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Multifunctional Agriculture: A Framework and Policy Design

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Multifunctional agriculture: A framework and policy design

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Abstract

We study the multifunctional character of agriculture in a model of endogenous input use and land allocation augmented by biodiversity, landscape amenity, and nutrient runoff. While biodiversity and landscape amenities represent the public good aspects of agriculture, nutrient runoff represents its negative externalities. We show that the private use of fertilizer input is higher and the size of buffer strips lower than the socially optimal solution requires. Also the socially optimal land allocation differs from the private solution due to the valuation of landscape diversity and runoff damages. The optimal policy is to use a differentiated fertilizer tax and a differentiated buffer strip subsidy and to determine their levels by the equality between the net value of their marginal product in food production and their effects on the marginal valuation of diversity and runoff damage in each parcel. We characterize empirically socially optimal multifunctional agriculture and the optimal design of the policy instruments by using Finnish data.

Key words: biodiversity, first-best instruments, landscape mosaic, multifunctional agriculture, nutrient runoff, Shannon diversity index, species-area relationship

1. Introduction

Multifunctional agriculture refers to the fact that agriculture produces jointly a number of food and non-food outputs, some of which exhibit the characteristics of externalities and public goods (OECD 2001). The primary source of this joint production is technical interdependence in the use of inputs and it is reinforced also by allocable fixed (or quasi-fixed) inputs, such as land (Shumway et al. 1984). In this paper we suggest an analytical framework for designing socially optimal multifunctional agriculture. We use Lichtenberg's model of agricultural production (1989), where the quality of lands varies and the land use patterns among crops are determined on the basis of relative rents. We augment this model by a description of landscape diversity, diversity of agro-ecosystems and nutrient runoff, which are linked to input and land allocation choices.

The privately optimal use of inputs, and land allocation create a market solution for nutrient runoffs and, through the landscape mosaic, for ecosystem diversity as well. We compare the private solution to the socially optimal way of producing both food and non-food products. Then we investigate the optimal use of two instruments, namely, a fertilizer tax and a buffer strip subsidy, to guide the private solution towards social optimum. By a buffer strip we mean a boundary habitat that is a managed, uncultivated area covered by perennial vegetation between arable land and watercourses; and it serves for both environmental (to reduce water pollution from nutrient runoffs) and ecological (agro-ecosystem biodiversity) purposes. Finally, we illustrate in a numerical application how to determine the use of inputs and land allocation, which maximizes social welfare from multifunctional agriculture, and how to design policy instruments so as to achieve this optimum with decentralized decisions by farmers.

The rest of the paper is organized as follows. In section 2 we formulate a model of agriculture with endogenous land allocation to different crops and study the properties of private agricultural production. Diversity valuation and runoff functions are developed in the beginning of section 3,

followed by the characterization of the socially optimal multifunctional production and by the optimal design of government instruments. In section 4 we provide a numerical application of our analytical model for policy design of multifunctional agriculture. A concluding section ends the paper.

2. The model of agricultural production

Consider a representative farm, which has a fixed amount of arable land *(G)* available for agricultural production. The land quality depends on physical, chemical and biological factors, such as soil erosion, soil acidity (pH), and soil organic matter. Following Lichtenberg (1989) we assume that the variation in land quality can be ranked by a scalar measure *q*, with scale chosen so that minimal land quality is zero and maximal land quality is one, i.e., $0 \le q \le 1$. Thus, *G(q)* is the cumulative distribution of *q* (acreage of having quality *q* at most), while *g(q)* is its density. For analytical convenience we further assume that *g(q)* is continuous and differentiable.

$$G = \int_0^1 g(q)dq \qquad [1]$$

We assume that the farmer wishes to allocate his arable land to two cereal crops, crop 1 and crop 2, and denote the shares of land devoted to them by L_1 and L_2, defined as $L_1 = \int_0^{q_1} g(q)dq = G(q_1)$ and $L_2 = \int_{q_1}^1 g(q)dq = G(1) - G(q_1)$. Production exhibits constant returns to land of any given quality but it is neoclassical with respect to inputs and land quality. Production of crops requires the use of fertilizer input *l*.

Next we introduce an additional type of land use problem into the model. We assume that the government pays a subsidy to the farmer for the arable land allocated to a buffer strip to be established between the field and waterways. Modeling this land allocation to buffer strips requires specific assumptions concerning the location and shape of the arable land in relation to the waterways. We assume that the land area is located by a waterway so that all parcels of different quality end in the shore. Thus, in order to get the buffer strip subsidy, the farmer has to establish a buffer strip on each of them (see Figure 1 below).

2.1 Input use

In the first and second stage the farmer takes the land allocation between the two crops as given and chooses the amount of fertilizer (*l*) applied on land of given quality *q* and crop *i* (first stage). Then farmer chooses the proportion of the land of quality *q* and crop *i* given fertilizer use on crop *i* to be allocated to a buffer strip (*m*) (second stage). Due to internal homogeneity of each parcel, production is linear in *m*. Finally, the production also depends positively on the land quality *q* so that agricultural productivity is greater at higher land qualities. Thus, the production per each parcel for both crops can be expressed as

$$y_i = (1 - m_i) f^i(l_i; q) \qquad \text{for } i = 1,2 \qquad [2]$$

This production function is assumed to be concave in both fertilizer and land quality, i.e.,

$f_l > 0; f_{ll} < 0$ and $f_q > 0; f_{qq} < 0$ (subscripts denote partial derivatives).[1]

Next we develop the corresponding per parcel profit function. The farmer takes the prices of crops p_i and fertilizer c as given. The government intervenes in agriculture by levying two environmentally motivated instruments, a fertilizer tax, t, on the use of fertilizers, so that the after-tax price of fertilizer is $c^* = c(1+t)$. We denote a subsidy on buffer strips by $b(m_i)$, and assume that it is decreasing in m reflecting decreasing ability of buffer strips to further reduce runoff and increase species diversity. The following parameterization is used to solve comparative statics $b(m_i) = (\lambda - \frac{1}{2}\lambda m_i)m_i$. Moreover, we assume that the ability of buffer strips to prevent runoffs and promote biodiversity is independent of land quality. The farmer's problem is to choose the inputs, l_i and m_i, so as to maximize the profit per parcel[2]:

$$\max_{\{l_i, m_i\}} \pi^i = p_i(1-m_i)f^i(l_i;q) - c^*(1-m_i)l_i + b(m_i) \quad \text{for } i = 1,2 \qquad [3]$$

The first-order conditions for the optimal solution are

$$\pi^i_{l_i} = p_i f^i_{l_i} - c^* = 0 \qquad [4a]$$

$$\pi^i_{m_i} = -(p_i f^i(l_i;q) - c^* l_i) + b'(m_i) = 0 \qquad [4b]$$

and require that the value of the marginal product of input use equals their respective costs. Because the productivity of each parcel differs due to q, the optimal fertilizer intensity and the size of buffer strip differs in every parcel, as well (see Figure 1). The comparative statics of the model is condensed to

$$l_i = l_i(\underset{+}{p_i}, \underset{-}{c}, \underset{-}{t}, \underset{0}{\lambda}) \quad \text{and} \quad m_i = m_i(\underset{-}{p_i}, \underset{+}{c}, \underset{+}{t}, \underset{+}{\lambda}) \qquad [5]$$

Hence, as regards to agri-environmental instruments we have

Result 1. *For internally homogenous parcels, a higher fertilizer tax decreases fertilizer intensity and increases the size of the buffer strips. A higher buffer strip subsidy increases the size of the buffer strips, but does not affect the fertilizer intensity.*

Result 1 is very intuitive. The own effects are conventional; tax decreases the profitability of fertilizer use and subsidy increases the marginal revenue from buffer strips. Cross-effects are asymmetrical, but intuitive. Fertilizer tax decreases the opportunity cost of buffer strips while higher subsidy for buffer strips does not change the marginal profitability of fertilizer application.

2.2 Land allocation

The next step is to determine the optimal land allocation between crop 1 and crop 2. Following Lichtenberg (1989) we assume that the lowest quality parcels suit better for crop 1, which is cultivated at lower fertilizer intensity than crop 2, so that it is optimal to allocate them for crop 1. The proportion of land of quality q allocated to crop 1 is denoted by $L_1(q)$. The farmer

[1] To avoid complex notation we do not index parcels, but naturally equation [2] and other per parcel equations hold for every parcel.

[2] We adopt the following wording. The notion of "fertilizer intensity" refers to l_i, while "fertilizer used per parcel" refers to $(1-m_i)l_i$.

maximizes the sum of restricted profit functions π_i^*, *i=1,2* by allocating the land for both crops, i.e.,

$$\max_{L_1(q)} \int_0^1 \left[\pi_1^* L_1(q) + \pi_2^*(1 - L_1(q))\right] g(q)dq \qquad [6]$$

First-order condition for the optimal land allocation is

$$\pi_1^*(q, p_1, c, t, \lambda) - \pi_2^*(q, p_2, c, t, \lambda) \leq 0 \qquad [7]$$

Hence, these first-order conditions lead to a corner solution for every homogenous parcel of given acreage with differential land quality. Thus, if $\pi_1^*(q) > (<) \pi_2^*(q)$ then all land of quality q is allocated for crop 1 (crop 2). Note, however, that in the case where $\pi_2^*(q, p_2, c, t, \lambda) > \pi_1^*(q, p_1, c, t, \lambda)$ at higher quality parcels and $\pi_q^2 > \pi_q^1$ for all land of quality q, there is only one crossing point and each crop will be cultivated on a unique, compact range of land qualities. In what follows we assume that this holds. The comparative static effects of exogenous parameters on land allocation are

$$L_1 = L_1(\underset{+}{p_1}, \underset{-}{p_2}, \underset{+}{c}, \underset{+}{t}, \underset{+}{\lambda}) \qquad \text{and} \qquad L_2 = L_2(\underset{-}{p_1}, \underset{+}{p_2}, \underset{-}{c}, \underset{-}{t}, \underset{-}{\lambda}) \qquad [8]$$

The effects of end prices and input costs on land allocation are familiar from Lichtenberg (1989). As regards to agri-environmental instruments we have

Result 2. *Both instruments shift land into the production of less-fertilizer intensive crop, thus promoting the extensification of agriculture.*

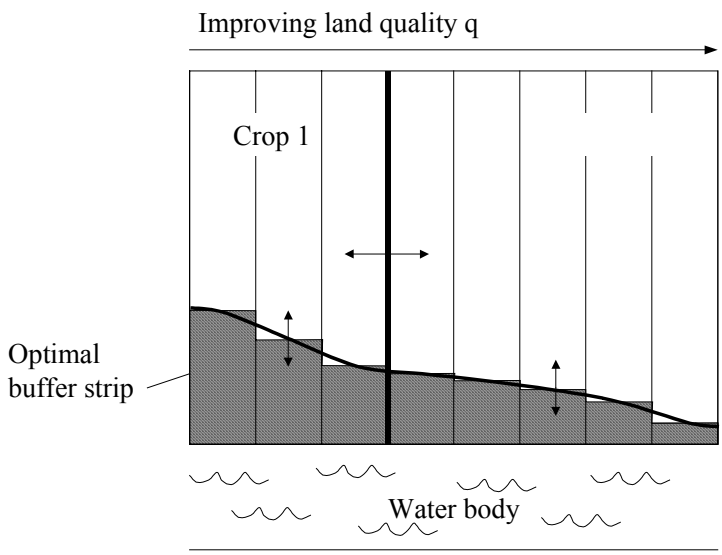

Figure 1. The land allocation and optimal amount of buffer strip in each parcel.

Figure 1 illustrates a specific spatial structure of the arable land, ordered from the lowest productivity parcel to the highest one. This structure is a function of the representative farmer's decisions concerning land allocation and the use of inputs. It forms the landscape in our model.

2000).[3]In Figure 1 the land quality improves from left to right and all parcels have a buffer strip. As the first-order conditions reveal, the optimal size of the buffer strip differs between parcels due to q (i.e. agricultural productivity). As the comparative statics revealed, the land allocation between crops and buffer strips depends on exogenous parameters, i.e. crop prices, fertilizer costs, and government instruments. Drawing on the comparative statics analysis, the vertical and horizontal arrows show that when the exogenous parameters change, they transform the landscape mosaic by inducing adjustments in the crop and buffer strip areas. Thus, besides market variables, also government instruments change the composition and configuration of this landscape mosaic (cf. Eiden et al.

3. Socially optimal multifunctional agriculture

Assume next that society promotes multifunctional agriculture by regarding the aesthetic value of agricultural landscape, the diversity of agroecosystems and the surface water quality as the most important non-food outputs. Designing optimal multifunctional agriculture requires that we first define how landscape diversity, agricultural ecosystem diversity and nutrient runoffs are related to food production.

3.1 Agricultural diversity and runoff functions

The effects of agricultural production practices on surrounding ecosystems and species diversity can be assessed from an ecological angle. Kleijn (1997), Wossink et al. (1999), and Bäckman et al. (1999) show that in arable fields the largest number of species of both flora and fauna are found at the field edge/boundary. Since, they provide forage, shelter, and a reproduction and over-wintering site, as well as ecological corridors for wildlife, field edges belong to the most important semi-natural habitats created and sustained by agriculture. Unlike the adjacent cultivated fields, field edges and buffer strips promote many flowering plants and thus the abundance of many insects such as butterflies and bees, which in turn are important for bird species. Moreover, they provide important habitats for pest predators, but also promote the abundance of weeds and insects (Swifth and Anderson 1993).

Recently researchers have attempted to describe the agricultural landscape mosaic by using different indices, such as Shannon's diversity index (see e.g. Eiden et al. 2000). These are indicators of the number and distribution of different patches in the landscape. Eiden et al. (2000) link these indices to landscape diversity, but they could be enlarged to cope with the overall diversity comprising both landscape diversity and biodiversity. We will use the aforementioned Shannon's diversity index in our empirical analysis as a proxy for landscape diversity. For the analysis of the species diversity of agro-ecosystems, we adopt an approach of Ma et al. (2001) and provide estimates of floral species richness as a function of buffer strip area.

In the theoretical analysis we apply a general description of people's diversity valuation and link the choice of crops and the land allocation to landscape valuation. For brevity we call this *landscape diversity valuation*, even though it is more than that. Then we express the diversity of the agro-ecosystem as a function of the fertilizer input intensity and buffer strips. This part of the diversity we call *agro-ecosystem diversity valuation*. Hence, our description of the diversity valuation function is a product of "landscape diversity" and "agro-ecosystem diversity". The

[3] An alternative spatial description would be the case where land quality improves from the bottom of the field adjacent to the water body towards the upper part of the field. In this case buffer strip would be like any crop, say crop 0 with a fixed return and thus all parcels would be allocated among crop 0, crop 1 and crop 2. Consequently, the buffer strip would locate besides the stream, above it would be parcels allocated to crop 1, and then parcels allocated to crop 2 would be located at the top (see Appendix 1.C. for the mathematical solution).

multiplicative form of the diversity valuation function reflects the fact that the greater the landscape diversity the greater the level of ecosystem diversity, ceteris paribus, as [9] suggests

$$\Omega = k(L_1, L_2)h(m, \bar{l}) \qquad [9]$$

where $\bar{l} = \int_0^1 (1-m_1)l_1L_1 + (1-m_2)l_2L_2)g(q)dq$, $m = \int_0^1 (m_1L_1 + m_2L_2)g(q)dq$ and L_1, L_2 are defined in equation (1). The term $k(L_1, L_2)$ indicates the valuation of landscape diversity as a function of land allocation to different crops, and the latter term $h(m, \bar{l})$ indicates the valuation of agroecosystem diversity as a function of input use. Via L_1, L_2, m and $\bar{l}$, the diversity valuation function also depends on land quality. We assume that increasing the acreage for each crop increases the landscape diversity in a diminishing way, i.e., $k_1 > 0$ and $k_2 > 0$, but $k_{11} < 0$ and $k_{22} < 0$. For the use of fertilizer input, we assume that $h_{\bar{l}} < 0$ and $h_{\bar{l}\bar{l}} < 0$ to indicate that the higher the fertilizer use, the greater the loss in agro-ecosystem diversity. Finally, we assume that the width of the buffer strip increases ecosystem diversity by enlarging the field edge but with decreasing returns, i.e., $h_m > 0$ and $h_{mm} < 0$ (this is confirmed e.g. by Ma et al. 2001).

The runoff of nutrients (kg) from each parcel can be expressed as a function of fertilizer use l_i and the size of the buffer strip m_i as follows: $z_i = v_i(\bar{l}_i(q), m_i(q))$; for i = 1,2, where $\bar{l}_i = (1-m_i)l_i$ with $v_{\bar{l}} > 0, v_{l\bar{l}} > 0$ and $v_m < 0, v_{mm} > 0$. Thus, the runoff function is convex in the fertilizer application but concave in buffer strips. Hence, we can describe the total amount of the runoff from the land area devoted to crop 1 and crop 2 as

$$z = z_1 + z_2 = \int_0^1 \left[v_1(\bar{l}_1(q), m_1(q))L_1 + v_2(\bar{l}_2(q), m_2(q))(1-L_1)\right]g(q)dq \qquad [10]$$

3.2 Socially optimal provision of multifunctional agriculture: command optimum

We turn next to the determination of the first-best solution for agricultural production as a command optimum in the absence of taxes and subsidies. By assumption the government maximizes the sum of consumers' and producers' surplus augmented with diversity valuation and damage function from nutrient runoff. The farmer's profit function, and thus the producers' surplus, has been defined earlier. We assume that the preferences of the representative consumer define an additively separable, quasi-linear utility function, $U = I + u(Y_1) + u(Y_2)$, where I is exogenous money income. This utility function is concave in its arguments (crops) so that $u'(Y_i) > 0$, but $u''(Y_i) < 0$. Moreover, the society values agro-ecosystem diversity, $k(L_1, L_2)h(m, \bar{l})$, but derives disutility from the nutrient runoff. This runoff damage function, $d(z)$, is convex, i.e. $d'(\cdot) > 0$ and $d''(\cdot) > 0$. Thus, the social welfare function can be expressed as

$$SW = U + \int_0^1 (L_1\pi_1 + (1-L_1)\pi_2)g(q)dq - d(z) + k(L_1, L_2)h(\bar{l}, m), \qquad [11]$$

In order to see how the inclusion of diversity valuation and runoff damages changes the privately optimal solution characterized in equations [4a] and [4b], we solve the command optimum by assuming exogenous crop prices and, therefore, abstract for a moment from the consumer utility. Choosing (the second stage) the use of inputs for each parcel so as to maximize [11] produces the

following first-order conditions under exogenous crop prices:

$$SW_l^i = p_i f_l^i - c - d'(z)\frac{\partial z}{\partial \bar{l}_i} + k(\cdot)h_{\bar{l}_i} = 0 \qquad [12a]$$

$$SW_m^i = -p_i f^i(l_i;q) + cl_i - d'(z)\frac{\partial z}{\partial m_i} + k(\cdot)h_{m_i} = 0 \qquad [12b]$$

According to [12a] in each parcel fertilizer is used up to the point where the value of its marginal product is equal to its unit price, adjusted by its marginal effects on runoffs and agro-ecosystem diversity. The buffer strip size is optimal when the net loss of income due to decreased production is equal to the marginal benefits from runoff reduction and ecosystem diversity promotion [12b]. Note first that the choice of the buffer strip clearly differs across parcels making the fertilizer used per parcel to do so, too. Hence, we can immediately see that it will be socially optimal to use differentiated instruments. Recall next the private per parcel solution in equations [4a] and [4b], from which we can deduce the private solution in the absence of taxes and subsidies to be $\Pi_l^i = p_i f_{l_i}^i - c = 0$ and $\Pi_m^i = -p_i f^i(l_i;q) + cl_i \leq 0$. Thus the private solution neglects the effects on the production of public goods and nutrient runoff. While the use of fertilizer input is excessive, the use of buffer strips is too small from the viewpoint of society. In fact, in the absence of incentives provided by the society the privately optimal level of buffer strips is zero due to net loss of income.

The social planner maximizes [11] by allocating land to crops 1 and 2 and accounting for the effects of land allocation on diversity and nutrient runoffs. Recalling our assumptions from section 2.2, the social planner's land allocation problem leads to a corner solution for every parcel, and a unique crossing point defined by

$$\pi_1 - d'(\cdot)v_1 + k_1 h(\cdot) + k(\cdot)h_{L_1}\bar{l}_1 + k(\cdot)h_{L_1}m_1 = \pi_2 - d'(\cdot)v_2 + k_2 h(\cdot) + k(\cdot)h_{L_2}\bar{l}_2 + k(\cdot)h_{L_2}m_2 \qquad [13]$$

indicating that all land of quality q is allocated to the crop with highest social return. Comparing this with the privately optimal solution, where $\pi_1^* = \pi_2^*$, reveals the difference. In addition to maximum profits, the land allocation will depend on the marginal valuation of the landscape benefits and runoff damages. Note that even in the case where the private solution would be to grow only one crop, the social optimum may require the production of both crops if marginal valuation of landscape diversity caused by the other crop is high.

Summing up, we have shown that

Proposition 1. *Socially optimal multifunctional agriculture promotes landscape diversity and agroecosystem diversity, as well as surface water protection by reducing the use of polluting fertilizer input, increasing the size of buffer strips and increasing the mosaic pattern of fields relative to privately optimal agricultural production.*

Naturally, correcting the privately optimal use of inputs and land allocation to reflect socially optimal multifunctional agriculture requires an appropriate use of (differentiated) policy instruments. Now we turn to solving for the optimal tax and subsidy rates.

3.3 Optimal level of chemical tax and buffer strip subsidy

The choice of the socially optimal fertilizer tax and buffer strip subsidy rates requires that the government know how farmers react to the tax and the subsidy. This reaction is given by the

comparative statics of the use of inputs and land allocation in terms of the tax and the subsidy.

As in the previous section, the government maximizes the sum of producers' and consumers' surplus from food production, augmented by the society's valuation of diversity and nutrient runoff. This time, however, the producers' surplus is defined by indirect profit functions in the presence of the fertilizer tax and buffer strip subsidy. Moreover, we assume that consumers are taxed by an income tax, the rate of which depends on the net-support to agriculture. Thus, consumers' surplus is given by the consumer's indirect utility function $U^* = (1-\tau)I + u_1(p_1(Y_1)) + u_2(p_2(Y_2))$, where $\tau = \tau(\underset{+}{\lambda}, \underset{-}{t})$ is the income tax rate as a function of net support to agriculture, and $p_i(Y_i)$ is the demand for both crops (solved from the constrained utility maximization problem).

The government chooses the fertilizer tax and buffer strip subsidy for each parcel so as to maximize

$$\max_{\{t,b\}} SW = U^* + \int_0^{1^*} \left[\pi_1^* L_1^* + \pi_2^*(1-L_1^*)\right] g(q)dq - d(z) + k(L_1, L_2)h(m,\bar{l}) \qquad [14]$$

Differentiating [14] for any parcel with respect to t and λ, treating crop prices as exogenous and accounting for the fact that only direct effects matter for the farmers' profit function due to the envelope theorem (see Mas-Colell, Whinston and Green 1995), we get the following first-order conditions for the differentiated optimal fertilizer tax and buffer strip subsidy

$$SW_t\big|_{p^{exog}} = \underbrace{\Pi_t^*}_{-} + \underbrace{U_t^*}_{+} - d'(\cdot)\left(\frac{\partial z}{\partial t} + (v_1 - v_2)\frac{\partial L_1}{\partial t}\right) + \underbrace{[k_1 - k_2]}_{?}\underbrace{\frac{\partial L_1}{\partial t}}_{+} h(m,\bar{l}) + k(L_1, L_2)\left(\underbrace{h_m \frac{\partial m}{\partial t}}_{+} + \underbrace{h_l \frac{\partial \bar{l}}{\partial t}}_{+}\right) = 0 \qquad [15a]$$

$$SW_\lambda\big|_{p^{exog}} = \underbrace{\Pi_\lambda^*}_{+} + \underbrace{U_\lambda^*}_{-} - d'(\cdot)\left(\frac{\partial z}{\partial \lambda} + (v_1 - v_2)\frac{\partial L_1}{\partial \lambda}\right) + \underbrace{[k_1 - k_2]}_{?}\underbrace{\frac{\partial L_1}{\partial \lambda}}_{+} h(m,\bar{l}) + k(L_1, L_2)\left(\underbrace{h_m \frac{\partial m}{\partial \lambda}}_{+} + \underbrace{h_l \frac{\partial \bar{l}}{\partial \lambda}}_{+}\right) = 0 \qquad [15b]$$

where

$\Pi_t^* = -c\bar{l}_1 L_1 - c\bar{l}_2(1-L_1) < 0$, $\quad \Pi_\lambda^* = \bar{m}_1 L_1 + \bar{m}_2(1-L_1) > 0$, $\quad U_t^* = -\tau_t I > 0 \quad U_\lambda^* = -\tau_\lambda I < 0$,

$$\frac{\partial \bar{z}}{\partial t} = \left[\underbrace{\frac{\partial z_1}{\partial t}L_1 + \frac{\partial z_2}{\partial t}L_2}_{-} + \underbrace{(z_1 - z_2)\frac{\partial L_1}{\partial t}}_{-}\right] < 0 \text{ and } \frac{\partial \bar{z}}{\partial \lambda} = \left[\underbrace{\frac{\partial z_1}{\partial \lambda}L_1 + \frac{\partial z_2}{\partial \lambda}L_2}_{-} + \underbrace{(z_1 - z_2)\frac{\partial L_1}{\partial \lambda}}_{-}\right] < 0.$$

The optimal fertilizer tax rate for each parcel is found by equating the direct economic loss of the farmer to the marginal benefits from runoff reduction and improvement in diversity, as well as lower income taxation of consumers. Looking more closely at the tax effects on diversity, we can see that while the agroecosystem diversity improves, landscape diversity may decrease depending on its marginal valuation. Nevertheless, for the expression [15a] to be zero at the interior solution, the sum of the changes in the marginal valuation of runoff damages and diversity must be positive. The optimal buffer strip subsidy for each parcel is set so as to equalize the disutility from higher income taxation to the sum of direct economic gain to the farmer and the marginal benefit from runoff reduction and diversity. While the runoff unambiguously decreases, the effect on the diversity is ambiguous, because the landscape diversity may or may not improve. These optimality conditions illustrate well the complexity of designing multifunctional agriculture. Because now both input intensity and land allocation are endogenous, their changes may easily go in opposite directions, as shown in both conditions. Moreover, consumer must be willing to pay for multifunctionality.

To collect, we have

Proposition 2. *Promotion of multifunctional agriculture when it depends on land quality, requires differentiated instruments:*
i) a fertilizer tax set at a level which equates the direct economic loss of the farmer to the marginal benefits from runoff reduction and improvement in diversity, as well as utility from lower income taxation,
ii) a buffer strip subsidy set at a level which equates the disutility from higher income taxation to the sum of direct economic gain to the farmer and the marginal changes in runoff and diversity.

Using differentiated instruments is difficult in practice. Hence, reducing the number of instruments is the option of the second best policy.

4. Numerical application of the analytical model

In this section we illustrate our approach to multifunctional agriculture in a parametric application of our analytical model. By using Finnish data we determine the basic features of socially optimal multifunctional agriculture and design optimal fertilizer tax (nitrogen tax) and buffer strip subsidy rates that can sustain this optimality. We first solve numerically both the private optimum in the absence of instruments as well as the command optimum. The latter allows us to define the rates of differentiated fertilizer tax and buffer strip subsidy for each parcel so as to maximize the target function in equation [14]. We also apply uniform fertilizer tax and buffer strip subsidy for each crop as a second-best solution. Finally, we compare the privately optimal solution in the absence of taxes and subsidies and under second-best instruments with the command optimum. Comparisons are made in terms of input-use, short-run profits, runoffs and diversity, for which we offer two measures, floral species richness (species diversity of agroecosystem) and Shannon's diversity index (landscape diversity), and finally in terms of social welfare under alternative solutions.

4.1 Parametric model

Following the analytical model we start with the farmer and the production function in equation [2]. In the parametric model we apply a quadratic nitrogen response function (with parameters estimated for barley (crop 1) and wheat (crop 2) in clay soils by Bäckman et al. 1997)

$$y_i = a_i + \alpha_i l_i + \beta_i l_i^2 \qquad \text{for } i = 1,2 \qquad [16]$$

where y_i = yield response in kg/ha, a_i = intercept parameter, l_i = nitrogen fertilizer applied in kg/ha, α_i, β_i = parameters, $\alpha_i > 0$, $\beta_i < 0$.

Land quality q is continuous and incorporated in equation (16) via the intercept parameter a_i, which is assumed to increase linearly:

$$\begin{aligned} a_1 &= e_0 + e_1 q \\ a_2 &= n_0 + n_1 q \end{aligned} \qquad [17]$$

where e_0 and n_0 are the lowest levels of natural productivity, e_1 and n_1 are the slopes of the productivity change and q is the number of hectares. The assumption of linearly improving quality is, of course, the simplest way of introducing heterogeneity of land quality.

The representative farmer's short-run profits, parametric version of [3], per parcel for crop i in the presence of a fertilizer tax and buffer strip subsidy are given by

$$\pi^i = p_i(1-m_i)\left[a_i + \alpha_i l_i + \beta_i l_i^2\right] - c^*(1-m_i)l_i + (\lambda - \frac{1}{2}\lambda m_i)m_i \qquad \text{for } i = 1,2 \qquad [18]$$

where λ is the maximum level of buffer strip subsidy and a_i is defined by [17]. Thus, we assume that the (quadratic) buffer strip subsidy is decreasing in the size of the buffer strip. This reflects the fact that the buffer strips have a decreasing ability to further decrease nutrient runoff and to increase species diversity.

Next we develop a parametric description for the environmental parts of the social welfare function, namely runoff damage and agroecosystem valuation. We use the following nitrogen leakage function (Simmelsgaard 1991) $y(N_i) = y_n \exp(b_0 + bN_i)$ for $i = 1,2$. where $y(N_i)$ = nitrogen leakage at fertilizer intensity level N_i, kg/ha, y_n = nitrogen leakage at average nitrogen use, b_0 = a constant (<0), b = a parameter (>0), and N_i = relative nitrogen fertilization in relation to normal fertilizer intensity for the crop, $0.5 \leq N \leq 1.5$. We, however, modify the leakage function to incorporate the reductive effect of the buffer strip on the nitrogen runoff Z_i to be

$$Z_i = (1 - jr)y(N_i) \qquad \text{for } i = 1,2 \qquad [19]$$

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

Based on Finnish experimental studies on grass buffer strips (Uusi-Kämppä and Yläranta 1992, 1996) and on the leaching of nitrogen (Turtola and Jaakkola 1987, Turtola and Puustinen 1998), we make the following assumptions. Of the total nitrogen load 50% is surface runoff. A 10-meter-wide grass buffer strip is able to reduce 50% of the total nitrogen of this surface runoff. Moreover, since in Finnish experimental studies combined surface and drainage nitrogen leakages (y_n) at the fertilization level of 100 kg N/ha have been in the order of 10-20 kg N/ha, the parameter y_n is set at the value of 15. We are obligated to use Finnish parameters in a Danish leakage function, because no estimations for a Finnish leakage function are available despite the leaching experiments in Finland. However, the Danish leakage function was estimated for sandy and clay soils cultivated by barley and wheat, and the Finnish leaching experiments also took place on clay soils cultivated by barley and wheat. Thus, data from these two sources can be reasonably combined.

For the social value of runoff damages we use an estimate provided by Vehkasalo (1999). He approximated the social benefits of reducing nitrogen runoffs from Finnish agriculture by applying the averting expenditure valuation method, and estimated the costs of a corresponding nitrogen reduction at municipal wastewater treatment facilities. The cost estimate is FIM 9.5 per reduced kg of nitrogen (when 10 to 20 per cent of the total nitrogen load is reduced). We assume a convex damage function from runoffs, i.e. $d(z) = (9{,}5 + 0{,}024z)z$.

Our estimate for agroecosystem diversity valuation function is given in buffer strip hectares. By using the contingent valuation method, Aakkula (1999) provides an estimate for the economic value of pro-environmental farming in Finland (pro-environmental farming was defined as an economic activity that enhances environmental and ecological quality of the rural environment).

He found that the average WTP/ha for pro-environmental farming was FIM 466.[4] However, besides landscape diversity and the diversity of agro-ecosystems, this estimate also includes the value of nutrient runoff reduction. Therefore, we use the estimate of FIM 326 per hectare, which is 30% lower than Aakkula's average WTP.[5] Therefore, we will use the following concave valuation function for agroecosystem diversity, i.e. $\mu = (340 - 70m_i)m_i$. Thus, the runoff damage and biodiversity valuation parts in the parametric model can be expressed as follows $(9{,}5 + 0{,}024z_i)z_i + (340 - 70m_i)m_i$ for i = 1,2 where $z_i = (1 - m_i)y(N_i)$, and $y(N_i)$ is defined in [19].

We link agroecosystem diversity valuation function to species diversity with the help of a study by Ma et al. (2001), which focuses on the relationship between floral species richness and buffer strip area using Finnish data. Ma et al. take as their starting point the conventional species-area relationship, $S = \psi A^{\varphi}$, where S is species richness, A is area, ψ is the number of species in the initial area, and φ describes the rate of species increase along with the increase of area. Then Ma et al. modify this relationship to include the length (L) and the width (W) of the buffer strip area as follows $S = \psi L^{\varphi_\alpha} W^{\varphi_\beta}$, where φ_α (φ_B) is an estimate for the average change in species richness due to an increase in the length (width) of the area while keeping the width (length) of the area constant. Hence, after having solved for m, we can assess the floral species richness by using the following coefficients estimated by Ma et al. (2001): $\psi = 1.6331$, $\varphi_\alpha = 0.0009$, $\varphi_\beta = 0.0977$.

Finally, we apply ex post the Shannon Diversity Index (*SHDI*) as a measure of landscape diversity (see Eiden et al. 2000). The Shannon Diversity Index (*SHDI*) is calculated by adding for each patch type in a reference area the proportion of area covered by that patch type multiplied by the natural logarithm of that proportion

$$SHDI = -\sum_{i=1}^{n} (P_i * \ln P_i) \qquad \text{for } i = 1,2,3,4 \qquad [20]$$

where n = number of patch types and P_i = the proportion of the area covered by patch type i out of the four patches in our model. The *SHDI* is a combination of the richness (number of different patch types) and evenness (proportional area distribution among patch types) of the landscape diversity.

Other parameter values for our parametric model are reported in Table 1. The arable land area is assumed to be 60 hectares. The calculation of the Shannon's diversity index requires assumptions concerning the specific shape of the field. We assume that the height of the field is 500 m and the length is 1200 m. The base case of our parametric model represents the private market solution (without taxes and subsidies) for cereals in Finland in 1999.

[4] More precisely, Aakkula used the contingent valuation method to elicit a monetary value for the conversion from conventional agriculture to pro-environmental farming.

[5] This 30% reduction closely corresponds to Vehkasalo's runoff damage estimate FIM 147,9 at the average runoff level of 15 kg N/ha.

Table 1. *Parameters of numerical application*

Parameter	*Symbol*	*Value*
price of barley	p_1	FIM 0.73/kg
price of wheat	p_2	FIM 0.83/kg
price of nitrogen fertilizer	c	FIM 5.95/kg
parameter of quadratic nitrogen response function	α	52.9 for barley 35.8 for wheat
parameter of quadratic nitrogen response function	β	-0.173 for barley -0.094 for wheat
Maximum subsidy for buffer strips	λ	FIM 3960/ha
Initial level of productivity for crop 1	e_0	800
Initial level of productivity for crop 2	n_0	780[6]
Slope of the productivity change for crop 1	e_1	10
Slope of the productivity change for crop 2	n_1	23
Share of surface runoff from combined runoff	j	0.5 (i.e. 50%)
Nitrogen removal effectiveness of buffer strip	r	0.5 (i.e. 50%)
nitrogen leakage at average nitrogen use	y_n	10-20 kg/ha
parameter of leakage function	b	0.7
constant parameter of leakage function	b_0	-0.7

Notes: Prices are from the year 1999. The price of nitrogen is calculated on the basis of a compound NPK fertilizer.
Sources: Bäckman et al. 1997, Turtola and Jaakkola 1987, Simmelsgaard 1991.

4.2 Results

We solve first solutions for private optimum in the absence of intervention and for the socially optimal multifunctional agriculture. Some results are highlighted in Tables 2 and 3. Table 2 represents the average solutions for the use of inputs under alternative solutions.[7] Expectedly, the use of fertilizer in each parcel is smaller under the social optimum than in the private solution. This holds true even more for buffer strips, for which the private solution provides a zero size.

Table 2. *Average input use per hectare under alternative solutions*

	Crop 1		Crop 2	
	fertilizer, kg	buffer strip, ha	fertilizer, kg	buffer strip, ha
Private optimum	129,3	0,00	152,3	0,00
Social optimum	121,4	0,016	139,2	0,014
Second-best instruments	106,6	0,136	123,5	0,125

As an example of second best policy, we have solved the optimal quadruple for the last parcel (in order to have an interior solution for buffer strips also in the highest quality parcels), which in our case is the 60th hectare, to yield crop-specific instruments that are uniform with respect to parcels and thus land quality. Solving the optimal level of instruments for the last parcel with highest productivity/land quality means that the marginal revenue of buffer strips is high at lower quality parcels. The optimal level of the instruments for the last parcel are defined as follows: fertilizer tax for crop 1 is 25% and 29% for crop 2. Buffer strip subsidy is FIM 2987 for crop 1 and FIM

[6] The estimated, average constant for these crops are a_1 = 1010 for barley and a_2 = 1274 for wheat (Bäckman et al. 1997).
[7] The quality is continuous in the parametric model, but we use hectare as our basic unit when reporting the results.

3387 for crop 2. As can be seen from Table 2 these second-best instruments are over optimal, since they result on average much wider buffer strips (and less fertilizer use) than is required from social point of view.

The first two rows in Table 3 condense the economic and environmental features of the private market solution and command optimum. We report land allocation, short-run profits, nitrogen runoffs, floral species richness, Shannon Diversity Index (*SHDI*), and the social welfare (*SW*), which is calculated as a sum of profits, runoff damage and diversity benefits.

Table 3. *Results*

Policy	Land allocation, ha crop 1 and crop 2	Profits, FIM	Runoffs, kg	Species richness	*SHDI*	*SW,* FIM
Private solution	20 40	184 667	1381	-	0,64	125 749
Command optimum	23 37	181 339	1206	79	0,74	135 268
Second-best instruments	19 41	156 442	763	97	1,01	133 696

As Table 3 shows, the private market solution in the absence of taxes and subsidies yields highest private profits, but also the highest runoffs and the lowest value for *SHDI*, resulting in the lowest value for social welfare. In the absence of buffer strip subsidy the optimal level of buffer strips is zero, and thus the estimate of floral species richness in buffer strip areas is zero as well in this case. The command optimum produces lower private profits because of the internalization of negative and positive externalities associated with runoffs and agro-ecosystem diversity. In the command optimum *SHDI* increases mainly due to the increased number of patch types via the emergence of buffer strip areas. The buffer strip areas in this solution (0,9 ha in total) provide 76 floral species.

How does the optimal multifunctional policy look like? As theoretical model predicts, the first-best policy consists of 60 pairs of fertilizer tax and buffers strip subsidy, that is, they are crop and parcel specific instruments. They are solved from the command optimum solution to reflect the size of positive and negative externalities per parcel.

In the case of second-best instruments, the net-support (i.e. subsidy minus tax) is taken into account, so that the welfare calculations between alternative solutions are comparable. We report the private solution under the second best instruments in the third row of Table 3. Now the private profits are lower than under command optimum. Nitrogen runoffs are clearly lower due to increase in buffer strip areas (total buffer strip area in this case is 7,7 ha). *SHDI* and floral species number increase also clearly compared to command optimum owing to a higher share of buffer strip areas. Moreover, more equitable area distribution between different patch types increases *SHDI* in this case compared to command optimum. Hence, this solution is very strong from environment point of view, but results in lower social welfare than command optimum. Thus, FIM 1572 (FIM 26,2 per hectare) difference in social welfare compared to that of command optimum is due to implementation of second-best instruments.

5. Conclusions

We developed a theoretical framework for analyzing the multifunctional agriculture as the joint production of a number of food and non-food products. The core of our framework was

Lichtenberg's model of agricultural production with endogenous input and land allocation choice for two alternative crops, augmented by a description of non-food aspects of agriculture. From among these non-food outputs we focused on diversity of agro-ecosystems and landscape diversity, as well as on nutrient runoffs. We defined the diversity valuation function of agriculture as a multiplicative product of landscape diversity valuation and agro-ecosystem diversity valuation. Both were expressed as a function of agricultural input choices and land allocation to alternative crops. Our nutrient runoff function followed conventional lines in agricultural economics.

We solved for the privately optimal land allocation and the choice of inputs, and compared this with the corresponding social optimum. The private optimum includes a higher fertilizer use and a smaller size of the buffer strips than those in the socially optimal solution. The socially optimal land allocation between crops 1 and 2 requires that the effects of land allocation on diversity and nutrient runoff is taken into account. How much social optimum differs from privately optimal solution depends on the relative valuation of landscape diversity vis-à-vis runoff damage.

As for the alternative means of achieving an optimal multifunctional agriculture, we studied the choice of fertilizer tax and buffer strip subsidy rates. The optimal differentiated tax rate for each parcel is chosen so as to offset the negative welfare effect of tax on farmers with the positive effect on consumer welfare in terms of lower income taxation and positive marginal valuation effect as a sum of diversity and runoff functions. The optimal buffer strip subsidy per parcel, in turn, increases directly farmers' profits and decreases consumers' surplus and this is counterbalanced by the changes in the marginal valuation of nutrient runoff and diversity.

In the numerical application of our analytical model we solved the private and command optimum in the absence of taxes and subsidies and demonstrated that private solution leads to excessive use of fertilizer, sub-optimal use of buffer strips and excessive land devoted for the production of crop 2. We then solved for the optimal first-best tax and subsidy levels yielding 60 pairs of crop and parcel specific fertilizer taxes and buffer strip subsidies. We also solved for second-best policy instruments and studied the social welfare loss and other properties of this solution relative to the first-best solution.

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