoned by Bernalillo County as O-1, C-N, C-1, or C-2
Quadrant Variables	
NWquad	Parcel located in northwest quadrant of study area
NEquad	Parcel located in northeast quadrant of study area
SEquad	Parcel located in southeast quadrant of study area
SWquad	Parcel located in southwest quadrant of study area

Residential development activity is modeled as a function of observable characteristics thought to affect either the value of the parcel in undeveloped use, in residential use, or both. These factors were based on the extant literature and can be categorized into six groups:

physical characteristics, neighboring land use, amenity access, sociodemographics, zoning, and study area quadrants (used as a proxy for additional sociodemographic differences).[8]

Consider first the physical characteristics of a parcel of land. *Slope* denotes whether a parcel has areas with slopes greater than 10 percent. *PrimeFarm* captures whether a parcel is primarily employed in agricultural production, contains potential prime farmland,[9] and is located within the Middle Rio Grande Conservancy District (MRGCD).[10] *OtherAg* captures parcels used primarily for agricultural purposes but that do not have especially productive soils and are not located within the MRGCD. Parcels located outside the wastewater service area (WWSA) that are developed for residential use must be serviced by septic systems. Information pertaining to the soil's capacity to serve as a septic absorption field is therefore of interest and was obtained from the Natural Resources Conservation Service (NRCS). The variable *LimSeptic* takes a value of 1 if a parcel is located outside the WWSA and has soils that are rated by the NRCS as somewhat limited for use as septic absorption fields; otherwise, it has a 0 value. A value of 1 is assigned to *VeryLimSeptic* if a parcel is located outside the WWSA and has soils rated as very limited for septic absorption fields and a value of 0 otherwise. Because steep slopes create additional concern for the use of septic fields, we interact *Slope* and *VeryLimSeptic*. Because only parcels in the sprawl area are outside the WWSA, the soil's capacity to serve as a septic absorption field will only negatively affect the development probability in the sprawl area.

We include a set of variables to capture accessibility to various amenities, such as open space and employment opportunities. The accessibility of city parks and open space areas is expected to increase the probability that a parcel is developed for residential purposes. The Rio Grande bosque runs north/south through Albuquerque, bisecting the city into its eastern and western halves.[11] The Rio Grande Valley State Park encompasses the bosque and consists of $4,300$ acres open to the public for a variety of recreational activities, including wildlife watching, hiking, and bicycling. Because accessibility to the bosque may increase the

[8]The following steps were used to which independent variables to include in our model. Univariate analysis was used to eliminate variables for which the likelihood ratio for the global $\hat{\beta}$ is insignificant, variables for which the p-value is less than 0.25, and variables for which the odds ratio includes the value 1. An ordinary least squares regression was subsequently used with the remaining variables to eliminate variables with very small tolerance values. We then used a logit model including only variables with tolerances of ≥ 0.40 and added variables with smaller tolerance values one at a time. For variables that had been excluded from the model, we next assessed whether the variables belonged in the model by adding each into the model individually and assessing the model's stability and likelihood ratio test. We next assessed whether nonlinear relationships existed between the dependent variable and the continuous explanatory variables. We did so by sectioning the data for continuous variables into quintiles, estimating the regression using the quintiles, and plotting the quintiles' average values against the corresponding $\hat{\beta}$s. After determining which non-linear variables to include in the model, we checked the log-likelihood function for statistical significance as we added the non-linear variables to the model one at a time. Finally, we added interaction terms to the model one at a time and kept only those that made a statistically significant improvement in the value of the log-likelihood function, were statistically significant themselves, and did not result in a large standard error for another variable.

[9]Data obtained from the Natural Resources Conservation Service identifies areas with soils that would be considered prime farmland *if* they received sufficient irrigation.

[10]Parcels located within the MRGCD area are likely to be more heavily irrigated than parcels located outside the MRGCD.

[11]The term "bosque" is derived from the Spanish word for woodlands and refers to a riparian forest area along the floodplain of a stream or river.

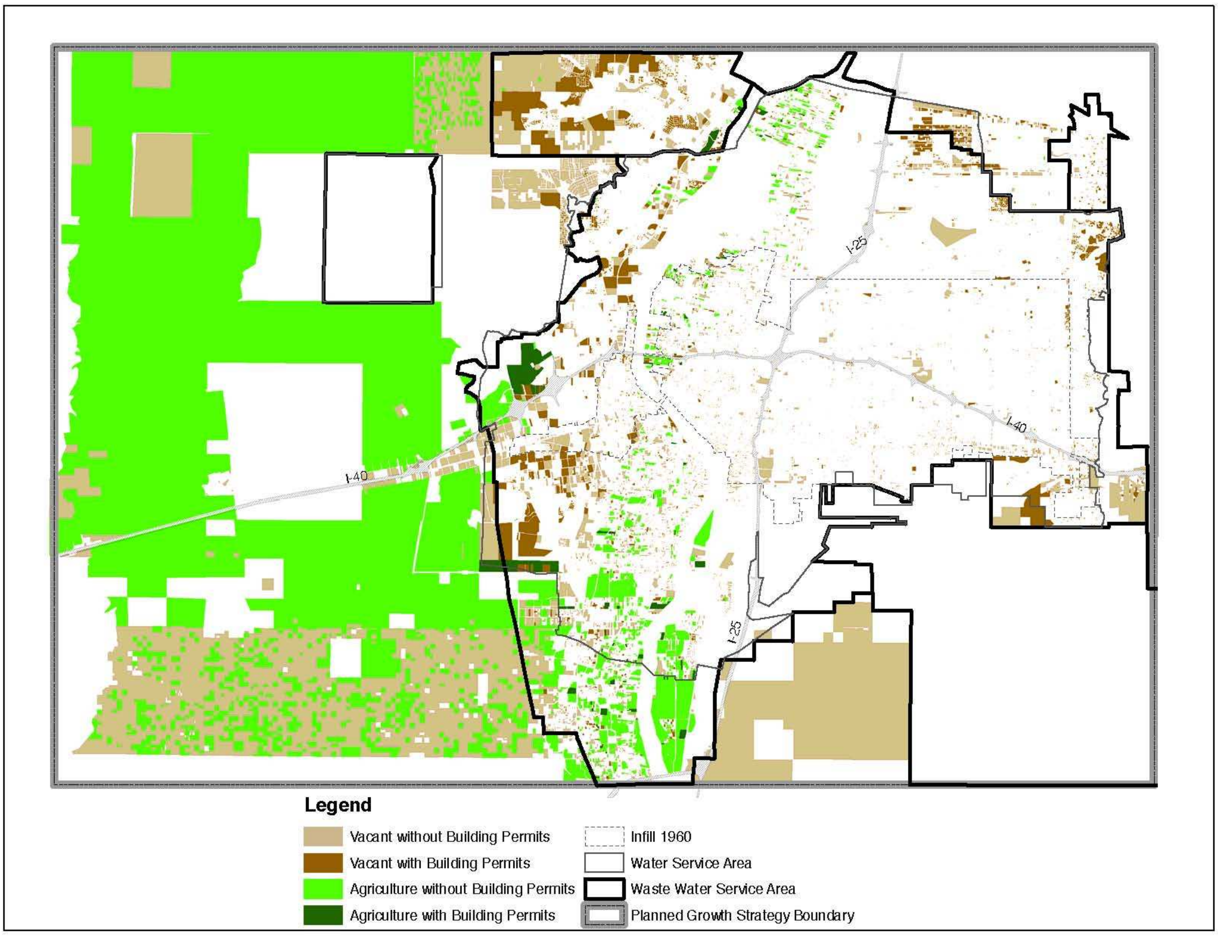


Figure 3.1. Buildable Parcels

likelihood that a parcel is developed for residential purposes, we include a variable *BosqueD* that provides the distance from the parcel centroid to the Rio Grande bosque.[12] Because accessibility to major employment centers is also expected to have a positive effect on a parcel's value in residential use, we include *BaseD* to capture the distance from a parcel to Kirtland Air Force Base.[13]

We also include a set of variables designed to capture the effects of neighboring land uses on residential development activity. Recognizing that land use within immediate proximity may have a different relationship with development activity than does neighboring land use that is not quite so immediate, we create concentric circular buffers extending out from the parcel's centroid 0 to 400 meters and 400 to 1600 meters (which roughly correspond to $1/4-$ and $1-$mile buffers) and measure the percent of land in each of these buffers used for

[12]Distances are measures "as the crow flies". To allow for a nonlinear relationship between *BosqueD* and the likelihood of development, we also include the squared distance, $BosqueD^2$.

[13]Kirtland Air Force Base and Sandia National Laboratories (located on Kirtland Air Force Base) employ more than $40,000$ people. The area's next largest employer is Albuquerque Public Schools, which employs fewer than $15,000$ people. To account for a nonlinear relationship between access to the base and the likelihood of residential development, we again include a squared distance term, $BaseD^2$.

commercial, office, industrial, or wholesale purposes (*Comm400* and *Comm4001600*) or for open space or parks (*OS400* and *OS4001600*). The percent of neighboring land in residential use is measured within 800 meters of the parcel centroid (approximately a 1/2−mile buffer) and captured with the variable *Res800*.[14]

Because Albuquerque's four quadrants differ in their demographic, economic, and ethnic differences, we account for sociodemographic factors by including *Income*, *Income*^{2}, and three quadrant dummy variables (*NWquad*, *NEquad*, and *SEquad*) that serve as proxies for additional sociodemographic differences. Finally, we use a set of zoning designation variables to proxy for differences in minimum lot sizes and residential use restrictions imposed by the City of Albuquerque and Bernalillo County. We do not, however, include separate dummy variables for each zoning designation, but rather summarize the zoning designations in such a manner that zoning designations with similar minimum lot sizes and permissible residential uses are combined in a single summary zoning designation.[15]

Table 3.2 provides descriptive statistics for variables used in our analysis.

Table 3.2: Descriptive Statistics – Urban and Sprawl Areas

	Urban & Sprawl		Urban		Sprawl	
Variable	Mean	StDev	Mean	StDev	Mean	StDev
Dependent Variable						
Building permit	0.26	0.44	0.22	0.42	0.28	0.45
Independent Variables						
Physical Characteristics						
LimSeptic	0.084	0.28	0	0	0.14	0.35
VeryLimSeptic	0.17	0.38	0	0	0.29	0.45
Slope	0.13	0.34	0.086	0.28	0.17	0.37
SlopeVeryLimSeptic	0.044	0.20	0	0	0.075	0.26
PrimeFarm	0.043	0.20	0.094	0.29	0.0068	0.082
OtherAg	0.055	0.23	0.0014	0.037	0.092	0.29
Sociodemographics						
Income	40	21	38	16	42	24
Income^2	2080	22581	1678	1515	2365	2624

[14] Although we attempted to use the same $\frac{1}{4}-$ and 1−mile buffers for residential land use as we did for open space & parks and commercial, office, industrial, & wholesale land uses, due to collinearity issues we were unable to do so. We again test for nonlinear relationships between the dependent variable and neighboring land uses, and when appropriate include squared terms.

[15] *CNTYOffComm* captures parcels zoned by Bernalillo County as O-1 (Office and Institutional Zone), C-2 (Community Commercial Zone), or C-N or C-1 (Neighborhood Commercial Zones); *CABQR2R3* captures parcels zone by the City of Albuquerque as R-G (Residential Garden Apartment Zone) or either R-2 or R-3 (Residential Zones); *CABQSU* captures parcels zoned by the City of Albuquerque as SU-1 (Special Use Zone), SU-2 (Special Neighborhood Zone), SU-3 (Special Center Zone), H-1 (Historic Old Town Zone), or PC(Planned Community Zone); *CABQRORA* captures parcels zoned by the City of Albuquerque as RO-1 (Rural and Open Zone), RO-20 (Rural and Open Agricultural Zone), RA-1 (Residential and Agricultural Zone, Semi-Urban Area), or RA-2 (Residential and Agricultural Zone); *CABQR1* captures parcels zoned by the City of Albuquerque as R-1 (Residential Zone).

Table 3.2 (continued)

Variable	Urban & Sprawl Mean	Urban & Sprawl StDev	Urban Mean	Urban StDev	Sprawl Mean	Sprawl StDev
Amenity Access						
BaseD	10	4.3	7.5	2.9	13	3.5
$BaseD^2$	139	103	65	42	191	102
BosqueD	3.7	3.1	2.4	2.7	4.6	3.1
$BosqueD^2$	23	36	13	24	30	41
Neighboring Land Use						
Res800	30	24	47	16	18	21
$Res800^2$	1474	1547	2454	1502	780	1153
Comm400	5.8	11	12	14	1.5	5.2
$Comm400^2$	154	485	331	669	29	217
Comm4001600	6.3	8.2	12	9.0	2.0	3.3
$Comm4001600^2$	107	238	237	324	14	43
OS400	3.7	8.7	3.2	6.7	4.0	9.9
OS4001600	7.2	9.5	7.1	6.5	7.3	11
$OS4001600^2$	142	382	93	155	177	480
Zoning						
CABQR1	0.15	0.36	0.16	0.37	0.14	0.35
CABQR2R3	0.019	0.14	0.038	0.19	0.0060	0.077
CABQRORA	0.019	0.14	0.041	0.20	0.0028	0.053
CABQSU	0.24	0.43	0.21	0.41	0.26	0.44
CNTYOffComm	0.015	0.12	0.028	0.17	0.0063	0.079
Quadrant						
NWquad	0.38	0.49	0.24	0.43	0.48	0.50
NEquad	0.14	0.34	0.13	0.34	0.14	0.35
SEquad	0.13	0.33	0.30	0.47	0.0046	0.068

3.3 Results

We use three logit models to separately analyze residential development activity in the urban area, the sprawl area, and the two areas combined. Results are summarized in Table 3.3. Because the combined model is simply a combination of the urban and sprawl models, we focus our discussion on a comparison of the urban and sprawl models.[16]

[16]The small number of sprawl-area parcels located in the southeast quadrant (56 parcels) causes estimation difficulties for the sprawl model. We have therefore omitted from the sprawl model all variables pertaining to the southeast quadrant.

Table 3.3: Logit Results – Full, Urban, and Sprawl Models

	Urban & Sprawl		Urban		Sprawl	
Parameter	Marg Eff	Sig	Marg Eff	Sig	Marg Eff	Sig
Intercept	.	***	.		.	***
NWquad	−0.22	***	−0.36	***	−0.11	
NEquad	0.92	***	−0.24		0.45	***
SEquad	0.48	***	−0.68	***	.	
Physical Characteristics						
LimSeptic	−0.16	***	.		−0.16	***
VeryLimSeptic	−0.26	***	.		−0.18	**
NWVeryLimSeptic	−0.15	*	.		−0.20	**
NEVeryLimSeptic	0.24	***	.		0.15	**
Slope	0.042		0.032		0.0058	
NWSlope	−0.032	*	−0.069	**	−0.035	
NESlope	−0.12	***	−0.17	***	−0.078	**
SlopeVeryLimSeptic	−0.076	*	.		−0.090	**
PrimeFarm	−0.16	***	−0.12	***	−0.10	**
OtherAg	−0.087	***	0.030		−0.082	***
Sociodemographics						
Income	0.0087	***	0.0085	***	0.0051	***
NEIncome	0.00062		0.0050	***	−0.00001	
SEIncome	0.00059		0.00043		.	
Income^2	−0.00007	***	−0.00007	***	−0.00004	***
Amenity Access						
BaseD	0.20	***	−0.091	***	0.12	***
NWBase	0.033	***	0.045	***	0.035	**
NEBase	−0.083	***	−0.0071		−0.045	***
SEBase	−0.11	***	0.042	*	.	
BaseD^2	−0.0099	***	0.0040	**	−0.0084	***

Table 3.3 (continued)

	Urban & Sprawl		Urban		Sprawl	
Parameter	Marg Eff	Sig	Marg Eff	Sig	Marg Eff	Sig
BosqueD	0.080	***	0.024	*	0.16	***
$BosqueD^2$	−0.0057	***	−0.00069		−0.014	***
Neighboring Land Use						
Res800	0.0092	***	0.0026	**	0.0084	***
NERes800	−0.0036	***	−0.0027	**	−0.0036	***
SERes800	−0.0012	*	0.00065		.	
$Res800^2$	−0.00011	***	−0.00005	***	−0.00009	***
Comm400	−0.0093	***	−0.0030	**	−0.019	***
NWComm400	0.0013		−0.0017		0.00064	
NEComm400	−0.0013		−0.00008		−0.0063	
SEComm400	0.0071	***	0.0062	***	.	
$Comm400^2$	0.00004	**	−0.00005	**	0.00025	***
Comm4001600	0.0061	***	0.00042		−0.0060	*
NEComm4001600	0.00078		0.0031		0.019	***
$Comm4001600^2$	−0.00019	***	−0.00004		0.00053	***
OS400	−0.0013	***	−0.0028	***	−0.00062	
OS4001600	0.0055	***	−0.0023		0.0039	***
NEOS4001600	0.0017	**	0.010	***	0.0032	***
OS4001600sq	−0.00011	***	0.00008		−0.00009	***
Zoning						
CABQR1	0.036	***	0.14	***	−0.015	
NER1	−0.19	***	−0.17	***	−0.18	***
SER1	0.17	***	0.076	***	.	
CABQR2R3	0.11	***	0.14	***	0.16	***
CABQRORA	−0.015		0.094	***	−0.10	**
CABQSU	0.12	***	0.096	***	0.14	***
NWSU	−0.12	***	0.11	***	−0.21	***
NESU	−0.15	***	−0.0055		−0.23	***

Table 3.3 (continued)

Parameter	Urban & Sprawl Marg Eff	Sig	Urban Marg Eff	Sig	Sprawl Marg Eff	Sig
SESU	0.12	***	0.17	***	.	
CNTYOffComm	−0.36	***	−0.35	***	−0.29	***
N	20814		8629		12185	
-2lnL	15209		6558		7987	
pseudo R^2	0.34		0.26		0.42	

[a] *, **, and *** denote significance at the 10, 5, and 1 percent levels, respectively.

Results indicate that a parcel's physical characteristics affect its attractiveness for residential development. In the sprawl area, where wastewater services may be unavailable, limitations in the soil's ability to serve as a septic absorption field reduce the probability of residential development. The negative sign on *SlopeVeryLimSeptic* indicates that steep slopes reinforce the effect of the soil's septic absorption field limitation. However, *Slope* is statistically insignificant in all three models (full, urban, and sprawl).[17] Negative coefficients on *PrimeFarm* and *OtherAg* indicate that parcels used primarily for agricultural activities are less likely to be developed. The negative effect on development activities is especially strong for prime farmlands.

Amenity access is also associated with residential development probabilities. The negative coefficient on *BaseD* indicates that access to Kirtland Air Force Base increases the probability of residential development in urban areas; i.e., the negative coefficient indicates that as distance from the Base increases, there is a corresponding decrease in the probability of development. In contrast, sprawl-area parcels are more likely to be developed the further they are located from the Base. Somewhat surprisingly, access to the bosque appears to decrease the probability of development in both urban and sprawl areas. This may indicate that the bosque is acting as a proxy for the central part of the city.

Surrounding land uses also affect residential development probabilities. Residential land use within $\frac{1}{2}-$mile of a parcel increseases the probability of residential development in both urban and sprawl areas, although the magnitude of the effect differs by city quadrant. Whereas nearby residential developments tend to promote residential development, commercial developments in immediate proximity ($\frac{1}{4}-$mile) to a parcel tend to dampen residential development, although the effect is smaller in urban areas than in sprawl areas. When located between $\frac{1}{4}-$ and $1-$mile from a parcel's centroid, commercial developments have no significant effect on the probability of residential development in urban areas, but has a small dampening effect in sprawl areas. Results suggest that in urban areas, neighboring open space and park areas decrease residential development probabilities. In contrast, sprawl model results suggest that park areas in immediate proximity to sprawl-area parcels have no effect on residential development, but increase development probabilities when located between $\frac{1}{4}-$ and $1-$mile from a parcel centroid.

Coefficients on the income and quadrant variables suggest that sociodemographics also influence residential development patterns. Areas with higher median incomes are more likely to be developed, especially in urban areas. The effect is most pronounced for the northeast quadrant, where incomes are especially high. Urban-area parcels located in the northwest and southeast quadrants are more likely to be developed than southwest urban-area parcels. Similarly, northeast quadrant sprawl-area parcels are more likely to be developed than southwest quadrant sprawl-area parcels.

Finally, zoning regulations also affect the probability of residential development. Parcels designated as *CNTYOffComm* are less likely to be developed for residential purposes, which likely reflects the close proximity of commercial developments. In the urban model, *CABQR1*, *CABQR2R3*, *CABQRORA*, and *CABQSU* have similar positive effects on the probability

[17]There are two possible explanations for the lack of statistical significance for *Slope*. First, although 15% slopes are often considered problematic and costly for construction activities (e.g., Irwin and Bockstael (2002)), the data we have available uses a 10% value. Second, results might be stronger if *Slope* were defined as the proportion of the parcel with slopes greater than 10%, rather than as a dummy variable.

of residential development, although results vary somewhat across the urban quadrants. In the sprawl area the *CABQRORA* zoning designation decreases the probability of residential development. Similar to the urban area results, *CABQR2R3* and *CABQSU* both increase the probability of residential development. Results again vary by quadrant, especially those for the special use (SU) zoning designation.

Examination of the results detailed in Table 3.3 suggests differences in the sign and statistical significance of parameter estimates do indeed exist between the urban and sprawl areas and that modeling the two areas using a single regression equation may be inappropriate. We use a log-likelihood ratio test to test the null hypothesis that the parameter estimates are equal for the sprawl and urban areas, $H_0 : \beta_S = \beta_U$. The relevant likelihood ratio statistic is

$$\text{LR} = -2\ln\hat{L}_O - [2\ln\hat{L}_U + 2\ln\hat{L}_S] = 379.44, \tag{3.7}$$

where O, U, and R denote the overall, urban, and sprawl study areas, respectively. Because LR exceeds the relevant 99 percent critical value from the chi-squared distribution ($\chi^2_{44} = 68.71$), we reject the null hypothesis at the 99% confidence level. This indicates that the process of residential development differs in the urban and sprawl portions of our study area. Because we have demonstrated that modeling the urban and sprawl areas separately provides results that are more statistically accurate than modeling the area as a whole, we use the disaggregated models for the remainder of our analysis.

To assess the predictive capabilities of the urban and sprawl models we apply the parameter estimates listed in Table 3.3 to (1) the 20,814 observations used to estimate the models, and (2) the random sample of $1,000$ observations that we extracted from the full sample of parcels considered to be available for residential development. To assess the predictive capabilities of the urban model, we apply the relevant parameter estimates only to those parcels located in the urban area. Likewise, to assess the predictive capabilities of the sprawl model we apply the relevant parameter estimates only to those parcels located in the sprawl area. Note that the models do not predict development with 100 percent certainty, but rather a probability of development is predicted for each parcel. As a result, it is necessary to impose a cutoff value; if the probability of development is above the cutoff value we assume the parcel is predicted by be developed. Alternately if the probability of development is below the cutoff value, we assume the parcel is predicted to remain undeveloped. We impose a cutoff value of $p = 0.20$ for both models.[18]

Table 3.4 provides information pertaining to the prediction accuracy of the models. For each observed/predicted combination Table 3.4 lists the frequency, row percent, and column percent. For example, if we consider the within-sample prediction accuracy we see that the urban model predicts a total of $5,726$ ($= 5,259 + 467$) parcels will remain undeveloped. In reality, $6,707$ ($= 5,259+1,448$) urban parcels remained undeveloped between 1999 and 2007. Of those $6,707$ parcels, the model accurately predicts $5,259$ (78%) of them. Conversely, of the $5,726$ parcels the model predicts to be undeveloped, $5,259$ were not developed between 1999 and 2007. The within-sample and random sample prediction results summarized in Table 3.4 illustrate that the models accurately predict between 76 and 84 percent of both development

[18]The cutoff value was chosen by assessing each model's within-sample prediction accuracy using different p values. The chosen p value yields high levels of accuracy for predicting occurrences of both non-development and development.

and non-development development activities. This suggests that our econometric models can be used to predict development activity with an acceptable level of statistical accuracy.

Table 3.4. Econometric Model Prediction Accuracy

Frequency
Row Pct
Col Pct

		Urban Model		Sprawl Model	
		Not Developed	Developed	Not Developed	Developed
		Predicted			
Within-Sample					
Observed	Not Developed	5259	1448	7356	1366
		78%	22%	84%	16%
		92%	50%	92%	32%
	Developed	467	1455	597	2866
		24%	76%	17%	83%
		8%	50%	8%	68%
Random Sample					
Observed	Not Developed	301	61	313	60
		83%	17%	84%	16%
		93%	44%	92%	30%
	Developed	21	78	29	137
		21%	79%	17%	83%
		7%	56%	8%	70%

3.4 Policy Analysis

To predict future development patterns we apply the econometric models' parameter estimates to a data set containing explanatory variables for all parcels still remaining undeveloped and therefore available for residential development as of 2007 (15,429 parcels). We predict whether a given parcel is likely to continue to remain undeveloped (corresponding to $p \leq 0.20$) or whether the parcel has a low, medium, or high development probability (corresponding to $0.20 < p \leq 0.47$, $0.47 < p \leq 0.73$, and $0.73 < p \leq 1.0$, respectively). To evaluate whether imposing smaller minimum lot sizes might be an effective means of curbing sprawl in the study area, development predictions are made under two scenarios:

(1) the current zoning ordinance structure and (2) a modified zoning ordinance structure. The modified zoning structure entails imposing the *CABQR2R3* zoning designation on all parcels currently zoned as either *CABQSU* or *CABQR1* (refer to footnote 15 on page 44 for definitions of the various summary zoning codes).[19] The zoning change affects 5,330 of the 15,429 parcels for which we are predicting the probability of development. Although the *CABQR2R3* zoning designation encompasses attributes other than just minimum lot size, we use *CABQR2R3* as a proxy for minimum lot size. Results are summarized in Table 3.5.

Table 3.5. Future Development Predictions

Prediction	Urban Model	Sprawl Model
Current Zoning		
Not Developed	5259	6326
	(78%)	(73%)
Develop, low probability	1097	1242
	(16%)	(14%)
Develop, medium probability	234	807
	(3%)	(9%)
Develop, high probability	117	347
	(2%)	(4%)
Modified Zoning		
Not Developed	5174	6231
	(77%)	(71%)
Develop, low probability	1142	760
	(17%)	(9%)
Develop, medium probability	251	1103
	(4%)	(13%)
Develop, high probability	140	628
	(2%)	(7%)

[a] Percentages are calculated as the number of parcels in a given prediction category divided by the total number of parcels in the urban (or sprawl) area.

Examination of the results suggests that imposing smaller minimum lot sizes is *not* an effective means of reducing sprawl. Rather, the results in Table 3.5 suggest that the smaller minimum lot size will have little effect on development in the urban area, but will increase development in the sprawl area. That is, there is a decrease in the number of parcels predicted to remain undeveloped as well as the those assigned a low probability of development, but an increase in the number of parcels assigned either a medium or high probability of development. Of the $1,034$ parcels for which the development probability increases, 148 (14

[19] *CABQR2R3* has a minimum lot size of 3,600 square feet, which is smaller than that of other zoning designations included in the model.

percent) are in the urban area, whereas the remaining 886 (86 percent) are in the sprawl area. The largest change occurs for parcels previously assigned a low (medium) probability of development under current zoning and a medium (high) probability of development under the modified zoning.

Although it would seem that imposing smaller minimum lot sizes might allow for a more dense development pattern and thus reduced sprawl, results suggest that smaller minimum lot sizes may in fact increase sprawl. A possible explanation for this result is that smaller minimum lot sizes translate into lower lot values and greater affordability. Smaller minimum lot sizes thus have the potential to make escaping the urban center more affordable.[20] This result is consistent with results derived by Carrion and Irwin (2001), who find that land with a minimum lot size of at least three acres is less likely to be developed, and that the spatial pattern of residential development is more dispersed as a result. However, other authors (e.g., Irwin et al. (2003)) have found that minimum lot sizes are positively correlated with development probabilities, i.e., a decrease in the minimum lot size is associated with a decrease in development probability.

3.5 Discussion and Conclusions

More land will be developed as cities grow to accommodate population growth, resulting in numerous negative environmental externalities, including additional sources of water pollution, decreased groundwater recharge, and increased water consumption. Improving our ability to forecast development patterns is key to improving our ability to manage urban development, urban sprawl, and the associated environmental impacts. We develop a statistical model of residential land use change in the central region of Bernalillo County, New Mexico. Our results indicate that physical characteristics (such as slopes and soils), sociodemographic differences, access to amenities, and surrounding area characteristics (such as surrounding land uses) are all statistically significant covariates. We estimate three statistical models: a model of the entire study area, an urban area model, and a sprawl area model. Estimating separate models for the entire study area and the urban and sprawl areas enables us to test the hypothesis that the vector of estimated coefficients derived from the urban model (β_U) differs from that derived using the sprawl model (β_S).

Results derived using the urban and sprawl models differ; parameter estimates vary in their signs, magnitudes, and statistical significance. We use a chi-squared test to test the null hypothesis $\beta_U = \beta_S$ and find that the model differences are statistically significant. This suggests that relationships between covariates and the pattern of residential development differ for urban and sprawl areas, and that our ability to accurately predict future development patterns is improved by using separate models for sprawl and urban areas. Applying a single statistical model to a diverse region that contains both urban and sprawl areas may yield

[20] This explanation is supported by the negative sign on *Bosque* in the sprawl-area logit models. Although it would appear that access to the bosque decreases the probability of development, our assessment is that the bosque serves as a proxy for the central portion of the city, and that the negative sign on *Bosque* indicates people's desire to live in areas further removed from the city center. Smaller minimum lot sizes make living in areas removed from the city center more affordable; i.e., smaller minimum lot sizes make sprawl more affordable.

inaccurate predictions and result in inappropriate management and regulatory approaches that have unintended and negative consequences for urban development, urban sprawl, and the environment. Our result has important implications for the Albuquerque-area, and potentially for other geographic areas as well.

We use the model to predict future residential development patterns under current and revised zoning designations. The change in zoning designation is intended to reflect a move toward smaller minimum lot sizes, with the aim of encouraging higher development densities and less sprawl. The zoning change does not dramatically alter urban-area development predictions. However, differences do occur in the sprawl area where the number of parcels assigned low, medium, and high probabilities of future development change by −72%, 72%, and 205%, respectively. The zoning change we assess therefore causes a decrease in the number of parcels in the sprawl area assessed a low probability of development, and an increase in the number of parcels in the sprawl area assessed either a medium or high probability of development. Rather than mitigating sprawl, the smaller lot size encourages sprawl. This suggests that, although reducing minimum lot sizes may seem like an avenue for increasing development densities and reducing sprawl, reducing minimum lot sizes may have the opposite effect. Other studies that include a measure of lot size have yielded mixed results. Thus it appears that either the effect of minimum lot size on development probabilities may vary from area to area, and/or that more analysis is necessary to correctly ascertain the relationship between lot size and residential development probabilities.

Chapter 4

Conclusions

Water quantity and quality issues will become increasingly important in U.S. as populations continue to rise. Nonpoint pollution from agricultural and urban areas is the largest contributor to current water quality problems in the United States. While there is a large literature dealing with point source pollution, there is relatively little research that deals with nonpoint source pollution. Two separate, but potentially intertwined aspects of nonpoint source pollution are considered in this research: (1) regulation of agricultural nonpoint pollution and (2) the conversion of land from vacant or agricultural use to residential use.

We first consider the efficiency of imposing taxes and standards on agriculture to reduce nonpoint source contributions from the agricultural activities. While taxes and standards have been well studied in the literature, several complexities are not included in the extant research. Paramount among these is the inclusion of farmers' risk preferences, which we incorporate through the use of a Just-Pope production function. Including risk aversion significantly complicates the outcome: blanket statements concerning the efficiency of taxes or standards to regulate nonpoint source pollution cannot be made; there is not a one size fits all solution. Rather, the efficient policy needs to be evaluated on a case-by-case basis.

To demonstrate how risk aversion might affect mechanism choice a simplified version of the theoretical model is applied to Oklahoma corn production. We assess the effect of risk preferences on mechanism choice under numerous scenarios: high and moderate risk aversion, risk-increasing and risk-decreasing inputs, and considering the effect of risk aversion on (a) the Weitzman term only and (b) the Weitzman term and one of the terms introduced by the inclusion of risk preferences. The empirical analysis illustrates that risk aversion can significantly affect the choice of regulatory mechanism.

The second issue we address is that of residential land use change. More land is developed as cities grow to accommodate larger populations, thereby altering the characteristics of the landscape and resulting in greater quantities of runoff to surface waters and new nonpoint source pollution sources. Better management of nonpoint source pollution from urban areas requires improving our ability to forecast urban development patterns. We develop an econometric model of land use change for Albuquerque, NM and the surrounding rural area. Our analysis approach differs from that used in prior research in that we model the urban and sprawl portions of our study area both jointly and separately in order to test our hypothesis that the process of residential development differs in urban and sprawl areas. Results indicate that development forces do indeed differ in urban and sprawl areas, and that using a single model to predict future development patterns in a diverse region may yield inferior and inaccurate results and inappropriate regulatory policies. This has important policy implications, as econometric models may be used to assess alternate regulatory policies intended to reduce sprawl. Assessing regulatory policies with a "one-size-fits-all" model may result in ineffective policies with potentially undesirable consequences. We use our model to assess the effectiveness of using smaller minimum lot sizes to encourage infill developments and reduce the occurrence of sprawl. Results indicate that rather than reducing sprawl, smaller minimum lot sizes would actually *increase* sprawl in the Albuquerque area.

The research presented herein is a first step in a larger research agenda aimed at developing a model that encompasses both agricultural and urban nonpoint pollution. It is important to consider these two primary water pollution sources jointly, as reductions in agricultural nonpoint pollution may yield an increase in urban nonpoint pollution. That is, attempts to regulate and reduce agricultural nonpoint pollution will increase farmers' costs and thus decrease their profits. As a consequence, farmers may opt for subidiving and selling their farms rather than continuing to operate at reduced profit levels. Although the subdivision and sale of farmland would indeed reduce agricultural nonpoint pollution levels, the subsequent rise in urban nonpoint pollution is an unintended consequence of the agricultural nonpoint pollution regulation. Water quality concerns would be more effectively and efficiently addressed if an integrated model of agricultural and urban nonpoint pollution were used to aid in the design of regulatory programs for controlling nonpoint pollution sources. Such an integrated assessment and regulatory approach would be especially fruitful for improving water quality in areas such as California and Colorado, which have agriculture and urban uses competing for scarce land resources.

In addition to developing a model that incorporates the regulation of both agricultural and urban nonpoint pollution, several other potential avenues of research exist. For example, numerous complexities relevant to agricultural production are not yet reflected in the theoretical model presented in Chapter 2. Such complexities include price uncertainty (another form of risk farmers face that may offset farmers' responses to production uncertainty (Isik, 2002)), asymmetric information, and multiple inputs (the model we present assumes only one input to the production process). The model could also be extended to include multiple crops; as illustrated by Lambert (1990), the ability to switch crops can mitigate the effects of taxes and standards. Alternate assumptions regarding the specific form of risk aversion could be incorporated; we have imposed constant absolute risk aversion (CARA), although several studies of farmers' risk preference structure have rejected CARA in favor of decreasing absolute risk aversion. Numerous extensions could also be made to the research presented in Chapter 3. Spatial autocorrelation is clearly of concern for a data set such as ours; in future research we will address spatial autocorrelation concerns. Because our data set includes information pertaining to the number and timing of building permits filed for each parcel, we will be able to consider residential development density and timing issues. Finally, our data set may allow us to consider differences that may exist in the development process of agricultural lands and that of vacant lands.[1]

[1] The issue of how the development process of agricultural lands differs from that of vacant land is an important consideration. However, because there are relatively few parcels classified as agricultural in our data set, such analysis may not be possible.

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