TO TILL OR NOT TO TILL?
SOCIAL PROFITABILITY OF NO-TILL TECHNOLOGY

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Abstract
We study from economic and environmental angles under what conditions no-till technology is socially optimal. We demonstrate theoretically that if yield under no-till is equal to or greater than under conventional technology, its adoption is socially optimal provided that herbicide runoff damages under both technologies are close enough. Finnish data shows, however, that only in one case out of three no-till provides higher social returns. In terms of nutrient runoffs no-till performs better than conventional technology. No-till reduces surface runoffs of nitrogen by 58%**,** and surface runoffs of particulate phosphorus by 70% relative to conventional technology, but causes more than three times higher dissolved phosphorus surface runoffs. The amount of total phosphorus surface runoff is, however, lower under no-till. No-till produces higher total herbicide runoff because of higher use of herbicides to control perennial weeds.

Key words: nutrient runoffs, herbicide runoffs, buffer strips, agri-environmental policy
JEL classification: Q16, Q18, H23

1. Introduction

Conservation tillage refers to cultivation practices that decrease disruption of the soil's structure, composition and natural biodiversity, thereby decreasing erosion and degradation and also contamination (Anonymous 2001). Among conservation tillage methods, no-till refers to a tillage system, such as direct drilling, that leaves the soil undisturbed from harvest to planting, as the only soil disturbance is caused by planting made directly through crop residues. No-till and other conservation tillage technologies are widespread in North- and South America and Australia; it is becoming increasingly used in tropical regions as well (Lal 2000). In the U.S. and Canada no-till covers 36.7% of total acreage in cultivation, in South-America the coverage is even higher, 47.5% (Holland 2004).

What are the potential off-farm benefits of no-till in European agriculture? No-till is generally found to provide considerable environmental benefits in reduced soil erosion, nitrogen runoffs, and particulate phosphorus runoffs (Soileau et al. 1994, Stonehouse 1997). Not all environmental effects of no-till are favorable, however. Three possible problems have been identified. First, many studies report that dissolved (orthophosphate) phosphorus runoffs may increase due to the accumulation of phosphorus in soil surface (see e.g. McIsaac et al. 1995, Holland 2004). Second, while surface water runoffs decrease, leaching to groundwater may increase (see e.g. Holland 2004 and Wu et al. 2004). Third, while no-till may initially have lower herbicide runoffs (e.g. sediment bound active ingredients), it may increase weeds requiring thus a higher use of herbicides. This may eventually increase herbicide runoffs (e.g. Tebrugge and During 1999, and Sturs et al. 1997; see also Fuglie 1999, who found no evidence for higher herbicide application).

As for the on-farm benefits, no-till seems to provide unambiguous cost reductions because of lower labor requirements and fuel consumption (see e.g. Uri 1998 for the U.S. and Nielsen 1987 for the Danish agriculture). Also capital investment and maintenance costs are reduced, because no-till requires only one tillage operation (planting) compared to two or more tillage operations plus planting for conventional mouldboard tillage. North-American studies generally find that yields for many crops are roughly the same under conventional and no-till (see e.g. Baylis et al. 2002). Evidence in Europe is sparse or indirect. Tebrugge and During (1999) argue that no-till is competitive with conventional tillage in many cases in Germany. According to Rasmunssen (2002), in Scandinavia no-till (for winter wheat, winter oil seed rape and late harvested potatoes) performs best in the heaviest clay soils which are the most difficult soils to prepare with conventional tillage. However, systematic and integrated environmental and economic analysis is missing.

In this paper we focus solely on no-till among the class of conservation tillage methods and ask under what conditions its adoption is socially optimal when yields, costs and runoff damages into surface water are explicitly taken into account. We extend the conventional crop production model to cover basic features of no-till technology. Following this theoretical framework, we develop a parametric model and calibrate it to Finnish agriculture. This model exhibits the same features of mixed effects on nutrient runoffs, increased use of herbicides, and lower production costs, as reported above. Parametric model allows us to quantify and assess more closely the mixed effects of no-till on runoffs and to estimate the range where no-till can provide the same returns as conventional tillage.

The rest of the paper is organized as follows. Section 2 describes the framework for analyzing no-till and conventional technologies and analyzes the socially optimal choice between them. Section 3 develops our parametric model and calibrates it to Finnish agricultural and environmental conditions. In section 4 we provide our empirical results. Concluding section 5 ends the paper.

2. Social choice between conventional and no-till technology

We start our analysis by focusing on the socially optimal conditions for the adoption of no-till technology. To this end, we first describe the properties of both technologies in terms of production and the nutrient and herbicide runoffs resulting from the use of inputs. We then conduct the analysis for homogenous cultivated land of (any) quality q.

2.1 No-till and conventional technology

Consider a parcel of cultivated land, which is homogenous in its quality. This parcel is cultivated differently under conventional and no-till technology. Consequently, both production process and environmental effects will differ between the technologies.

Production

The conventional technology includes mouldboard ploughing and seedbed tillage before drilling, whereas in no-till technology the direct drilling equipment places the fertilizer input and the seeds directly through residues of the previous crop. Reflecting the difference in technologies, the pattern of crop growth will differ as well. Conventional technology gives higher growth at the beginning of the growing season, but no-till technology starts to catch this up due to higher growth in later periods of the season. We express, the production of crop under technology i in a parcel of quality q in a general form as

$$y_i = f^i(l_i;q), \qquad i = 1,2 \tag{1}$$

where f^i indicates yields under both technologies and l_i is fertilizer input. In what follows, the subscript 1 refers to the conventional technology and subscript 2 to no-till technology. For the properties of the production function we have that $f_l^i > 0$ but $f_{ll}^i < 0$. We do not impose any a priori restrictions on the relative marginal products of fertilizer under these technologies, thus, $f_l^1 \geq (<)\ f_l^2$ are possible.

Next we introduce damages caused by weeds. We assume that the amount of weeds causes damage by decreasing yields and that this damage can be reduced by herbicide application. We denote weed population size by H_i and the amount of herbicides applied by x_i. Following Feder (1979), Carlsson et al. (1993), Horowits and Lichtenberg (1994) and others, we express the damage of weed in terms of yield, Φ^i, as a function of weed population and its control in (2):

$$\Phi^i(H_i, x_i), \tag{2}$$

with $\Phi_H^i > 0$, $\Phi_x^i < 0$ and $\Phi_{xx}^i > 0$. Naturally, we scale the loss to the size of production: $0 \leq \Phi^i(H_i, x_i) \leq f^i$. In (2), the amount of weeds, H_i, is a technology dependent variable. We specifically assume that $H_1 \leq H_2$, i.e., that no-till entails weeds at least as much as, or more than conventional technology. This assumption implies that $\Phi_x^1 \leq \Phi_x^2$, i.e., the marginal productivity of herbicide use is higher under no-till technology.

Equation (1) describes crop growth under conventional and no-till technology, but we also have to define the per-parcel use of labor, fuel and capital inputs. In the literature, the use of labor and capital is often assumed to be fixed per parcel, and we make the same assumption. Empirical evidence unambiguously shows that the conventional technology includes more tillage operations and higher amount of capital than no-till. We measure the use of labor by working hours h_i, and assume that $h_1 > h_2$. Similarly, we assume that conventional technology uses more capital than no-till, i.e., $K_1 > K_2$. As machinery and working hours differ between the two technologies, the size of these fixed costs per parcel differs as well.

Profits from production

Let *p* denote the crop price, *c* the price of fertilizer and α the price of herbicide. Labor costs, w_h, and fuel costs, w_{ff}, can be directly linked to the working hours, h_i, spent on the parcel, and we express them as $\hat{w}h_i$, where $\hat{w} = w_h + w_{ff}$. Under a constant unit price for capital, we can express the capital costs by k_i, measuring the annual per parcel costs of capital (including depreciation, interest and maintenance). From our previous assumptions it follows that $k_1 > k_2$. For the purposes of environmental policy we, finally, assume that, under both technologies field edges have an important role in preventing surface runoffs. Hence, a share of the parcel, *m*, is allocated to a buffer strip between the field and waterways. Under this additional input choice, the labor input related costs become lower. Note, however, that the size of buffer strips does not affect the size of capital costs. We value economic losses from weeds by the price of the crop, thus, the agricultural revenue under technology *i* is given by

$$\pi_i = (1-m_i)\left[pf^i(l_i;q) - cl_i - p\Phi^i(H_i, x_i) - \alpha x_i - \hat{w}h_i\right] - k_i \qquad (3)$$

In (3), the third and forth terms in bracket indicate the economic loss from weeds. Next we develop the description of environmental effects of production under both technologies.

Surface runoffs

As discussed in the introduction, no-till technology leads to reductions in soil erosion, nitrogen and particulate phosphorus surface runoffs, but it may increase surface runoffs of dissolved phosphorus. In the theoretical part, we focus on the aggregate runoffs and describe them as a function of three variables, fertilizer use, buffer strips and the chosen technology. The runoff differences between technologies stem from the inherent features of our tillage forms. Conventional technology includes mouldboard ploughing in the autumn, which leaves soil bare for the wintertime. In the spring soil is harrowed before drilling. Hence, the land is subject to high soil erosion during autumn precipitations and during spring smelting snow waters. No-till technology has plant cover throughout year (either crop or stubble), which considerably reduces soil erosion.

Following typical agricultural production practices, we assume that the fertilizer input contains all necessary nutrients in fixed proportions, the main nutrients being nitrogen, phosphorus and potassium. The runoffs depend on the actually applied amount of fertilizer, $\hat{l}_i$, which is a function of fertilizer intensity (fertilizer used per hectare) and of the share of the hectare allocated to the buffer strip, i.e., $\hat{l}_i = (1-m_i)l_i$. Hence, nutrient runoffs from technology *i* can be expressed as a function of fertilizer use and buffer strips,

$$z_i^n = g^i(\hat{l}_i, m_i) \tag{4a}$$

The effects of fertilizer use and buffer strip size on runoffs are conventional. Thus, $g^i_{\hat{l}} > 0$, $g^i_{\hat{l}\hat{l}} > 0$; and $g^i{}_m < 0$, $g^i{}_{mm} > 0$ (see e.g. Lankoski and Ollikainen 2003).

Next we introduce herbicide runoffs. Like above, herbicide runoffs are assumed to depend on the actually applied amount of herbicides given by $\hat{x}_i = (1 - m_i)x_i$ and on the share of the hectare allocated to the buffer strip. Thus, we have

$$z_i^h = e^i(\hat{x}_i, m_i) \tag{4b}$$

with similar assumptions concerning herbicide runoffs as nutrient runoffs.

Recall finally that empirical evidence suggests that for equal amount of fertilizer, herbicides and buffer strips ($\hat{l}_1 = \hat{l}_2$; $m_1 = m_2$; $\hat{x}_1 = \hat{x}_2$) no-till technology has lower nutrient and herbicide runoffs because of lower amount of surface runoffs. Armed with equations (3), (4a) and (4b), we now go on to study the socially optimal choice of technologies and the use of inputs under both technologies.

2.2 Socially optimal choice of cultivation technology

Society will choose technology that produces a higher social welfare. The maximum social welfare under both technologies can be defined by solving the socially optimal use of inputs and then inserting them back to the social welfare function. A comparison of these (indirect) social welfares indicates which technology gives the highest welfare.

We assume that the social planner maximizes the sum of consumers' and producers' surplus. Under exogenous crop prices and input costs, this entails maximizing producers' surplus, defined in equation (3), augmented with the disutility of consumers from nutrient and herbidice runoff damages, $d\left(g^i(\hat{l}_i, m_i)\right)$ and $D\left(e^i(\hat{x}_i, m_i)\right)$, respectively, with $d'(\cdot) > 0$, $D'(\cdot) > 0$ and $d''(\cdot) > 0$, $D''(\cdot) > 0$.

Under technology *i* the social planner's economic problem is to

$$\max_{l_i, x_i, m_i} SW^i = \pi^i - d\left(g^i(\hat{l}_i, m_i)\right) - D\left(e^i(\hat{x}_i, m_i)\right), \quad i = 1,2 \tag{5}$$

The first-order conditions for the problem are well known

$$SW^i_{l_i} = pf^i_l - c - d'(\cdot)g^i_{l_i} = 0 \tag{6a}$$

$$SW^i_x = -p\Phi^i_x - \alpha - D'(\cdot)e^i_x = 0 \tag{6b}$$

$$SW^i_{m_i} = -\left[pf^i(\cdot) - cl_i - p\Phi^i(H_i, x_i) - \alpha x_i - \hat{w}h_i\right] - d'(\cdot)\left[g^i_m - g^i_{\hat{l}}l\right] - D'(\cdot)\left[e^i_m - e^i_{\hat{x}}x\right] = 0 \tag{6c}$$

Economic interpretation of (6a) and (6b) is straightforward. The use of fertilizer (herbicide) input is increased up to the point where the value of marginal product of fertilizer (herbicide) equals the sum of its unit price and marginal environmental damage. From (6c) we have that the size of the buffer strips is chosen so that the value of lost net revenue is equal to the net marginal benefits from reduced runoff damages.

How do input intensities relate to each other under no-till and conventional technologies? We provide our answer in Lemma 1.

Lemma 1. *The socially optimal input intensities under no-till and conventional technology are related as follows:*

(i) $l_2^* > l_1^*$ *and* $m_2^* < m_1^*$ *for* $f_l^2 \geq f_l^1$,

(ii) $l_2^* < l_1^*$ *and* $m_2^* > (<)\ m_1^*$ *for* $f_l^2 < f_l^1$, *if nutrient runoffs do not differ "too much",*

(iii) $x_2^* > x_1^*$ *over a large range of herbicide runoffs.*

Proof. Follows directly from the first-order conditions.
Point (i): is obvious, because the social costs of fertilizer application and other costs, too, are lower under no-till than conventional technology. Point (ii): $l_2^* < l_1^*$ and $m_2^* > m_1^*$ is obtained when the difference in nutrient runoff damages is low enough, so that higher productivity of conventional technology dominates its higher social costs. Point (iii): no-till uses more herbicide than conventional technology up to a point where herbicide runoff damages are "very high", which is unlikely due to lower runoffs.

At a first glance it may look strange that no-till is tied in (i) to higher fertilizer intensity and smaller buffer strips. This result is, however, natural and emerges because of two facts. First, if $f_l^2 \geq f_l^1$ no-till is more productive technology resulting in a more intensive production. Second, given its lower nutrient runoffs, it requires less effort to reduce negative environmental effects and therefore has smaller buffer strips than conventional agriculture. Ambiguity in (ii) for $f_l^2 < f_l^1$ emerges from the following: if the marginal productivities are "close enough" then outcome in (ii) still holds, but if they are "far enough" the inequalities will change their direction, so that conventional cultivation entails higher fertilizer intensity and smaller buffer strips than no-till. Finally, as expected, under no-till the socially optimal use of herbicides is higher than in conventional agriculture.

Inserting next the socially optimal values of inputs, l_i^*, x_i^*, m_i^*, into the respective social welfare functions allows us to compare the outcomes in terms of the resulting social welfare. Allowing, again, for all possibilities of the marginal productivity of inputs we end up with

Proposition 1. *The socially optimal adoption of no-till versus conventional technology depends on a) the net revenue from crop production and b) nutrient and herbicide runoff damages as follows:*

- *if no-till technology has higher yields than conventional technology then it becomes adopted if herbicide runoff damages under both technologies are "close enough".*
- *if the conventional technology has higher yields then the choice between technologies is ambiguous: either conventional or no-till technology may be socially optimal.*

Proof.
Define $SW^2 - SW^1 = (r_2^* - r_1^*) + w\left[-(1-m_2^*)h_2 + (1-m_1^*)h_1\right] + (-d^2 + d^1) + (-D^2 - D^1)$,
where $r_i^* = (1-m_i^*)\left[pf^i(l_i^*;q) - cl_i^* - p\Phi^i(H_i, x_i^*) - \alpha x_i^* - \hat{w}h_i\right] - k_i$, with i = 1,2.

$(-d^2 + d^1) = -d^2(g^2(\hat{l}_2^*, m_2^*)) + d^1(g^1(\hat{l}_1^*, m_1^*)) > 0$ and

$(-D^2 + D^1) = -D^2(e^2(\hat{x}_2^*, m_2^*)) + D^1(e^1(\hat{x}_1^*, m_1^*)) < (\geq) 0$.

Assume now that $f_l^2 \geq f_l^1$, then all other terms are positive except the last one. Provided that it is positive or negative but small enough, no-till becomes adopted. But if $f_l^2 < f_l^1$, then the first, third and fifth terms can be either positive or negative making social returns of either conventional or no-till higher.

3. Data and parametric model

We develop in this section a parametric model to examine the relative profitability of conventional and no-till technology by using Finnish data. We focus on wheat, barley and oats production in clay soils, which is the typical soil type in South and South-Western Finland. Our sample contains 46 cereal farms, average size being 74 ha of arable land, drawn from a larger data set. This set on costs and prices is from Finnish bookkeeping farms, collected from about 1,000 farms and it is part of the Farm Accountancy Data Network of the EU (FADN).

3.1 Costs, production and profits

We define conventional tillage method as mouldboard plough tillage and no-till as direct drilling. Mouldboard plough tillage includes primary tillage (ploughing), seedbed tillage (harrowing) and combidrilling (fertilizer and seed are placed in the same time), while in a direct drilling system seed and fertilizer are placed (planted) directly into the soil through stubble. We assume that, except the tractor/tractors, the farmer invests in new tillage equipment for both technologies.

In Table 1 we present the machinery expense per hectare, measured by the depreciation cost, for conventional and no-till technologies.

Table 1. Machinery expense €/ha (depreciation cost) for conventional and no-till.

Machinery	Conventional €/ha	No-till €/ha
Tractor		
70 kW	70	70
55 kW	49	-
Grain drill, 3 m	36	67
Plant protection sprayer, 500-700 l	7	7
Harrow, 4-4.9 m	19	-
Mouldboard plough, 3x16’’	22	-
Total machinery expense	203	144

Table 1 makes it clear that the machinery costs differ in favor of no-till technology, because it does not utilize harrow and mouldboard at all, and requires using only one tractor. Table 2 in turn presents the relevant cost items for both technologies in the absence of taxes. We selected only those cost items that are directly related to cereal cultivation (except fertilizer cost which will be included into the analysis later on). They include fuel, labor, machinery, seed and plant protection costs. Costs and prices are from year 2001.

Table 2. Per hectare costs (€/ha) for conventional and no-till technology.

	Conventional	No-till	Notes
Fuel and labor costs			
hours/ha	4.78	1.76	
Labor cost	37.8	13.9	Wage of € 7.9 /h
Fuel cost	6.4	1.1	
Subtotal	44.2	15.0	
Machinery costs			
Depreciation	203	144	Total costs for tractor operations from Table 1.
Seed costs			
Barley	29.9	29.9	
Oats	26.2	26.2	
Wheat	63.2	63.2	
Plant protection			MCPA is used in both technologies to control weeds. Glyphosate is used in no-till as additional herbicide to control perennial weeds with a cost of € 20/ha.
Barley	28	48	
Oats	30	50	
Wheat	44.5	64.5	
Total costs			

Barley	305.1	236.9
Oats	303.4	235.2
Wheat	354.9	286.7

As Table 2 reveals, the main relative difference between our two technologies can be found in the fuel and labor costs. Under conventional technology, these costs are almost three times higher than under no-till. Also with respect to machinery costs, conventional technology is more expensive than no-till. In line of the studies examining weed problems related to no-till, we have imputed additional herbicide cost (Glyphosate) of € 20/ha to control perennial weeds (e.g. *Elymus repens*).

All in all, from Tables 1 and 2 we can infer that costs under no-till technology are lower than under conventional technology predominantly because of lower amount of capital and associated labor and fuel costs. This cost difference between technologies is € 68.2 /ha. Thus, our data confirms the findings by Nielsen (1987), Danfors (1988) and Lätti (2002).

Next we define the farmer's production function under both technologies. The farmer applies compound NPK fertilizer (*l*), in which nitrogen content is 20%, by choosing the level of nitrogen application (*N*). Therefore, we express our parametric model in terms of *N* and apply a quadratic nitrogen response function with parameters estimated for spring wheat, barley and oats in clay soils by Bäckman et al. (1997)

$$y_i = A_i + \chi_i N_i + \gamma_i N_i^2 \quad \text{for } i = 1,2 \tag{7}$$

where y_i = yield response in kg/ha, A_i = intercept parameter, N_i = nitrogen intensity in kg/ha, and χ_i, γ_i = parameters, $\chi_i > 0$, $\gamma_i < 0$. The yield difference between technologies is incorporated into production function via the slope parameter χ_i. Its size has been chosen so that the nitrogen response function for both technologies reflects the experimental results for different crops on clay soils (clay content 30-60%) presented in Table 3. This data is based on short-term field experiments in South-Western Finland (Alakukku 2003, Salo 2003). Table 3 shows the average yields for wheat, barley and oats in clay soils for conventional and no-till technology.

Table 3. Per hectare yields for wheat, barley and oats in clay soils: average, max and min yields from experiments (max and min are averages from replicates). (Alakukku 2003, Salo 2003).

Crop	**Conventional**			**No-till**		
	Average	**Max**	**Min**	**Average**	**Max**	**Min**
Wheat	4655	5387	3276	2960	4111	1799
Barley	4191	5750	3108	3946	5526	3191
Oats	5122	6154	4400	4196	4840	2796

As Table 3 reveals, only in the case of barley the average yield levels are close to each other. Moreover, in the two remaining cases, the yield difference between our two technologies is quite remarkable.

3.2 Nutrient and herbicide runoffs

We start with the surface runoffs of nutrients by defining nitrogen, particulate phosphorus, and dissolved (orthophosphate) phosphorus runoffs under both technologies. The compound NPK fertilizer contains, in addition to 20% of nitrogen, 3% of phosphorus. Because these main nutrients are in fixed proportions, nitrogen fertilizer intensity determines also the amount of phosphorus used. Part of this phosphorus is taken up by crop, while the rest accumulates and builds up soil P. Concentration of dissolved phosphorus in surface runoff is found to depend linearly on the easily soluble soil P, as determined by extractions employing deionized water or acidic ammonium acetate solution (Uusitalo and Jansson 2002). Runoff of particulate phosphorus depends on the rate of soil erosion and P content of eroded soil material (see e.g. Uusitalo et al. 2000), but only a part of particulate P is considered bioavailable.

We start by tailoring the following nitrogen runoff function (Simmelsgaard 1991) for our purposes,

$$Z_N^i = \phi_i \exp(b_0 + bN_i), \quad \text{for } i = 1,2. \tag{8}$$

where Z_N^i = nitrogen runoff at fertilizer intensity level N_i, kg/ha, ϕ_i = nitrogen leakage at average nitrogen use, $b_0 < 0$ and $b > 0$ are constants and N_i = relative nitrogen fertilization in relation to normal fertilizer intensity for the crop, $0.5 \leq N \leq 1.5$. We incorporate the reductive effect of the buffer strip on the nitrogen runoff Z_N^i via two channels, via nitrogen uptake by buffer strips and via reduction of the actually applied fertilizer, as follows

$$Z_N^i = [1 - m_i^{0.2}]\phi_i e^{-0.7[1-0.01(1-m_i)N_i]} \tag{9}$$

The first RHS brace term of (9) describes nitrogen uptake by buffer strips. It is calibrated to reflect Finnish experimental studies on grass buffer strips (Uusi-Kämppä and Yläranta, 1992, 1996, Uusi-Kämppä and Kilpinen 2000). The second RHS term represents nitrogen runoffs from technology *i* generated by a nitrogen application rate of N_i per hectare when buffer strips take up a share of land m_i. Parameter ϕ_i reflects technology differences and calibrates equation (9) to both technologies by describing their nitrogen runoffs generated by a nitrogen application rate of 100 kilos per hectare in the absence of buffers strips. Based on Puustinen et al. (2004) and Puustinen (2004) $\phi_i = 15$ kg N/ha for conventional technology and $\phi_i = 8$ kg N/ha for no-till technology.

For phosphorus we explicitly describe both dissolved and particulate runoffs. Drawing on Finnish experiments (e.g. Saarela et al. 1995) it is assumed that 1 kg increase in soil phosphorus reserve increases the soil P status (i.e., ammonium acetate-extractable P) by 0,01 mg/l soil when soil P status is on the range 9 mg/l to 13 mg/l. In Finnish bookkeeping farms situated in Southern and South-Western of Finland the average soil P status is 10.6 mg/l (95% confidence level for mean is 8.9 - 12.5 mg/l) (Myyrä et al. 2003). Uusitalo and Jansson (2002) estimated the following linear equation between soil P and concentration of dissolved phosphorus in runoff: *water soluble P in runoff (mg/l) = 0.021* AAAc_P (mg/l soil) – 0.015 (mg/l)*, where *AAAc* refers to ammonium acetate buffer (Vuorinen and Mäkitie 1955). Surface runoff of potentially bioavailable particulate phosphorus is approximated from the rate of soil loss and the concentration of potentially bioavailable phosphorus in eroded soil material as follows: potentially bioavailable particulate phosphorus PP (mg/kg eroded soil) = 250 * ln [*AAAc_P* (mg/l soil)]-150 (Uusitalo, pers. comm.).

Based on Finnish experimental studies on grass buffer strips (Uusi-Kämppä and Kilpinen 2000) the potentially bioavailable particulate (PP) and dissolved reactive phosphorus (DRP) uptake by buffer strips is calibrated as follows: $(1 - m^{0.3})PP$ and $(1 - m^{1.3})DRP$. Thus, the parametric description of surface phosphorus runoffs is given by

$$Z_{DRP}^i = (1 - m_i^{1.3})\sigma_i[\psi_i(0.021(\theta + 0.01 * 0.15(1 - m_i)N_i) - 0.015]/100 \tag{10a}$$

$$Z_{PP}^i = (1 - m_i^{0.3})\Delta_i[\zeta_i\{250\ln(\theta + 0.01 * 0.15(1 - m_i)N_i) - 150\}] * 10^{-6} \tag{10b}$$

where ψ_i is runoff volume (mm), θ is *AAAc_P* (common to both technologies) and ζ is erosion kg/ha, and $0.15(1-m_i)N_i$ is the amount of phosphorus applied. As in the case of nitrogen, the technology-based difference in the runoffs of dissolved and the potentially bioavailable particulate phosphorus is captured by parameters σ_i and Δ_i, respectively. As for the *AAAc_ P*, following Myyrä et al. (2003) we set $\theta = 10$. For runoffs, erosion and technology differences we utilize experimental results from

South-Western Finland by Puustinen (2004) and Puustinen et al. (2004) which examined surface runoffs of erosion, particulate phosphorus, dissolved phosphorus, and total nitrogen under conventional and no-till technology presented in Table 4.

Table 4. Surface runoffs of erosion, particulate phosphorus, dissolved phosphorus, and total nitrogen under conventional and no-till technology (Puustinen et al. 2004; Puustinen 2004).

Technology	**Runoff, mm**	**Erosion, kg/ha**	**Particulate phosphorus, kg/ha**	**Dissolved phosphorus, kg/ha**	**Total nitrogen kg/ha**
Conv.	234	2100	3.71	0.58	15.7
No-till	233	620	1.13	2.02	9.00

The experimental data presented in Table 4 is quite revealing. No-till technology reduces erosion and particulate phosphorus by 70% and nitrogen by 43% from the level of conventional technology. Instead, it seems indeed to increase the runoffs of dissolved phosphorus; in fact, the runoffs are over three times higher relative to those caused by conventional technology.

Next we focus on the herbicide runoffs. We assume that standard application rates of active ingredients for MCPA (1500 g/ha) are used under both technologies and additional Glyphosate (1020 g/ha) is used under no-till. Both herbicides are degradable. Therefore, we assume that Glyphosate is applied into stubble one week before direct drilling on 1st May and MCPA is applied for both technologies on 1st June.

Herbicides decay according to equation $B_i e^{kt}$, where B_i denotes the amount of herbicide applied, t is the number of days after application and the coefficient of degradation, k, is defined as $k = \frac{\ln 2}{DT50}$. Thus we obtain the following degradation equations for Glyphosate (GLY) and for MCPA,

$$GLY = 1020 * e^{-0.014145t} \text{ and } MCPA = 1500 * e^{-0.0693t}. \qquad (11)$$

Equation (11) defines the amount of herbicides in the soil at each point of time. It is easy to ascertain from (11) that the half-life for Glyphosate is 49 days in uppermost 20 cm of the soil surface and for MCPA it is 10 days.

For glyphosate, the adsorption coefficient, κ, indicates how the herbicide is divided between liquid and solid phases, because it defines the ratio of liquid and solid phases. Thus, letting α denote the share of herbicide in soil particles and $(1-\alpha)$ in soil water, an estimated value ($\bar{\kappa}$) of the adsorption coefficient can be used to define the actual shares of glyphosate (GLY) from $\bar{\kappa} = \frac{\alpha GLY}{(1-\alpha)GLY}$. From the Finnish experiments, Autio et al. (2004) estimated the adsorption coefficient 58 for Glyphosate.

Using degradation of Glyphosate and its adsorption coefficient, we obtain the following liquid and solid runoffs for Glyphosate:

$$Z^i_{GLY_l} = (1 - m_i^{1.3})\left[\psi_i (0.02 * GLY_l)/100\right] \quad \text{for } i = 2 \qquad (12a)$$
$$Z^i_{GLY_s} = (1 - m_i^{0.3})\left[\zeta_i (GLY_s) * 10^{-6}\right] \quad \text{for } i = 2, \qquad (12b)$$

where ψ_i is runoff volume (mm), ζ_i is erosion kg/ha, GLY_l is the concentration of glyphosate in soil water (mg/l) and GLY_s is the adsorption of glyphosate in soil particles (g/ha), which is converted into mg/kg eroded soil and then multiplied by erosion kg/ha.

MCPA runoffs behave differently and those are modeled using equation (13), adapted from Kreuger and Törnqvist (1998):

$$\log Z^{i}_{MCPA} = (1 - m_i^{0.3})\left[-0.1 + (1.1 * \log MCPA(g/ha) + 0.00004 * Koc - 0.005 * DT50\right]$$
$$i = 1,2 \qquad (13)$$

where K_{oc} is the soil sorption coefficient (normalized to soil organic carbon content) which is 125 in our case, DT50 is the soil half-life, 10 days for MCPA (Laitinen et al. 1996).

3.3 The Social welfare function

The final step in developing our parametric model is to define the social welfare function, which consists of profits and damages from nutrient and herbicide runoffs. We next define the social damages from the runoffs, starting with the nutrient runoffs.

The social valuation of agricultural surface nutrient runoff damages is closely tied with the fact how the society trade-offs inland and sea waters in reducing euthrophication. Following Kiirikki et al (2003), we transform total P into N equivalents in the damage function by multiplying total P by Redfield ratio 7.2. Redfield ratio describes the optimum N/P ratio for the growth of phytoplankton, relevant for algal growth in sea waters. Moreover, we assume that the marginal damage from nitrogen equivalents is constant, so that the damage function is given by

$$d(Z^{i}) = R_n(N_i + 7.2P_i)\,, \qquad (14a)$$

where N_i is defined in equation (9) and P_i is the sum of equations (10a) and (10b) and R_n is the constant social marginal damage. For the social value of runoff damages we can only derive a rough estimate from the works of Aakkula (1999) and Yrjölä and Kola (2004). Drawing these works, our estimate indicates that Finnish consumers experience a damage value of 35 euros from average per hectare agricultural runoffs (13 kg/ha N and 2 kg/ha P).

For the herbicide runoffs we also postulate constant marginal damage, so that the damage function is given by

$$D(Z^{i}) = R_h Z_i^h\,, \qquad \text{for } i = 1,2 \qquad (14b)$$

where Z_1^h consists of MCPA runoffs only and Z_2^h consists of the sum of MCPA and GLY runoffs. As for the size of R_h, herbicide runoffs differ from nutrient runoffs because of their toxic nature. Thus, one can expect that the social value of herbicide runoff damage is higher than that of nutrient runoff damages. Indeed, this is the case. Siikamäki (1997) suggests the average WTP/ha of € 113.6 for the total abandonment of herbicide use in Finnish agriculture, and we use this estimate.

Combining equations (7) – (14b) allow us to express our social welfare function in the following simple form for both cultivation technologies as,

$$SW^{i} = \pi^{i} - d(Z_i^n) - D(Z_i^h)\,, \qquad i = 1,2. \qquad (15)$$

We use the following crop prices in π^i for both technologies: wheat € 0.133/kg, barley € 0.109/kg and oats € 0.112/kg. The price of the compound fertilizer is € 0.23/kg and, thus, the price of nitrogen is (with 20% nitrogen content) € 1.15/kg.

We are finally in the position to produce empirically sound and meaningful comparison of the two cultivation methods in our parametric model.

4. No-till and conventional technologies: empirical findings

Above all, we are interested in whether no-till technology is more profitable than conventional technology in terms of social returns in the Finnish crop cultivation. Because herbicides are typically given in fixed portions, instead of optimizing we take their amount as fixed. Moreover, we assume that applied herbicides control successfully both annual and perennial weeds, so that weeds do not cause yield losses to the experimental yields reported in Table 3.

Table 5 reports our results in terms of nitrogen applied, buffer strips, yields and social returns for the given application of MCPA and GLY defined above. We report the buffer strips as the shares of the field, and exemplify their size as a width in meters for a field of 200m*50m.

Table 5. Socially optimal nitrogen intensity (N), buffer strips (BS), production and social returns under no-till and conventional technologies

Crop	**N, kg/ha**		**BS, width m (share)**		**Yield, kg/ha**		**Social returns, €/ha**	
	Conv	No-till	Conv.	No-till	Conv	No-till	Conv	No-till
Wheat	160.1	87.5	2.6 (0.0130)	4.5 (0.0227)	5109	2700	105.9	-54.0
Barley	107.9	101.6	4.1 (0.0206)	2.4 (0.0121)	4200	3911	-24.7	17.9
Oats	113.4	91.5	2.2 (0.0108)	1.7 (0.0083)	5247	4080	104.6	71.5

Only for barley no-till produces higher social returns than conventional technology; for wheat and oats conventional technology is definitely more competitive. This is not especially surprising, given that the yield differences reported in Table 3 were so great. The cost advantage of no-till is not enough to compensate for lower yields it provides. Nitrogen application levels differ between technologies and are higher under conventional technology. For wheat, the nitrogen use is exceptionally high and much higher than the Finnish Agri-Environmental Programme would allow. Conventional cultivation entails larger buffer strips than no-till in the cases of barley and oats cultivation, whereas under conventional wheat cultivation buffer strips are smaller than under no-till (due to higher profits forgone). In the cases of barley and oats cultivation the socially optimal buffer strips under no-till are narrower than required in the Finnish Agri-Environmental Programme (3 meters). The socially optimal buffer strips for conventional technology are also smaller than the Finnish Agri-Environmental Programme requires (3 m) in the cases of wheat and oats.

Recall the empirical findings, discussed above, which indicated that no-till decreases particulate phosphorus runoff but this reduction may be offset by increased dissolved phosphorus runoffs. To see whether no-till leads to unambiguously lower overall nutrient runoffs or not, we calculated the nitrogen and phosphorus runoffs associated with the socially optimal solution. Table 6 provides a summary of nutrient runoffs under the social optimum.

Table 6. Socially optimal solution: surface runoffs of nitrogen (N), particulate phosphorus (PP) and dissolved phosphorus (DRP) under conventional and no-till technologies.

Crop	**Conventional, kg/ha**			**No-till, kg/ha**		
	N	**PP**	**DRP**	**N**	**PP**	**DRP**
Wheat	13.07	2.719	0.574	3.83	0.767	1.879
Barley	8.43	2.557	0.567	4.70	0.830	1.892
Oats	9.73	2.763	0.570	4.62	0.862	1.891

Table 6 demonstrates that nitrogen runoffs are roughly 50% lower under no-till than conventional technology for barley and oats, and 70% lower for wheat. Particulate phosphorus runoffs are 70% lower but dissolved phosphorus runoffs are 3.3 times higher under no-till than conventional technology. Changes in phosphorus runoffs over crops are quite modest. Assuming that all particulate phosphorus is readily available to algal growth we can focus on total phosphorus. The total phosphorus runoff for all crops under conventional technology is about 3.2 kg/ha, and under no-till 2.7 kg/ha. Hence, the difference is 0.5 kg/ha in favor of no-till technology. Keeping in mind that we are dealing here with small amounts, this difference must be regarded as an advantage for no-till.

In order to analyze the effect of herbicide runoffs in a sharp focus, we regard t = 180 as the representative of average runoff. The chosen point of time entails the Autumn rains, which are responsible for the highest runoffs from cultivated land. We collect herbicide runoffs in Table 7.

Table 7. Socially optimal solution: surface runoffs of MCPA, solid glyphosate and liquid glyphosate under conventional and no-till technologies, kg/ha.

Crop	**Conventional kg/ha**	**No-till, kg/ha**		
	MCPA	***MCPA***	***solid GLY***	***Liquid GLY***
Wheat	0.0208	0.0193	0.053	0.000298
Barley	0.0196	0.0209	0.058	0.000299
Oats	0.0212	0.0217	0.060	0.000299

From Table 7, MCPA runoffs do not differ between technologies and are on average slightly over 1 per cent of the amount applied. The reason for this similarity lies in the fact that MCPA is fast degradable herbicide with weak adsorption to soil. Only no-till entails glyphosate runoffs. Solid GLY runoffs are over 5 % of the applied amount and liquid GLY runoffs are 0.03 %. Hence, total herbicide runoff is higher for no-till, because MCPA runoffs are quite the same but glyphosate is used only for no-till. To further assess the importance of this difference, we define the economic value of herbicide damages. It is on average € 2.3/ha for conventional and € 8.9/ha for no-till. Thus, in terms of social welfare this component does not change much the overall size of welfare.

6. Conclusions

We characterized analytically conditions for the socially optimal choice between conventional and no-till cultivation technology. Drawing on our theoretical model, we developed a detailed description of cultivation technologies and surface runoffs of nutrients and herbicides in a parametric model to assess empirically the relative merits of conventional and no-till technology. Concerning crop yields for wheat, barley and oats and surface runoffs a new field experiment data was used.

Using Finnish data we found that the adoption of no-till technology is socially optimal only for barley cultivation. Conventional cultivation turned out to be optimal for wheat and oats, because, despite considerable costs savings, no-till has much lower yields than conventional technology in this new, short-term experimental data we utilized. Our model predicts that in order to become adopted, yield under no-till can entail at most 700-800 kg/ha smaller yield than conventional technology. Now the difference for wheat was 1845 kg/ha and 1117 kg/ha for oats.

With respect to environmental aspects, both technologies behaved as one could expect. Under no-till buffer strips are considerably lower than under conventional technology. In fact, buffer strips under no-till are quite close to the normal field edges. No-till reduces the nitrogen runoffs about 50%, and particulate phosphorus runoffs 70% relative to conventional technology, but it causes 3.3 times more dissolved phosphorus runoffs. However, no-till entails lower total surface runoffs of phosphorus. Total herbicide runoff is higher for no-till because of the use of glyphosate to control perennial weeds.

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