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Targeting Farm Income and Nutrient Runoffs through Agrienvironmental Policy Mixes: Experience from Finland

INTRODUCTION

Recent agricultural policy and trade reforms are expected to improve the environmental performance of the agricultural sector as a result of the reinstrumentation of domestic agricultural policies from market price supports to decoupled direct payments. However, directed agrienvironmental policies must still play an important role in internalizing environment-related agricultural externalities.

Agricultural pollution is a typical example of non-point source pollution, which makes control and monitoring very difficult. Hence traditional direct instruments, such as effluent standards and effluent taxes, are inapplicable in agriculture. When effluents cannot be dealt with directly, the regulator has to use indirect instruments, for example input and ambient taxes and standards on farming practices (see, for example, Segerson, 1988; Braden and Segerson, 1993, for theoretical analysis and Vatn *et al.*, 1997, for applied research and interdisciplinary modelling of agricultural non-point pollution).

One of the major objectives of the Finnish application of European Union agrienvironmental regulation EEC 2078/92 is the reduction of nutrient runoffs. In what follows we assume that the government issues decision-in-principle water protection targets for the reduction and prevention of eutrophication, with the main goal of reducing nutrient runoffs from agriculture. From this starting point we consider how this kind of agrienvironmental policy should be executed by focusing on those policy instruments that are appropriate for achieving this goal (area-based subsidy, price support, fertilizer tax and buffer zone subsidy). Specifically, we assume that the government adjusts the relative rates of taxes and subsidies so that farmers' profits are kept constant (see Ollikainen, 1999). Consequently, however, the relative prices of inputs change so that the environmentally friendlier input use becomes more profitable and the farmer reoptimizes input use. We characterize alternative tax/subsidy mixes first qualitatively and then quantitatively by using a parametric simulation model, into which agrienvironmental measures can be introduced. The analysis is based on a standard profit maximization model of a representative farmer.

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THE MODEL OF AGRICULTURAL PRODUCTION

Consider a competitive farm producing cereals using fertilizer l and capital k as inputs in the production. The total amount of arable land q is fixed, and the farmer can allocate it to cereal production $\hat{q}$ and to a buffer zone m (m is a share of total arable land) so that the acreage under cereal cultivation is $\hat{q} = (1 - m)q$. By a buffer zone we mean a managed, uncultivated area covered by perennial vegetation between arable land and watercourses. The aim is to reduce surface water pollution from nutrient runoffs.

The production function is given by:

$$Q = f(l, \hat{q}, k) \tag{1}$$

where Q denotes the cereal produced. That obviously depends on the use of fertilizer and capital, and on the area under cultivation. We assume that the quality of land is diminishing so that the production function is concave in its arguments; that is, each factor of production exhibits diminishing marginal productivity and the production function is linear homogeneous. Thus we have

$$f_l, f_k, f_q > 0; f_{ll}, f_{kk}, f_{qq} < 0 \tag{2}$$

For the buffer zone it holds that $f_m = -qf_q < 0; f_{mm} = q^2 f_{qq} < 0$.

We make the following assumptions concerning the cross-derivatives. Fertilizer and capital are assumed to be independent of each other; that is, their cross-derivative is zero. The same assumption holds for capital and soil. This can be justified on the grounds that technological improvements (like precision farming) are not feasible in the short run and thus an increase in capital does not increase the marginal product of soil. The cross-derivative of fertilizer and soil is positive, implying that these inputs are complements to each other. Thus an increase in fertilizer use increases the marginal product of soil. The sign of the cross-derivative between fertilizer use and land allocated to the buffer zone depends on the quality of land (especially in the field edges). If agricultural land is homogenous then allocating part of it to a buffer zone does not affect the marginal productivity of fertilizer. But if the land in the edge of the field is of lower (higher) quality, then allocating a part of it to the buffer zone will increase (decrease) the marginal productivity of fertilizers. In this paper we assume that the latter case is relevant for the analysis. Summing up, we impose the conditions that

$$f_{ql} > 0, f_{lk} = 0 = f_{qk} \text{ and } f_{lm} = -qf_{lq} < 0$$

The representative farmer, by assumption, is a price taker. Hence the prices of fertilizer c, capital r and cereal p are exogenous. The government pays a price support a so that the unit price of cereal is $p^* = p(1 + a)$. Moreover, a fertilizer tax t is levied on fertilizer use so that the after-tax price of fertilizer is $c^* = c(1 + t)$. For buffer zones the government pays a subsidy

b. The cultivated arable land is entitled to a unit acreage subsidy s. The farmer's problem is to choose the input use of l, k and m to maximize the farm's profit; that is,

$$\underset{\{l,k,m\}}{Max}\,\Pi = p^* f(\hat{q},l,k) - c^* l - rk + bmq + s\hat{q} \tag{3}$$

The first-order conditions for the optimal choice of inputs are the following:

$$\begin{aligned} \Pi_l &= p^* f_l - c^* = 0 \\ \Pi_k &= p^* f_k - r = 0 \\ \Pi_m &= -p^* q f_q + (b-s)q = 0 \end{aligned} \tag{4}$$

These first-order conditions require that the value of the marginal product of fertilizer and capital use equal the fertilizer price and the price of capital, respectively. Moreover, the land allocated to the buffer zone will be increased to the point where the reduction of the value of the marginal product of cultivating cereal equals the difference between the buffer zone subsidy and acreage subsidy. Note that the buffer zone subsidy must be greater than the acreage subsidy for an interior solution.

Comparative statics of input use

Given that the second-order conditions hold, we can derive the comparative-static analysis by perturbing the first-order conditions with respect to exogenous variables to obtain the following (see Appendix 1 for details):

$$\begin{aligned} l &= l(\underset{+}{p},\underset{-}{c},\underset{0}{r},\underset{-}{b},\underset{+}{s},\underset{-}{t},\underset{+}{a}) \\ k &= k(\underset{+}{p},\underset{0}{c},\underset{-}{r},\underset{0}{b},\underset{0}{s},\underset{0}{t},\underset{+}{a}) \\ m &= m(\underset{-}{p},\underset{+}{c},\underset{0}{r},\underset{+}{b},\underset{-}{s},\underset{+}{t},\underset{-}{a}) \end{aligned} \tag{5}$$

Equation (5) shows that input demand depends on exogenous parameters in the usual way; that is, the own-price effects are negative. More specifically, the use of fertilizer and capital depends positively on the output price, while the size of the buffer zone is negatively related to it. Increasing the buffer zone subsidy results in reduced fertilizer use and a larger buffer zone. An increase of acreage subsidy boosts the use of fertilizer and decreases the buffer zone area, whereas a fertilizer tax has the opposite effects. Higher producer price support, a, increases the use of fertilizer and capital and decreases the land area allocated to the buffer zone. Thus the area subsidy and producer price support tend to re-enforce environmental distortions, since they encourage the use of fertilization and discourage the allocation of arable land to the buffer zone.

Comparative statics of output supply

The comparative-static analysis of output supply is derived in Appendix 2, equation [A2.3]. It shows that the output supply depends on exogenous parameters in the conventional way. Increases in factor prices, fertilizer tax and buffer zone subsidy will decrease supply, while increases in output price, producer price support and acreage subsidy will increase output supply.

ENVIRONMENTAL EFFECTIVENESS OF ALTERNATIVE AGRIENVIRONMENTAL POLICY MIXES

Assume now that the government issues decision-in-principle water protection targets for the reduction and prevention of eutrophication and wishes to design an agrienvironmental policy so that it keeps the profits of the farmer constant. This latter goal can be achieved by changing one instrument and compensating it by a change in another. Before going into a detailed analysis of the policy, we must clarify first how to model the nitrogen runoff from the fields.

Runoff function of nutrients

Consider the following runoff function for nutrients:

$$z = g(l, \alpha, m) \tag{6}$$

This formulation, based on an economic interpretation of empirical runoff studies, was first proposed in Ollikainen (1995). According to (6), the runoff, z, depends on three factors: fertilizer use l, the gradient of fields near watercourses α and the size of the buffer zone m. The runoff depends positively on fertilizer use and on the gradient coefficient, and negatively on the size of the buffer zone. The coefficient can be regarded as a function of the size of the buffer zone; the larger the area allocated to it, the smaller the impact of the gradient coefficient on runoff, so we have $\alpha = \alpha(m)$. Thus the runoff from fields can be described as a function of fertilizer use l and $\alpha(m)$. The runoff function is assumed to be convex in l and concave in $\alpha(m)$:

$$z = \alpha(m)g(l) \tag{7}$$

where $g'(l) > 0; g''(l) > 0$ and $\alpha'(m) < 0; \alpha''(m) > 0$.

According to Gilliam *et al.* (1997), buffer zones are very effective in the removal of sediment-associated nitrogen from surface runoff and nitrate from subsurface flows, with removals of 50–90 per cent being common. However, the effectiveness of buffer zones in removing nutrients from surface and groundwater is highly dependent on hydrology. For example, surface flows should occur as sheet flow rather than focused flows, and groundwater should move at a slow speed through the buffer in order to remove nitrates effectively

(Correll, 1997). According to Hill (1996), vegetation uptake and microbial denitrification are two major mechanisms in buffer zones for removing nitrates from subsurface water, though the relative importance of these two processes is uncertain. Moreover, as pointed out by Gilliam *et al.* (1997), the increased denitrification in buffer zone areas may trade water pollution for atmospheric pollution due to increased generation of NO_2.

Environmental and supply effects of alternative policy mixes

The principle of changing the relative tax and subsidy rates so that the farmer's profits remain constant implies that, when one instrument entering into the profit function is increased, another instrument is decreased, so that profits remain constant. This kind of switch in the tax/subsidy rates changes the relative prices of inputs in favour of environmentally friendlier production, leading the farmer to reoptimize input use. Hence, after reoptimization, the farmer's profits may be higher or lower than before policy implementation, even though the government's net impact on the profit function remains unchanged. Notice that the government budget revenue constraint is not binding. This means that, after the farmer has reoptimized input use, the required overall net support may be higher or lower than before the policy. Hence this policy can be interpreted as reflecting a situation where the government finds the size of environmentally adjusted agriculture to be optimal and allows the overall net support to adjust as necessary. The basic features of this are outlined in equations (8)–(10).

Differentiating the profit function (3) with respect to t, b, s and a, while keeping the profits constant, gives the following differential equation to guide the instrument switches

$$0 = pf(\cdot)da - cldt + mqdb + \hat{q}ds \tag{8}$$

The resulting change in the agricultural runoff of nutrients is given through changes in fertilizer use and buffer zone area

$$dz = \underbrace{\alpha'(m)g(l)dm}_{(-)} + \underbrace{\alpha(m)g'(l)dl}_{(+)} \tag{9}$$

where the adjustment in the farmer's use of fertilizer (dl) and the buffer zone (dm) is given by the following differential equations, in which i and j denote the policy instruments that the government is adjusting:

$$\begin{aligned} dl &= l_i di + l_j dj \\ dm &= m_i di + m_j dj \end{aligned} \tag{10}$$

In what follows we study the qualitative effects of four alternative agrienvironmental policy mixes. First, the producer price support or acreage subsidy is reduced, and the environmentally motivated buffer zone subsidy is increased to compensate for this reduction. This derivation is followed by the analysis of fertilizer tax increase, which is compensated by an increase in acreage subsidy and buffer zone subsidy, respectively.

Policy mix 1 This involves a decrease in the producer price support and an increase in the buffer zone subsidy. As a result of intensification effects and related nutrient runoff, the government wishes to switch from producer price support towards buffer zone subsidy while keeping profits constant. From $mqdb + pf(\cdot)da = 0$ we obtain the required compensation to keep the profits constant:

$$da = -\frac{mq}{pf(\cdot)}db \tag{11}$$

Using (11) in (10) and applying comparative static results from input use (equation (5)) produces

$$\frac{dl}{db} = \left[-\frac{mq}{pf(\cdot)}\underset{(+)}{l_a} + \underset{(-)}{l_b}\right] < 0 \quad \text{and} \tag{12a}$$

$$\frac{dm}{db} = \left[-\frac{mq}{pf(\cdot)}\underset{(-)}{m_a} + \underset{(+)}{m_b}\right] > 0 \tag{12b}$$

Applying these results to equation (9) yields the following effect on agricultural nutrient runoff:

$$dz = \underbrace{\alpha'(m)g(l)}_{(-)}\underset{(+)}{\frac{dm}{db}} + \underbrace{\alpha(m)g'(l)}_{(+)}\underset{(-)}{\frac{dl}{db}} < 0 \tag{13}$$

Thus a switch from a producer price support towards a buffer zone subsidy decreases the use of fertilizers and increases the buffer zone area, resulting in unambiguously reduced nutrient runoffs. The shift also reduces output supply (see Appendix 2).

Policy mix 2 Here we have a decrease in the acreage subsidy and an increase in the buffer zone subsidy. Because of the production-stimulating and negative environmental side-effects of area subsidy, the government switches from that to a buffer zone subsidy. Applying the same procedure given in the previous policy mix, one obtains:

$$\frac{dl}{db} = \left[-\frac{m}{(1-m)}\underset{(+)}{l_s} + \underset{(-)}{l_b}\right] < 0 \quad \text{and} \tag{14a}$$

$$\frac{dm}{db} = \left[-\frac{m}{(1-m)}\underset{(-)}{m_s} + \underset{(+)}{m_b}\right] > 0 \tag{14b}$$

Using these results in equation (9) shows that the runoff decreases unambiguously. This policy mix also results in reduced output (see Appendix 2).

Policy mix 3 This policy mix includes an increase in the fertilizer tax and a rise in the acreage subsidy. Assume that the government increases the fertilizer tax and compensates this by increasing the acreage subsidy. From equations (15a) and (15b) it can be seen that the effects are ambiguous, at first, but by using comparative static results (see Appendix 3 for details of proving the sign) the signs of the effects are as follows:

$$\frac{dl}{ds} = \left[\frac{1}{cl} \underset{(-)}{l_t} + \underset{(+)}{l_s}\right] < 0 \qquad \text{and} \qquad (15a)$$

$$\frac{dm}{ds} = \left[\frac{1}{cl} \underset{(+)}{m_t} + \underset{(-)}{m_s}\right] > 0 \qquad (15b)$$

Hence this switch also results in unambiguously reduced nutrient runoffs according to (9). However, the effect may now be weaker than in the previous cases since the increase in the acreage subsidy reduces the impact of the fertilizer tax. The output supply decreases as well, but this reductive effect may be weaker than in the previous cases owing to production-stimulating effects of the acreage subsidy (see Appendix 2).

Policy mix 4 Finally, we have an increase in the fertilizer tax and an increase in the buffer zone subsidy. In this alternative, the government establishes its agrienvironmental policy by increasing the fertilizer tax and compensating this by increasing the buffer zone subsidy in order to have a substantial reduction in nutrient runoff. This leads to

$$\frac{dl}{db} = \left[\frac{mq}{cl} \underset{(-)}{l_t} + \underset{(-)}{l_b}\right] < 0 \qquad \text{and} \qquad (16a)$$

$$\frac{dm}{db} = \left[\frac{mq}{cl} \underset{(+)}{m_t} + \underset{(+)}{m_b}\right] > 0 \qquad (16b)$$

As in the previous cases, applying these results in equation (9) results in unambiguously reduced nutrient runoff. However, in this case the reductive effect on nutrient runoff is stronger, since the fertilizer tax and buffer zone subsidy reinforce each other. Naturally, the output supply decreases as well, and the effect is stronger than in the previous cases (see Appendix 2).

On the basis of the qualitative analysis, we can conclude that a policy mix of equation (16a) and (16b) is superior in terms of achieving the environmental goals, but it reduces output more than other mixes. As we cannot rank the other mixes qualitatively, it is useful to conduct a quantitative analysis.

PARAMETRIC MODEL AND SIMULATIONS

In this section we illustrate and compare numerically the environmental and economic effects of alternative agrienvironmental policy mixes developed in the previous section. For this purpose we build a parametric model of agricultural production with exogenous crop price, and execute the instrument mixes 1–4. Then we briefly rank the instrument mixes. As all switches will have the property of keeping the profits constant and achieving the environmental target (10 per cent reduction in nitrogen runoffs), these cannot be the yardsticks of ranking. Therefore we adopt the following properties as means of comparison. First we calculate the increase in the government net support per hectare required to keep the farmer's profits constant when nitrogen runoffs are reduced by 10 per cent. Then we calculate net support per output when profits are kept constant, and, finally, we compare the policy mixes in terms of the output produced per runoff to highlight the 'eco-efficiency' aspects of policy mixes.

Parametric model

Following the theoretical model, we start with agricultural production function and apply a quadratic nitrogen response function (with parameters estimated for barley) and augment it with buffer strips as follows:

$$y = a(1-\phi m^2) + \alpha l + \beta l^2 \tag{17}$$

where
a = production of unfertilized land,
l = fertilizer applied,
ϕm^2 = the share of output lost from unfertilized land if a share m of land is allocated to buffer strip.

We use the nitrogen leakage function estimated by Simmelsgaard (1991) on the basis of Danish leakage research:

$$y(N) = y_n \exp(b_0 + bN) \tag{18}$$

where $y(N)$ = nitrogen leakage at fertilizer intensity level N, kg/ha., y_n = nitrogen leakage at average nitrogen use, b_0 = a constant (<0), b = a parameter (>0) and N = relative nitrogen fertilization in relation to normal fertilizer intensity for the crop, $0.5 \leq N \leq 1.5$.

This leakage function measures changes in nitrogen leakages solely as a function of the fertilization intensity level. Information on average fertilizer intensity and nitrogen leakages from average nitrogen use y_n is needed when applying this function to Finnish conditions. In the Finnish experimental studies on nitrogen leaching, the average nitrogen fertilization level for cereals has usually been 100kg/ha. Combined surface and drainage nitrogen leakages (y_n) at this level have been in the order of 10–20kg N/ha. (Sumelius, 1994).

We modify the leakage function to incorporate the reductive effect of buffer zone on nitrogen runoff Z as follows

$$Z = (1-jr)y(N) \tag{19}$$

where Z = nitrogen runoff, $y(N)$ = nitrogen leakage at fertilizer intensity level N, kg/ha., j = share of the surface runoff from combined surface and drainage runoff, and r = nitrogen removal effectiveness of buffer zone.

In Finland, Uusi-Kämppä and Yläranta (1992, 1996) have analysed the reductive effects of a grass buffer zone 10 metres wide on sediment and nutrient losses. Barley and oats were cultivated on experimental fields during the experimental period with fertilization levels of 90kg of nitrogen per hectare and 18kg of phosphorus per hectare. A grass buffer zone reduced surface runoff of total nitrogen and nitrates by 50 per cent. Note, however, that buffer zones reduce surface runoff of nutrients, but not runoff through drainage pipes. For example, in Finnish experiments measuring total nitrogen runoff from cultivated fields, over 50 per cent ran through drainage pipes (Turtola and Jaakkola, 1985; Turtola and Puustinen, 1998).

On the basis of these Finnish experimental studies on grass buffer zones and on the leaching of nitrogen, we make the following assumptions. In the policy simulations we assume that 50 per cent of the total nitrogen load is surface runoff (that is, parameter value j is 0.5) and a grass buffer zone, 10 metres wide, is able to reduce 50 per cent of the total nitrogen of this surface runoff. Thus parameter value r is set at 0.5. Moreover, since in Finnish experimental studies combined surface and drainage nitrogen leakages (y_n) at fertilization level 100kg N/ha. have been in the order of 10–20 kg N/ha., parameter value y_n is set at 15 in simulations.

Policy simulations

Parameter values used for the policy simulations are reported in Table 1. A quadratic nitrogen response function for barley has been estimated by Bäckman *et al.* (1997) on the basis of the long-term field trials (1973–93).

The base simulation of our parametric model is chosen to represent the policy regime for cereals (barley) in Finland in 1999. We execute the policy mixes 1–4 so as to reduce nitrogen runoffs by 10 per cent (from 18.6kg N/ha. in base simulation to 16.8kg N/ha. in policy mixes) while keeping the farmer's profits constant. Then we compare the effects of policy mixes 1–4 with each other and with the base simulation in terms of government net support per hectare and per output produced, as well as in terms of output per runoffs.

Simulation results

The simulation results for the policy mixes are given in Table 2 in terms of production, government net support per hectare, net support per kilogram of barley produced, and kilogram of barley produced per kilogram of nitrogen runoff.

All policy mixes achieved the required 10 per cent reduction target in nitrogen runoff. If we focus on the net support per hectare, then policy mixes 1, 2 and 4 achieve runoff reduction of 10 per cent even with lower government net support per hectare than in the base scenario. Hence these policy mixes give a more efficient instrument base than the current one, because with less

TABLE 1 *Simulation parameters*

p	= price of barley, FIM 0.73/kg,
c	= price of nitrogen fertilizer, FIM 5.95/kg,
a	= constant parameter of response function, 1010 for barley,
α	= parameter of quadratic nitrogen response function, 52.9 for barley,
β	= parameter of quadratic nitrogen response function, –0.173 for barley,
y_n	= nitrogen leakage at average nitrogen use, 10–20kg/ha.,
b	= the value of b and $b0$ is 0.7, based on Danish leakage experiments,
N	= relative nitrogen fertilization level, that is, optimal rate from economic model in relation to normal intensity for the crop,
j	= share of surface runoff from combined surface and drainage runoff,
r	= nitrogen removal effectiveness of buffer strip,
s	= area support, FIM 2402 per hectare,
B	= buffer zone support, FIM 3200–3600 per hectare.

Notes: Prices and support figures are from 1999. Price of nitrogen is calculated from compound fertilizer N–P–K. Area support is calculated for the support area A and it includes Common Agricultural Policy (CAP) compensation payments, environmental aid, and national support for crop production.

Sources: Bäckman *et al.* (1997), Ministry of Agriculture and Forestry, Association of Rural Advisory Centres.

TABLE 2 *Per hectare effects of alternative agrienvironmental policy mixes: 10 per cent of nitrogen runoffs are reduced and farmer's profits are kept constant*

Policy mix[1]	Production (kg/ha.)	Net support, (FIM/ha.)	Net support/ production (FIM/kg)	Production/ runoffs
Base	4 620	2 407	0.52	248
Policy mix 1	4 270	2 385	0.56	254
Policy mix 2	4 248	2 390	0.56	252
Policy mix 3	4 581	2 479	0.54	272
Policy mix 4	4 274	2 395	0.56	254

Notes: [1]Policy mix 1 = price support ↓ buffer zone subsidy ↑; policy mix 2 = acreage subsidy ↓ buffer zone subsidy ↑; policy mix 3 = fertilizer tax ↑ acreage subsidy ↑; policy mix 4 = fertilizer tax ↑ buffer zone subsidy ↑.

support we have better environmental quality and still the profits remain unchanged. Note, however, that in terms of output produced the required net support will increase.

If our yardstick is the net support per output produced, notice first that agricultural production decreases in all policy mixes, mainly because of a higher share of buffer zone in policy mixes 1, 2 and 4 and to reduced fertilizer use in policy mix 3. Policy mix 3, which compensates for the fertilizer tax with higher acreage subsidy, is second to none with respect to level of production. Therefore, policy mix 3 is the best one if our yardstick is the net support per unit of output produced. Moreover, owing to the higher level of production, policy mix 3 is second to none also with respect to the criterion of weight of barley produced per kilogram of nitrogen runoff. Hence we can conclude that, if either net support per output produced or output per runoff is used as the yardstick, policy mix 3 performs best. If net support per hectare is the yardstick, mix 1 is optimal.

CONCLUSIONS

We have analysed agrienvironmental policy in a simple model of agricultural production, where the farmer chooses the use of inputs so as to maximize profits. The input choice was affected by price support, fertilizer tax, buffer zone subsidy and area subsidy. Having determined the comparative static effects of these instruments, we studied both theoretically and empirically an agrienvironmental policy where the government searches for the best combination of instruments so as to promote environmental goals, while keeping the farmer's profits constant.

We demonstrated that an area subsidy and a producer price support create environmental distortions, since they encourage the use of fertilizer and discourage the allocation of arable land to the buffer zone. Thus, when land allocation is endogenized through the choice of a buffer zone, an area subsidy becomes a distortionary instrument. This clearly contradicts the conventional wisdom, which regards it as neutral. When alternative agrienvironmental policy mixes were theoretically evaluated from the viewpoint of environmental effectiveness, all policy options resulted in an unambiguously reduced nutrient runoff from agriculture. However, a policy mix which compensated for the increase in the fertilizer tax with higher buffer zone subsidy had the strongest reducing effect on nutrient runoff, since the instruments reinforced each other.

Policy simulations showed that all policy mixes achieve the target of 10 per cent reduction of nitrogen runoff. Moreover, policy mixes 1, 2 and 4 achieve runoff reduction with lower government net support per hectare than in the base scenario. Policy mix 3, which compensates for the fertilizer tax with higher acreage subsidy, was second to none with respect to level of production but performed poorly with respect to net support per hectare criterion. However, because of the higher level of production than in other policy options, policy mix 3 performed best with respect to the criteria of net support per unit of output produced and output produced against runoff.

To conclude, through selecting the correct instrument combination and adjusting the level of instruments, government is able to keep farmers' profits constant and to reduce nitrogen runoffs while keeping the required net support at its minimum. The selection of the policy mix depends on the weight given for production effects.

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APPENDIX 1: COMPARATIVE STATICS OF INPUT USE

The profit function of the representative farmer is

$$\Pi = p^* f(\hat{q}, l, k) - c^* l - rk + bmq + s\hat{q} \tag{A1.1}$$

where $\hat{q} = (1-m)q$.

The first-order conditions for profit maximization are

$$\begin{aligned} \Pi_l &= p^* f_l - c^* = 0 \\ \Pi_k &= p^* f_k - r = 0 \\ \Pi_m &= -p^* q f_q + (b-s)q = 0 \end{aligned} \tag{A1.2}$$

Sufficient conditions for profit maximization require that the second partial derivatives are negative:

$$\begin{aligned} \Pi_{ll} &= p^* f_{ll} < 0 \\ \Pi_{mm} &= p^* q^2 f_{qq} < 0 \\ \Pi_{kk} &= p^* f_{kk} < 0 \end{aligned} \tag{A1.3}$$

The cross-partial derivatives are imposed as

$$\begin{aligned} \Pi_{lk} &= 0 = \Pi_{kl} \\ \Pi_{km} &= 0 = \Pi_{mk} \\ \Pi_{lm} &= -p^* q f_{lq} < 0 \end{aligned} \tag{A1.4}$$

Moreover, profit maximization requires that the determinant of the Hessian matrix is negative definite:

$$H = \begin{bmatrix} p^* f_{ll} & 0 & \Pi_{lm} \\ 0 & p^* f_{kk} & 0 \\ \Pi_{lm} & 0 & p^* q^2 fqq \end{bmatrix} \tag{A1.5}$$

$$\Delta = p^* f_{kk} [p^{*2} f_{ll} f_{qq} - \Pi_{lm}{}^2] < 0$$

In order to solve comparative statics, the first-order conditions are differentiated with respect to parameters, and then Cramer's Rule is applied to sign the effects.

APPENDIX 2: OUTPUT SUPPLY AND ALTERNATIVE AGRIENVIRONMENTAL POLICY MIXES

A Output supply

The supply function can be derived from the profit function by differentiating the profit function (3) with respect to output price (Hotelling's lemma), to give

$$\frac{\partial \Pi}{\partial p} = f(\hat{q}, l, k) \tag{A2.1}$$

so that we obtain the production function of this farm. Next we substitute the optimal input use into the production function and we get the profit maximizing level of output:

$$Y^* = f(m^*, l^*, k^*) \tag{A2.2}$$

Thus the supply function of this farm is

$$Y^* = Y^*(\underset{+}{p}, \underset{-}{c}, \underset{-}{r}, \underset{-}{b}, \underset{+}{s}, \underset{-}{t}, \underset{+}{a}) \tag{A2.3}$$

B The effects of alternative agrienvironmental reforms on output supply

A decrease in the producer price support and an increase in buffer zone subsidy:

$$dY = \underset{(+)}{f_k} \underset{(-)}{\frac{\partial k}{\partial b}} + \underset{(+)}{f_l} \underset{(-)}{\frac{\partial l}{\partial b}} + \underset{(-)}{f_m} \underset{(+)}{\frac{\partial m}{\partial b}} < 0 \tag{A2.4}$$

A decrease in acreage subsidy and an increase in buffer zone subsidy:

$$dY = \underset{(+)}{f_k} \underset{(0)}{\frac{\partial k}{\partial b}} + \underset{(+)}{f_l} \underset{(-)}{\frac{\partial l}{\partial b}} + \underset{(-)}{f_m} \underset{(+)}{\frac{\partial m}{\partial b}} < 0 \tag{A2.5}$$

An increase in fertilizer tax and a rise in acreage subsidy:

$$dY = \underset{(+)}{f_k} \underset{(0)}{\frac{\partial k}{\partial s}} + \underset{(+)}{f_l} \underset{(-)}{\frac{\partial l}{\partial s}} + \underset{(-)}{f_m} \underset{(+)}{\frac{\partial m}{\partial s}} < 0 \tag{A2.6}$$

An increase in fertilizer tax and an increase in buffer zone subsidy:

$$dY = \underset{(+)}{f_k} \underset{(0)}{\frac{\partial k}{\partial b}} + \underset{(+)}{f_l} \underset{(-)}{\frac{\partial l}{\partial b}} + \underset{(-)}{f_m} \underset{(+)}{\frac{\partial m}{\partial b}} < 0 \tag{A2.7}$$

APPENDIX 3: A PROOF FOR THE SIGNS OF (15A) AND (15B)

The government increases fertilizer tax and compensates for this with an increase in the acreage subsidy. One has for the fertilizer use

$$\frac{dl}{ds} = \left[\frac{1}{cl} \underset{(-)}{l_t} + \underset{(+)}{l_s} \right] \tag{A3.1}$$

Using the comparative statics effects yields

$$\underset{(-)}{\Delta}^{-1}\left[(\Pi_{lm} pf_{kk} q) + (cpf_{kk} pq^2 f_{qq}) + (clpf_{kk}\Pi_{lm})\right]$$

$$= \underset{(-)}{\Delta}^{-1}\left[\underbrace{\Pi_{lm}(pf_{kk}q + clpf_{kk})}_{(+)} + \underbrace{(cpf_{kk} pq^2 f_{qq})}_{(+)} \right] < 0$$

The change in the buffer zone is given by

$$\frac{dm}{ds} = \left[\frac{1}{cl} \underset{(+)}{m_t} + \underset{(-)}{m_s} \right] \tag{A3.2}$$

The relevant comparative statics effects are

$$m_s = \underset{(-)}{\Delta}^{-1}\left[qp^2 f_{ll} f_{kk}\right]$$

$$m_t = \underset{(-)}{\Delta}^{-1}\left[clp^2 f_{ll} f_{kk}\right] \underbrace{- \underset{(-)}{\Delta}^{-1}\left[c\Pi_{lm} pf_{kk}\right]}_{(+)}$$

Using these in (A3.2) yields

$$\underset{(-)}{\Delta}^{-1}\left[-qp^2 f_{ll} f_{kk} - \frac{1}{l}\Pi_{lm} pf_{kk} + qp^2 f_{ll} f_{kk} \right] > 0$$