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Profitability of Crop Cultivation in Small Arable Fields When Taking Economic Values of Ecosystem Services into Account

Daniel Nilsson [1,*] and Håkan Rosenqvist [2]

[1] Department of Biosystems and Technology, Swedish University of Agricultural Sciences, P.O. Box 190, S-234 22 Lomma, Sweden
[2] Independent Researcher, Prästvägen 5, S-268 73 Billeberga, Sweden; hak.rosenqvist@telia.com
* Correspondence: Daniel.nilsson@slu.se

Abstract: Small arable fields are beneficial with regard to ecosystem services, e.g., concerning biodiversity. By selecting appropriate crops and cultivation practices, arable fields can also be used as carbon sinks. The objectives of this study were to investigate what impact field conditions (e.g., field size and shape) and payments (subsidies) for environmental benefits have on profitability. A dynamic simulation model was used to simulate machine operations in fields of two different shapes and five different sizes (from 0.75 to 12.00 ha). A wide range of crops cultivated in Sweden were investigated (fallow land and plantation of Norway spruce were also included). A perimeter-based subsidy was suggested in order to conserve and promote biodiversity, and an area- and crop-based subsidy was suggested in order to promote sequestration of soil organic carbon (SOC). The results showed that, without financial support and from a purely economic point of view, most field types investigated should be planted with Norway spruce. With currently available subsidies, e.g., EU Common Agricultural Policy (CAP) direct payments, hybrid aspen, poplar, fallow, and extensive ley cultivation are the most profitable crops. Perimeter-based subsidies favoured the net gain for small fields. As expected, a subsidy for sequestration of SOC favoured cultivation of specific SOC-sequestering crops such as ley, willow, and poplar. Our recommendation for future studies is to investigate a well-balanced combination of perimeter-based support and SOC sequestration support that benefits biodiversity and climate under different cultivation conditions.

Keywords: profitability; small fields; biodiversity; field perimeter; carbon sequestration; direct payment

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1. Introduction

1.1. Background

In Sweden, there are large areas of arable land, perhaps up to half a million hectares, that are cultivated at low intensity. The area of fallow land has been around 0.15 million ha in recent years [1] and the area of low-intensity cultivation of ley is estimated to be 0.2–0.3 million ha [2]. Furthermore, the area of arable land abandoned in the past two decades is estimated to be around 0.1 million ha [3]. The total area of arable land in Sweden at present is around 2.6 million ha [1]. Arable fields cultivated with low intensity or at risk of being abandoned are usually small, irregular-shaped, stony, wet, and/or have soils with low fertility. Such fields can be characterised as marginal from an economic point of view, as the revenues from the products sold do not balance the costs of production [4,5]. Marginal fields in Sweden are often, but not exclusively, located in rural regions with less favourable cultivation conditions [6]. From a political and societal point of view, there is often a desire to keep the landscape open and to preserve economically vital farming activities in these regions. Therefore, it is important to find suitable crops and cultivation practices that result in profitable and sustainable utilisation of marginal arable land.

Ecosystem services can be defined as "direct and indirect contributions of ecosystems to human well-being" [7]. Small arable fields have been shown to be beneficial with regard to biodiversity and ecosystem services [8], especially in regulating and maintaining ecosystem services (for definitions, see CICES [9]). For example, the biodiversity of birds, insects, and red-listed plants increases as landscape heterogeneity increases with more small, irregular-shaped fields [10–12]. One important factor in this regard is the length of the perimeter in relation to the area of the field [13]. The current Common Agricultural Policy (CAP) direct payment to farmers in the European Union (EU) is based on area, and not on the perimeter of fields. Thus, small and irregular-shaped fields are not favoured over large, homogeneous fields with regard to potential increases in biodiversity.

Another regulating ecosystem service is the sequestration of soil organic carbon (SOC) in soils. By selecting appropriate crops and cultivation practices, agriculture can act as a carbon sink [14,15]. Large carbon stocks in arable soils are also beneficial from a food and feed sustainability perspective, as they increase soil fertility [16]. There has been financial support to farmers in California for sequestration of SOC [17]. There are also discussions in the EU about introducing direct financial support to farmers for sequestration of soil carbon [18], although the current "green" direct payment scheme is aimed at increasing soil carbon stocks through e.g., the concept of ecological focus areas (EFA) [19]. However, the quantities of SOC sequestered in a specific field and the corresponding economic value, as well as the potential long-term effects of carbon sequestration subsidies, are uncertain. Nevertheless, direct support coupled to a specific soil carbon-sequestering crop, e.g., short rotation coppice willow (SRCW), could be beneficial from an agricultural, environmental, and societal point of view.

In economic analyses of crop production, the costs of in-field machine operations are usually based on machine capacity data (e.g., expressed in hours per hectare) that are assumed to be valid for a wide range of field sizes and shapes. It is clear, however, that the operating time needed may differ considerably between fields as a result of variations in time spent for e.g., turnings, headland stops, and acceleration [20–22]. The size and shape of the field; as well as the effective implement width; possible driving speed; and time needed for in-field preparation, loading, and emptying, all have an impact on the total time per hectare needed in a specific field. The smaller the field, the more important such factors often become. This indicates that the number of work operations should normally be kept low in small, irregular-shaped fields, to reduce costs [23]. However, this in turn has an impact on the choice of crops cultivated and on cultivation intensity.

Studies on the economic profitability of a wide range of crops cultivated under Swedish conditions, taking field-specific machinery costs and financial support for ecosystems services such as biodiversity and carbon sequestration into account, are lacking in the literature (there are, however, a few studies that cover parts of this question (e.g., [24])). There is thus a need for research on using arable land in a more profitable and sustainable way, from both farmers' and society's point of view.

1.2. Objectives and Delimitations

The objectives in the present study were (a) to examine the impact of field size, field shape, cultivation intensity, and yield on profitability; and (b) to examine the impact payments (subsidies) for environmental benefits would have on profitability.

Profitability calculations were made for the following scenarios: (1) Without financial support; (2) with currently available subsidies, e.g., CAP direct payment; (3) with field perimeter-based support; and (4) with soil carbon sequestration support.

This study focused on cultivation in small arable fields under Swedish conditions from a farmer's economic perspective. In contrast to small farms having mainly small fields, the focus was on middle-scale farms having some small fields. The economic profitability was assessed using the net present value method for individual crops. Profitability analyses in a crop rotation perspective was beyond the scope of this study.

2. Materials and Methods

2.1. Field and Crop Data

Cultivation in fictitious fields in two municipalities in southern Sweden: Svalöv (55°55′ N, 13°07′ E) and Ronneby (56°12′ N, 15°16′ E) were investigated. Svalöv is located in the plain districts of Sweden, where the average field (parcel) area is 6.0 ha and the soils can be characterised as 'high-yielding' in a Swedish context (expected "standard" yields are presented in Table 3). Ronneby is located in a region with mixed agriculture and forestry, where the average field (parcel) area is 1.8 ha and the soils can generally be characterised as 'intermediate-yielding' (Table 3).

Two field shapes were investigated. Shape A (Figure 1) was assumed to represent 'normal-shaped' fields and shape B (Figure 2) 'irregular-shaped' fields. Five field areas were used in the calculations for fields with shape A: 0.75 ha, 1.50 ha, 3.00 ha, 6.00 ha, and 12.00 ha, and two field areas for fields with shape B: 0.75 ha and 1.50 ha (Table 1). It was assumed that headland width was mainly 16 m in each field, but shorter for some specific machine operations, e.g., 12 m for mowing, with four passes and an effective working width of 3.0 m.

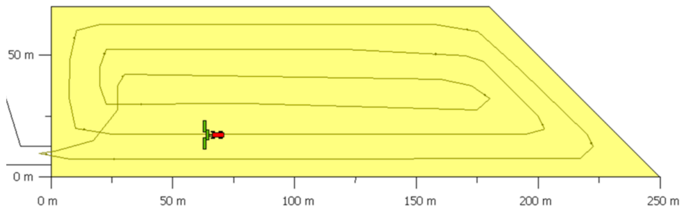

Figure 1. Simulation of soil rolling (effective machine working width 12.0 m) in field 1.50A, which has an area of 1.50 ha and normal shape (shape A).

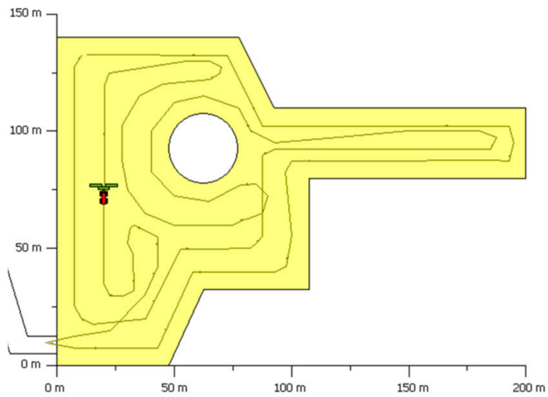

Figure 2. Simulation of soil rolling (effective machine working width 12.0 m) in field 1.50B, which has an area of 1.50 ha and irregular shape (shape B).

The crops included in the analysis were spring barley, winter wheat, ley, reed canary grass (RCG), SRCW, poplar, hybrid aspen, and Norway spruce. The economic profitability of fallow land was also calculated. For spring barley and winter wheat, an extensive farming alternative with no nitrogen fertilisation, no use of fungicides and insecticides, and where the yield of these crops was assumed to be 50% [25,26] of that in normal cultivation conditions, was also considered.

On headlands, crop yield is often lower than in the main field because of increased soil compaction, inadequate or non-optimal doses of fertilisers and pesticides, run-over damage, and field edge effects (e.g., shading trees). It is reasonable to assume that cereal yield on headlands is 30% lower than in the main field [27–30]. A 30% reduction in yield was therefore assumed in this study for spring barley, winter wheat, ley, and RCG.

Table 1. Area, perimeter, headland area, and headland area in relation to total area (with headland width 16 m) for the field types investigated (where A is 'normal-shaped' fields and B is 'irregular-shaped' fields).

	Field Type (ha)	Perimeter (m)	Headland Area (ha)	Headland Area (%)
0.75A	0.75	421	0.193	25.7
0.75B	0.75	537	[a]	[a]
1.50A	1.50	595	0.273	18.2
1.50B	1.50	759	[a]	[a]
3.00A	3.00	841	0.386	12.9
6.00A	6.00	1190	0.546	9.1
12.00A	12.00	1683	0.772	6.4

[a] Headland area and percentage of total area depend on type of operation and driving directions (see Figure 2).

Ley duration was assumed to be 3 years, with the forage harvested twice a year either as silage or hay by round balers. An extensive farming alternative with no nitrogen fertilisation was also considered for ley. In the extensive silage and hay options, it was assumed that yield was 80% and 70% of the normal yield [31], respectively, and that the ley had a significant proportion of legumes, was harvested once a year, and ran for 5 years.

RCG was assumed to be harvested in early spring by square balers for 9 years of its total duration of 10 years (no harvest in the first year). An extensive farming option with no nitrogen fertilisation and yield corresponding to 70% of that in normal cultivation conditions was considered for RCG.

SRCW was assumed to be harvested for 7 years throughout its total lifetime of 22 years and fertilised with nitrogen after each harvest. In the extensive alternative for SRCW, no nitrogen fertilisation and five harvests in a total lifetime of 21 years were assumed.

For poplar, hybrid aspen, and Norway spruce, the age at harvest was assumed to be 23, 26, and 50 years, respectively, at Svalöv, and 31, 33, and 62 years, respectively, at Ronneby. Hybrid aspen and Norway spruce were assumed to be grown to produce timber, pulpwood and bioenergy, and poplar to produce pulpwood and bioenergy.

2.2. Economic Model

The economic model used in the present analysis was developed specifically for comparison of annual and perennial crops. In the model, the net gain (NG) per ha and year was calculated as [32]:

$$\mathrm{NG} = \frac{\mathrm{r}}{1-(1+\mathrm{r})^{-\mathrm{n}}} \sum_{\mathrm{t}=0}^{\mathrm{T}} (1+\mathrm{r})^{-\mathrm{t}} \mathrm{A_t} \quad (1)$$

where n is the length of the cultivation period (in years), which in the present case was dependent on the type of crop (annual or perennial), r is the discount rate (here 3% was assumed), t is the year in which the payment takes place, and A_t is the value of the payment per ha ($A_t > 0$ for revenues and $A_t < 0$ for costs). Thus, the sum of net present values of revenues and costs, from the first to the last year (T) with revenues/costs, was equally distributed among all cultivation years of perennial crops using an annuity factor, enabling comparisons with annual crops.

The economic calculations considered all costs of machinery operations (Section 2.3), costs of seed, fertilisers, pesticides, transport to storage, storage, transport to user (Section 2.4), revenues from sold products (Section 2.5), revenues from currently available subsidies (Section 2.6), and revenues for promoting ecosystem services (Section 2.7). Land rental costs were not included. Further information on assumptions and input data used in the calculations can also be found in [6].

A price level corresponding to the situation in 2017 was used. This year can be regarded as an average year representing the price levels during 2015–2020. In that period, the inflation rate in Sweden was 1.3% on a yearly basis. An exchange rate of €1.0 = SEK10.0 was used.

2.3. Costs of In-Field Machine Operations

In-field machine operations were simulated using the Arena/Siman software package [33], in order to get field-specific performance data. This software employs a dynamic simulation approach and has animation facilities, making it possible to follow machine operations in detail. In the model, machines perform their work following a driving network pattern described by links and intersections (or nodes). The driving patterns were laid in the fields studied, and the machines then followed these tracks according to data specifications about operation speed (depending on type of work and machine width), turning times, preparation/adjustment and other stoppage times, etc. A headland pattern was used for shape A (except when e.g., rolling (Figure 1)) and a circuitous pattern for shape B (except when e.g., ploughing). It was assumed that these patterns represented common practice [20]. Optimisation techniques [34,35] to find optimal paths for each type of work, machine width, and field was beyond the scope of this study. For details of the model, see Table S1 and [22,23].

Important time-related machine efficiency factors considered in the model were preparation time before starting work in the field, extra time for reduced driving speed on bends (Figure S1), time for turnings (Figure S2), time for acceleration, time for adjustments and stoppages (e.g., due to stone clearing or bale wrapping), time for filling (seed, fertilisers, spraying water/chemicals), time for emptying (threshed grain), and finishing-off time. Factors related to the type of operation and machine size were effective work width and (maximum) driving speed at work [6].

After adjusting the model parameters "install time", "finishing-off time", and "stoppage time" to reasonable values, the model was calibrated to a machine capacity corresponding to 'normal' capacity data for machines presented by Maskinkalkylgruppen [36]. In the calibrations, the capacity data in [36] for specific machine working widths was assumed to be valid for fields with area 6.00 ha and shape A [6]. Resulting driving speeds (in the pass) from the calibrations and 'standard' hourly costs reported by Maskinkalkylgruppen [36] are presented in Table 2 (see also Table S2).

Table 2. Effective working width and speed in row/pass (after calibration) used in the simulations, and 'standard' hourly costs used for machines and tractors in the economic calculations.

Operation	Eff. Working Width (m)	Speed (km h^{-1})	Hourly Machine Costs (€ h^{-1}) [a]	Hourly Tractor Costs (€ h^{-1}) [b]
Stubble cultivation	4.0	7.0	42.4	66.9
Ploughing	2.0	7.5	36.4	66.9
Harrowing	8.0	10.5	38.4	66.9
Grain drilling	6.0	7.5	34.7	60.4
Rolling	12.0	7.5	47.6	55.0
Fertiliser distribution	24.0	10.0	21.3	55.0
Spraying	24.0	7.0	49.2	55.0
Combine harvesting	6.0	5.5	206.1	-
Mowing	3.0	10.0	40.9	60.4
Windrowing	6.0	8.0	40.8	55.0
Silage baling	3.0	9.0	71.0	66.9

[a] Costs include depreciation, repairs, interest, insurance, and shelter (excl. costs of tractor, fuel, and driver) for "normal" annual use [36].
[b] Costs include depreciation, repairs, interest, insurance, shelter, fuel, and driver for "normal" annual use of two tractors (90 kW ("interm." and "heavy" work) and 110 kW ("heavy" work)) [36].

The time demand for machine operations in cultivation and harvest of SRCW was assumed to have the same field type dependence as silage baling in relative terms. For poplar, hybrid aspen, and Norway spruce, machines used in forestry were assumed for harvesting. The productivity [37] of these machines was assumed to be independent of field type.

2.4. Costs of Seed, Fertilizers, Pesticides, Transports, Storage, etc.

Costs of cultivation commodities such as seeds, fertilizers, and pesticides are presented in Table S3. Other costs playing a significant role in the calculations, e.g., transport, storage, agency, decommissioning, and overhead costs, are also shown in Table S3.

2.5. Revenues from Sold Products

Yield per ha and product prices are presented in Table 3. The prices of products were based on price levels in 2017 in southern Sweden.

Table 3. Yield per ha ("standard yield", or expected yield in normal weather conditions at Svalöv and Ronneby) and product prices for the crops investigated (t = metric tonnes, mc = moisture content, DM = dry matter, N = nitrogen fertiliser, m^3f = forest cubic metres) [37,38].

Crop	Yield Units	Yield Amount		Product Price
		Svalöv	Ronneby	(€ per Unit)
Spring barley	t, 14% mc	5.20	4.10	119
Spring barley, extensive	t, 14% mc	3.64	2.87	119
Winter wheat	t, 14% mc	7.30	5.50	136
Winter wheat, extensive	t, 14% mc	5.11	3.85	136
Ley, silage	t DM	7.50	6.70	130
Ley, silage, no N	t DM	5.25	4.69	130
Ley, hay	t DM	7.50	6.70	150
Ley, hay, no N	t DM	5.25	4.69	150
Reed canary grass (RCG)	t DM	5.40	5.00	76
RCG, no N	t DM	3.78	3.50	76
Short-rotat. willow (SRCW)	t DM	9.00	6.50	72.6
SRCW, no N	t DM	5.60	4.00	72.6
Poplar pulpwood	m^3f	140	140	30
Poplar, bioenergy	t DM	92	92	74.1
Hybrid aspen, timber	m^3f	170	170	44
Hybrid aspen, pulpwood	m^3f	140	140	30
Hybrid aspen, bioenergy	t DM	92	92	74.1
Norway spruce, timber	m^3f	362	362	50
Norway spruce, pulpwood	m^3f	193	193	30
Norway spruce, bioenergy	t DM	40	40	74.1

2.6. Revenues from Currently Available Subsidies

CAP direct payment (€200 ha^{-1} yr^{-1} basic plus greening payments) can be received for all crops except spruce, and establishment (€580 ha^{-1}) and fence-in (€1000 ha^{-1}) support can be received for poplar and hybrid aspen [39]. These payments have more or less been unchanged during the years 2015–2020, but will change when the new CAP is to be implemented in 2023.

2.7. Revenues for Promoting Ecosystem Services

2.7.1. Biodiversity in Small Arable Fields

A number of studies have shown that small crop fields benefit biodiversity (e.g., [8,11,12,40,41]). Fahrig et al. [11] investigated the abundance and biodiversity of birds, plants, butterflies, syrphids, bees, carabids, and spiders in different agricultural landscapes, and found that field size had a strong effect on biodiversity. They attributed this effect to easier access to field boundary habitats when fields are small. In a comprehensive study, Sirami et al. [12] investigated 435 landscapes in Europe and North America with regard to the biodiversity of similar species to those studied by Fahrig et al. [11] and found that "the effect of decreasing mean field size from 5 to 2.8 ha was as strong as the effect of increasing semi-natural cover from 0.5 to 11%". Even in the absence of semi-natural cover between fields, multitrophic biodiversity increased with smaller fields and higher crop heterogeneity. Hass et al. [42] showed that increased density of crop-crop borders without permanent vegetation facilitated the movement of pollinators. According to Dainese et al. [41], landscape simplification, e.g., larger arable fields with monocultures, has a negative effect on ecosystem services because of diminished abundance of service-providing organisms.

It has been suggested that the length of semi-natural boundaries is more important for biodiversity than the semi-natural area in a landscape [13]. The length of field edges in relation to total area increases for small, irregular-shaped fields. The machinery costs in crop cultivation usually also increase, as a result of e.g., more turnings. Rodrígues and Wiegand [43] investigated the trade-off between machine efficiency in harvest of cereals and loss of biodiversity-friendly habitats, and found that the increase in machine efficiency was small in fields larger than around 2 ha. Thus, they concluded that there is no economic benefit in having fields larger than ~2 ha, while there are biodiversity benefits in having fields of that size or smaller [43].

2.7.2. Quantification of SOC Sequestration Rates

Sequestration of SOC is a reversible and highly complex process. Its rate is dependent on a large number of factors, such as initial SOC stocks (i.e., earlier land use), crops cultivated, soil texture, temperature, precipitation, nitrogen fertilisation, farming practices, and tillage, etc. [14–16]. The process may have a non-linear pattern over time and is finite and long-term, as it may take 100 years to reach equilibrium [14]. Considering the uncertainty of specific values, indicative values of SOC sequestration rates were considered for the crops included in the present analysis.

There is consensus that ley crops increase SOC sequestration in arable soil previously used for annual crops [44–47]. The main reason is the increased quantity of roots in combination with reduced tillage, which increases SOC sequestration in both topsoil and subsoil. Roots appear to contribute more to long-term sequestration of SOC than above-ground crop residues [48]. Under Swedish conditions, SOC sequestration is estimated to be around 0.65 t ha^{-1} yr^{-1} (of which 0.56 t ha^{-1} yr^{-1} is in topsoil and 0.09 t ha^{-1} yr^{-1} is in subsoil), when ley is cultivated instead of annual crops, according to a review by Bolinder et al. [45]. Cultivation of RCG also increases SOC stocks [49], but no long-term quantification values are reported in the literature for Swedish conditions. However, it is reasonable to assume that the SOC sequestration rate is similar to that of ley.

The rate of change in SOC on fallow land is dependent on the vegetation. On bare soil, there may be a reduction in SOC of ~0.5 t ha^{-1} yr^{-1} [50]. There may also be a slight net reduction in SOC in weedy fallow fields [45]. When catch crops are grown in fallow fields, however, the sequestration rate may be around 0.3 t C ha^{-1} yr^{-1} [45].

Several studies have shown that SOC content increases when SRCW is cultivated on arable land, especially in fields previously devoted to annual crops [45,51,52]. Rytter [52] found that the quantity of SOC increased by 0.4–0.5 t ha^{-1} yr^{-1}, while Bolinder et al. [45] suggest that 0.45 t SOC ha^{-1} yr^{-1} is a reasonable average sequestration rate under Swedish conditions. Rytter et al. [53] recorded no statistically significant increases, but the SRCW stands were, on the other hand, only 5 years old.

There seem to be only small differences in SOC sequestration rates between SRCW and poplar stands [54,55], so a reasonable average value for poplar is 0.45 t SOC ha^{-1} yr^{-1} [45]. There are no published values on SOC sequestration by hybrid aspen, but it is reasonable to assume that the sequestration rate is of the same order of magnitude as for SRCW and poplar [45].

In a Danish study, Vesterdal et al. [56] found no significant increase in SOC content in the whole soil profile 29 years after Norway spruce had been planted on former arable land. The SOC content in the forest floor and in the upper 5 cm layer of the mineral soil increased, while that in the 5–15 cm and 15–25 cm mineral soil layers decreased. Thus, there was SOC redistribution in the soil, rather than an increase in total content. This redistribution of SOC was verified in a meta-analysis studying SOC changes following afforestation in Northern Europe, but that study also found significant increases in SOC, although small within a 30-year perspective, after afforestation of croplands [57]. Under Swedish conditions, Olsson [58] estimated that the total increase in SOC is 0.1 t ha^{-1} yr^{-1} in a 50-year perspective after planting Norway spruce on cropland.

To summarise, the SOC sequestration rates used in the economic calculations in this study were: 0.65 t SOC ha^{-1} yr^{-1} for ley and RCG; 0.3 t SOC ha^{-1} yr^{-1} for fallow; 0.45 t SOC ha^{-1} yr^{-1} for SRCW, poplar, and hybrid aspen; and 0.1 t SOC ha^{-1} yr^{-1} for Norway spruce. No long-term net increases in SOC were assumed for spring barley and winter wheat, which often cause a decrease in SOC stocks [47,59], although changed cultivation practices, e.g., cultivation of intermediate crops, can increase SOC stocks [60].

2.7.3. Monetary Valuation of Biodiversity and CO_2 Emissions

There are several approaches for valuing ecosystem services in monetary terms (see e.g., Costanza et al. [61] and Tinch et al. [62]). The Swedish Environmental Protection Agency [63] presents monetary values for biodiversity of arable land, primarily based on the willingness-to-pay (WTP) approach used by Ciaian & Paloma [64] and Hasund et al. [65]. The value of a so-called "biodiversity field" in flat landscapes is within the range €200–750 ha^{-1}, with a recommendation to use €400–500 ha^{-1} as the "most likely" value, depending on location in Sweden [63–65]. The monetary value of a small (<0.3 ha) irregular-shaped field is estimated to be €7–40 per field, with a recommendation to use €20 per field as the "most likely" value [63].

There are two main methods for valuing reductions in emissions of greenhouse gases. The marginal abatement cost (MAC) approach estimates the marginal cost of reaching a certain emissions reduction target, while the social cost of carbon (SCC) approach estimates the damage costs of climate change [66,67]. Both approaches consider the cost to society of 1 additional tonne of CO_2 emitted. Carbon dioxide taxes and emission trading systems can be viewed as subcategories to MAC [67].

The Swedish Transport Administration [68] recommends that emissions of CO_2 be valued according to the Swedish CO_2 tax, which is currently €118 t^{-1} CO_2 [69], for socioeconomic analyses in the transport sector. However, this value can be used in the non-trading sector as well [67]. In a recent report, the Swedish Transport Administration [70] proposed an increase to €700 t^{-1} CO_2, which corresponds to the fee imposed if the Swedish greenhouse gas reduction mandate for blending renewable fuels into diesel and gasoline is not fulfilled. This mandate stipulates that fuel suppliers must reduce emissions of greenhouse gases from fossil-based vehicle fuels by increasing the content of renewable fuels by a certain percentage each year [71].

Another MAC-oriented approach is to value emissions based on allowances in the EU Emission Trading Scheme (EU ETS)). The price of emission allowances in EU ETS has varied considerably during recent years, e.g., from around €30 t^{-1} CO_2 in June 2008 to around €3 t^{-1} CO_2 in April 2013, back to around €30 t^{-1} CO_2 in July 2019 and to €60 t^{-1} CO_2 in August 2021 [72]. These figures indicate that the trading market has not worked under optimal circumstances. For example, the system has been criticised for having an oversupply of allowances, resulting in too low prices and consequently insufficient emissions reductions [73]. The EU ETS will be reformed, e.g., the overall number of emissions allowances will decline at an annual rate of 2.2% from 2021 onwards, compared with the current rate of 1.74%, in order to increase the pace of emissions cuts [73].

Values based on future damage costs (SCC) are inherently uncertain depending on, for example, physical (e.g., what is the 'real' climate sensitivity?), spatial (e.g., national or global?), and time-related (e.g., time perspective and discount rate?) aspects, as well as ethical standpoints. The Swedish Environmental Protection Agency [63] presents values based on studies by Ackerman & Stanton [74], Tol [75], and Isacs et al. [67]. In short-term socioeconomic analyses (with 2015 as the base year) and under the assumptions that the climate sensitivity is low, time preferences are high (using a rate of 3%), and the level of risk-taking is low, a value of €5.7 t^{-1} CO_2 should be used. For long-term studies (to 2050), a value of €12.5 t^{-1} CO_2 should be used. Under the assumptions that the climate sensitivity is high, time preferences are low (using a rate of 0.1%) and the risk of future disastrous climate change events is high, a value of €677 t^{-1} CO_2 should be used in a short-term view and a value of €1136 t^{-1} CO_2 in a long-term view [63,67,76].

According to the review above, profitability calculations were made for a field perimeter-based support of €0.5 m^{-1} (scenario 3), with a sensitivity analysis of using a support of €0.7 m^{-1}, and a soil carbon sequestration support of €400 t^{-1} C (i.e., €112 t^{-1} CO_2) (scenario 4), with a sensitivity analysis in the range €0–1000 t^{-1} C (i.e., €0–279 t^{-1} CO_2).

3. Results

3.1. Performance and Costs of Machine Operations

The simulation results, which were used in the economic calculations, showed that field area and field shape had significant impacts on the time demand of machines, i.e., the smaller the field, the greater the impact of field area on machine performance (Table 4). For shape A, for example, the time demand increased more steeply when the area decreased to around 2 ha. For wide machines with few passes, field shape may also be important for larger fields, as the time for idle pass driving may be considerable in relative terms (cf. fertiliser distribution in fields of 6.00A and 12.00A in Table 4). The values in Table 4 were multiplied (expressed in hours) by hourly costs (Table 2) to calculate total costs of in-field operations (Table S4).

3.2. Net Gain without Financial Support (Scenario 1)

With no financial support, the net gain was negative for all crops grown at Svalöv except Norway spruce (in all field types), winter wheat (in field types 6.00A and 12.00A), and hybrid aspen (in field type 12.00A) (Figure 3). The area and shape of fields had a significant impact on economic profitability for most crops. The net gain for crops with many field visits per year (e.g., spring barley, winter wheat, and ley) was more sensitive to field area and field shape than the net gain for crops with few annual visits, e.g., fallow. Extensive cultivation was less profitable (smaller negative net gain) than intensive cultivation for ley, RCG, and SRCW, whereas intensive cultivation was less unprofitable for spring barley and winter wheat. For small fields (0.75A, 0.75B, 1.50A, and 1.50B), hay with no nitrogen fertilisation, fallow land, hybrid aspen, and Norway spruce had the highest net gain. For small and irregular-shaped fields (0.75B), fallow land and hybrid aspen were the least unprofitable and Norway spruce showed positive net gain.

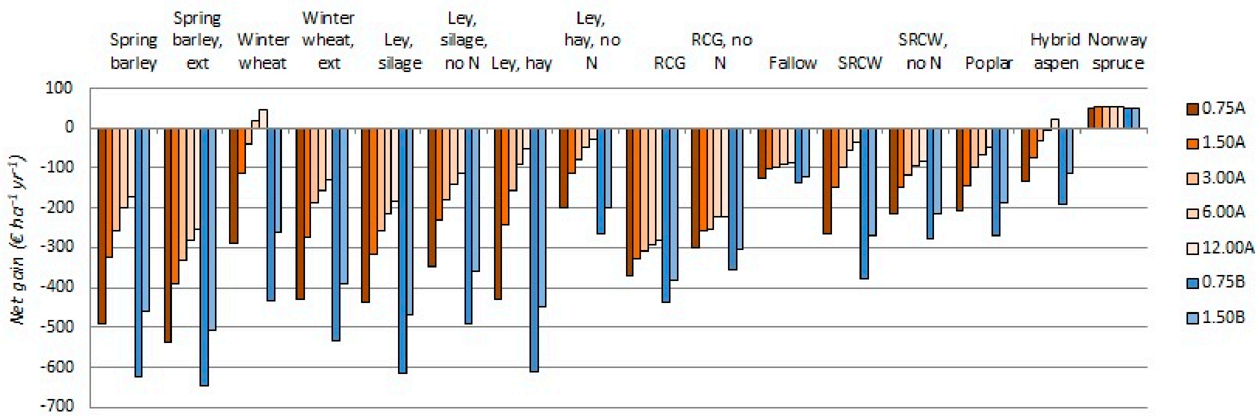

Figure 3. Net gain for the crops investigated at Svalöv without financial support (ext—extensive farming) (for figures, see Table S5).

The net gain was even more negative at Ronneby for all crops except RCG, which showed a small improvement (around €+3 ha^{-1} yr^{-1}) in comparison with Svalöv (Figure 4). The crop with the lowest profitability in comparison with Svalöv was winter wheat (around €−150 ha^{-1} yr^{-1}). The land use alternative with the highest net gain at Ronneby was Norway spruce.

Table 4. Total time demand for different machine operations, where A is 'normal-shaped' fields, B is 'irregular-shaped' fields, and 0.75–12.00 is field size in ha.

Operation	Time Demand (min ha^{-1})						
	0.75A	0.75B	1.50A	1.50B	3.00A	6.00A	12.00A
Stubble cultivation	40.9	43.8	32.8	38.0	29.0	26.7	25.2
Ploughing	78.6	100.4	61.8	80.2	54.9	51.0	47.5
Harrowing	18.8	23.9	16.3	18.0	13.6	12.0	10.4
Grain drilling	36.3	41.7	26.7	34.5	23.3	20.3	19.1
Rolling	21.5	23.2	14.5	17.1	12.5	9.9	9.3
Fertiliser distrib.	13.5	22.6	13.0	19.6	11.4	10.0	10.7
Spraying	20.8	26.5	12.2	19.2	11.7	8.6	8.5
Combine harvesting	53.6	60.0	39.9	50.5	34.7	30.3	28.1
Mowing	42.6	56.8	33.5	44.9	29.1	26.5	24.9
Windrowing	26.2	26.4	20.4	25.5	18.2	16.1	15.4
Silage baling	48.6	61.2	38.6	50.0	34.5	31.7	30.1

3.3. Net Gain with Direct Payment, Establishment and Fence-in Support (Scenario 2)

With direct payment support for all crops except Norway spruce and with establishment and fence-in support for poplar and hybrid aspen (scenario 2), fallow, hybrid aspen, and Norway spruce showed positive net gains in type 0.75B fields at Svalöv (Figure 5). In fields of type 12.00A, hybrid aspen, winter wheat, poplar, ley (hay, no N), and SRCW, in descending order, were most profitable. Only RCG, spring barley (extensive), and RCG (no N) had negative net gains in fields of type 12.00A (Figure 5).

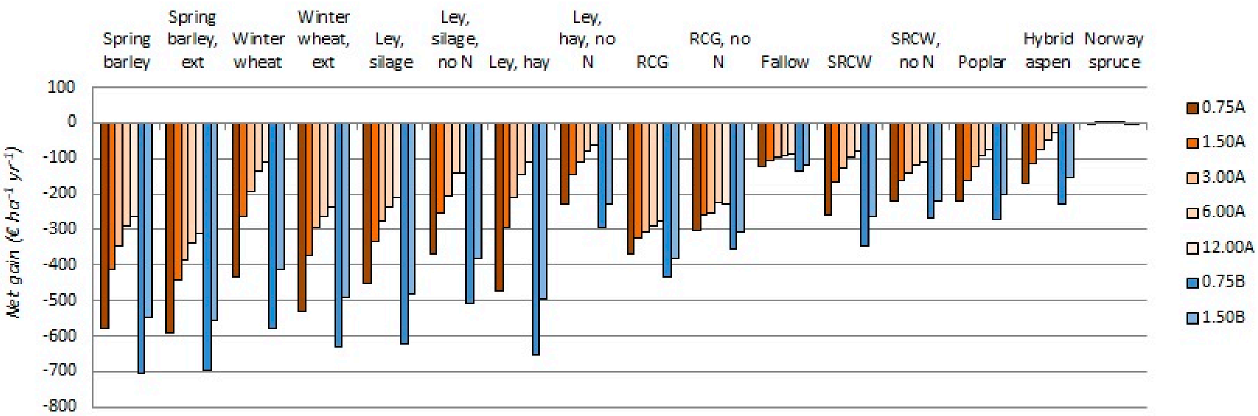

Figure 4. Net gain for the crops investigated at Ronneby without financial support (ext—extensive farming) (for figures, see Table S6).

At Ronneby, the net gain increased by €200 ha^{-1} yr^{-1} for all crop alternatives except poplar, hybrid aspen, and Norway spruce, in comparison with the results in scenario 1 (Figure 4). For poplar and hybrid aspen, the net gain increased by €263 ha^{-1} yr^{-1} and €260 ha^{-1} yr^{-1}, respectively. Taking these increases into account, only fallow and hybrid aspen had positive net gains in fields of type 0.75B, while hybrid aspen, poplar, ley (hay, no N), SRCW, fallow, ley (hay), winter wheat, SRCW (no N), ley (silage, no N), and Norway spruce, in descending order, had positive net gains in fields of type 12.00A. Thus, with the support levels in scenario 2, passive land use (fallow) and tree plantations (hybrid aspen and poplar) were most profitable under the cultivation conditions assumed for Ronneby.

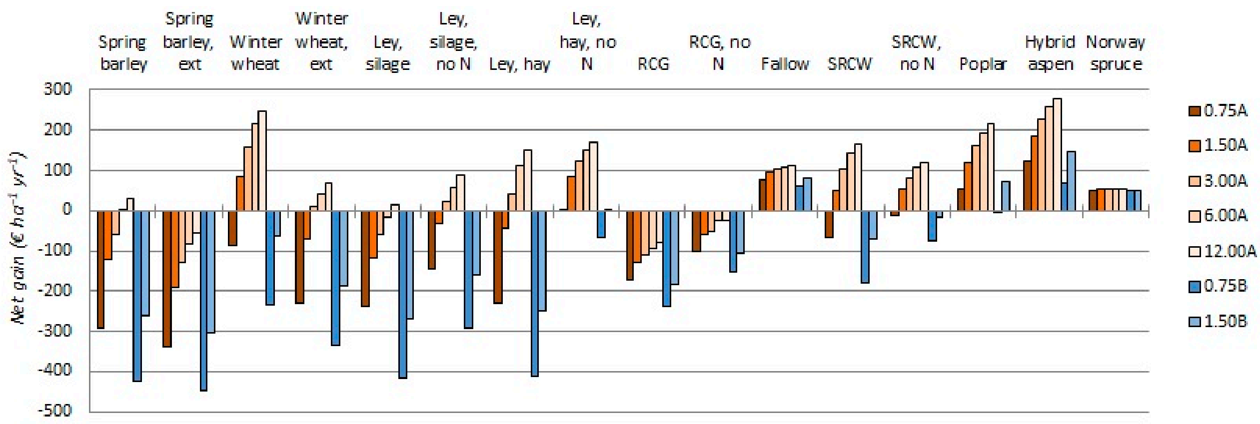

Figure 5. Net gain at Svalöv with direct payment (€200 ha^{-1} yr^{-1}) support for all crops except Norway spruce, and with establishment (€580 ha^{-1}) and fence-in (€1000 ha^{-1}) support for poplar and hybrid aspen (ext—extensive farming) (for figures, see Table S7).

3.4. Net Gain with Field Perimeter-Based Support (Scenario 3)

With field perimeter-based support (€0.5 $m^{-1}yr^{-1}$) for all crops at Svalöv except poplar, hybrid aspen, and spruce (scenario 3), fallow had the highest net gain in small, irregular-shaped (B) fields (Figure 6). Extensive cultivation of hay in small, irregular-shaped fields also showed a positive net gain, which even exceeded the net gain of Norway spruce. The profitability for A-shaped fields increased as the field area decreased when hay (no N), RCG, RCG (no N), fallow, SRCW (not 0.75A), and SRCW (no N) were cultivated. Total support per field type increased linearly as the amount per perimeter metre increased, irrespective of crop cultivated (poplar, hybrid aspen, and spruce not considered). Therefore, the net gain at Svalöv increased by a corresponding amount in an example where perimeter-based support increased from €0.5 m^{-1} yr^{-1} to €0.7 m^{-1} yr^{-1} (Table 5). At Ronneby, the net gains increased in a corresponding way, relative to the results presented in Figure 4.

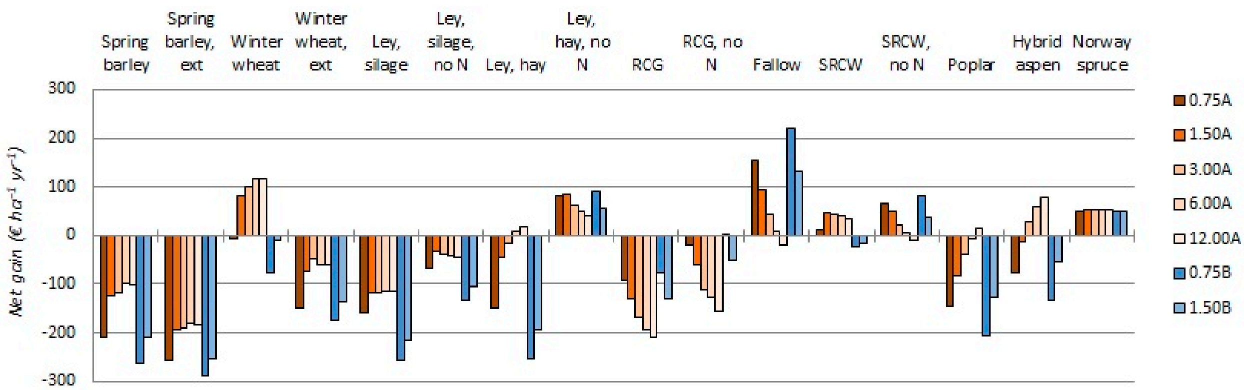

Figure 6. Net gain at Svalöv with perimeter-based support (€0.5 $m^{-1}yr^{-1}$) for all crops except poplar, hybrid aspen, and Norway spruce, and with establishment (€580 ha^{-1}) and fence-in (€1000 ha^{-1}) support for poplar and hybrid aspen (ext—extensive farming) (for figures, see Table S8).

Table 5. Total support per field with perimeter-based support (PBS) of €0.5 m^{-1} yr^{-1} and €0.7 m^{-1} yr^{-1} (increase shown in brackets).

Field Type	Perimeter Length (m)	Support (€ $field^{-1}$ yr^{-1}) for PBS of €0.5 m^{-1} yr^{-1}	Support (€ $field^{-1}$ yr^{-1}) for PBS of €0.7 m^{-1} yr^{-1}
0.75A	421	281	393 (+112)
1.50A	595	198	278 (+80)
3.00A	841	140	196 (+56)
6.00A	1190	99	139 (+40)
12.00A	1683	70	98 (+28)
0.75B	537	358	501 (+143)
1.50B	759	253	354 (+101)

These calculations show that perimeter-based support should be limited to a certain value per ha, since otherwise the amount of support per ha would be unreasonably high for fields with long perimeter in relation to their area. With support of €0.5 m^{-1} yr^{-1} and a maximum support value of €300 ha^{-1} yr^{-1}, 22% of all arable fields at Svalöv (n = 3404) and 36% of all arable fields at Ronneby (n = 3964) would reach the maximum value (Figure 7). Introduction of perimeter-based support would benefit farmers at Ronneby, as the support amounts per ha would generally be higher than at Svalöv (Figure 7).

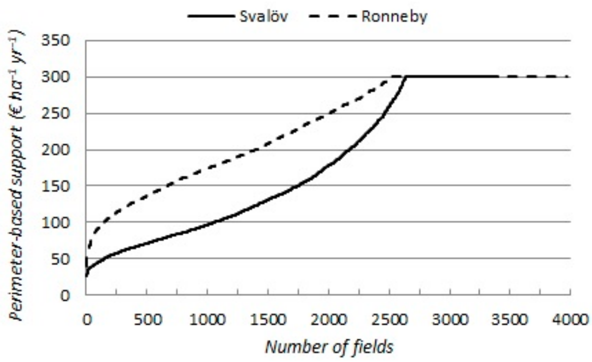

Figure 7. Total perimeter-based support (€ ha^{-1} yr^{-1}) for arable fields at Svalöv and Ronneby in ascending order up to a maximum of €300 ha^{-1} yr^{-1} (based on a perimeter support of €0.5 m^{-1} yr^{-1} and field perimeter data for 2016 (there were 3400 and 3960 arable fields (parcels) in the municipalities of Svalöv and Ronneby, respectively)).

The calculations also revealed that, with perimeter-based support of €0.5 m^{-1} yr^{-1} and a maximum value of €300 ha^{-1} yr^{-1}, support per ha at Svalöv was around five-fold higher for all fields in the area range 0–1 ha than for all fields larger than 10 ha (Figure 8). For Ronneby, the corresponding difference was around 3.7-fold. Thus, there is clear evidence that small fields would be favoured by perimeter-based support in these two areas.

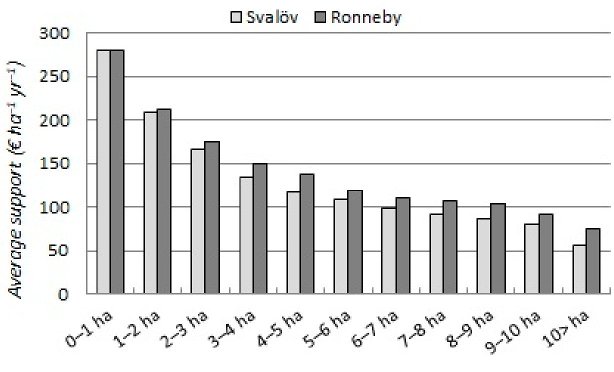

Figure 8. Average support for different field size classes (ha) at Svalöv and Ronneby with perimeter-based support of €0.5 m^{-1} yr^{-1} and a maximum value of €300 ha^{-1} yr^{-1} (based on field data for 2016).

At Svalöv, the total area of all fields larger than 10 ha was around 12,700 ha (62%), compared with around 420 ha (2%) for all fields smaller than 1.00 ha, so the total perimeter-based support in the municipality is only 42% of the current total direct payment (€200 ha^{-1} yr^{-1}). The corresponding value for perimeter-based support at Ronneby is 82% of the current total direct payment.

3.5. Net Gain with Soil Carbon Sequestration Support (Scenario 4)

With soil carbon sequestration support of €400 t^{-1} C, approximately corresponding to the current Swedish CO_2 tax, the net gain at Svalöv increased considerably for ley, RCG, SRCW, poplar, and hybrid aspen (Figure 9). This was expected, as these crops have the highest soil carbon sequestration rates.

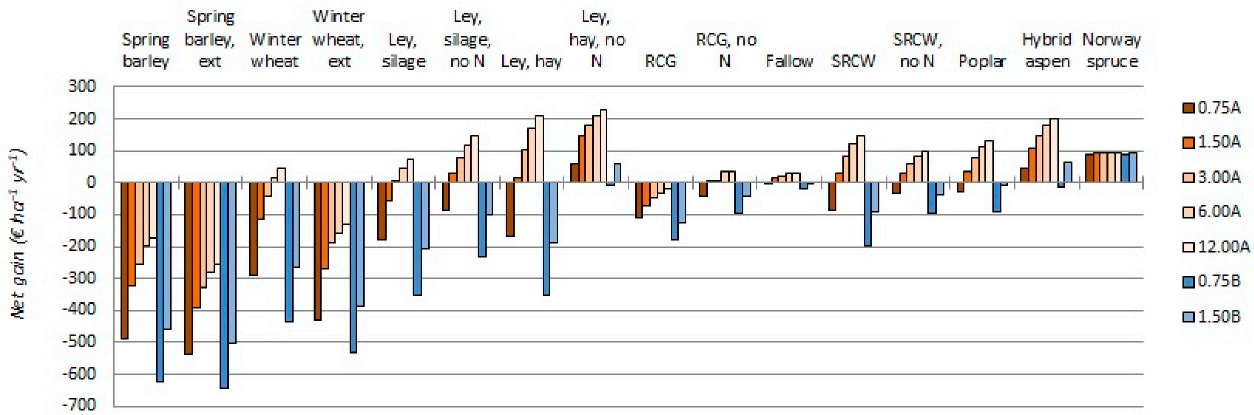

Figure 9. Net gain for the crops investigated at Svalöv with soil carbon sequestration support of €400 t^{-1} C (ext—extensive farming) (for figures, see Table S9).

The effect of increasing soil carbon sequestration support from €0 t^{-1} C to €1000 t^{-1} C for ley (silage, normal cultivation intensity), SRCW (normal cultivation intensity), poplar, fallow, and Norway spruce is shown in Figures 10 and 11. The results for winter wheat (normal cultivation intensity) are also shown as a reference, although this crop was assumed not to sequester soil carbon. The profitability of ley increased most rapidly as the support increased (as a result of the high carbon sequestration rate of this crop). However, the support level for field type 12.00A had to be around €300 t^{-1} C to give a positive net gain (Figure 10). Stands of SRCW and poplar were profitable at a support level of €100 t^{-1} C, which approximately corresponded to the value of the EU ETS allowances in May 2019. Norway spruce and winter wheat were profitable irrespective of support level. At support corresponding to the current CO_2 taxes in Sweden, all land use alternatives investigated were profitable (Figure 10, see also Figure 9). Field type had an important impact on the results (cf. Figures 10 and 11). Except in the case of Norway spruce and winter wheat, the support level had to be around €600–800 t^{-1} C before the crops reached positive net gains in type 0.75B fields.

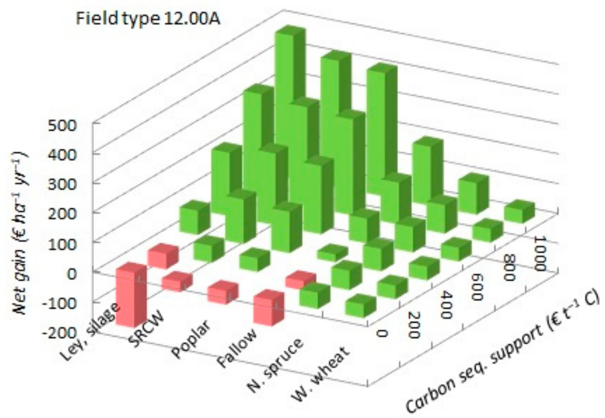

Figure 10. Net gain for ley (silage), short rotation coppice willow (SRCW), poplar, fallow, Norway spruce, and winter wheat with carbon sequestration support of €0−1000 t^{-1} C in fields of type 12.00A (best case). Red columns show negative net gain and green columns positive net gain (for figures, see Table S10).

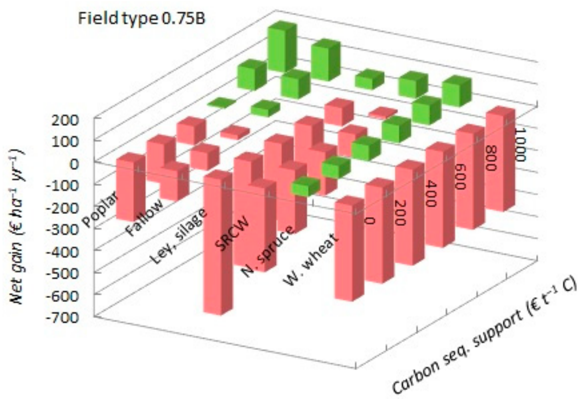

Figure 11. Net gain for poplar, fallow, ley (silage), short rotation coppice willow (SRCW), Norway spruce, and winter wheat with carbon sequestration support of €0−1000 t^{-1} C in fields of type 0.75B (worst case). Note that the order of crops was changed from that in Figure 10 to increase visibility. Red columns show negative net gain and green columns positive net gain (for figures, see Table S11).

4. Discussion

4.1. Impact of Field Size, Field Shape, Cultivation Intensity and Yield on Profitability

This analysis showed that field size and field shape had a major influence on profitability and choice of crops. The greatest difference in net gain between best and worst (field types 0.75B and 12.00A) was around €400–500 ha^{-1} yr^{-1} for spring barley, winter wheat, and ley (see Figure 3). One important reason for the difference in profitability between field types was the longer time spent per hectare for in-field operations in small, irregular-shaped (type B) fields (Table 4). It can be argued that smaller and older (i.e., investment costs written off) machines are usually used in small fields and that the farmer's working time is valued lower on such farms, making these fields more competitive than shown in this study. However, full cost coverage was used here for fair economic comparisons. Furthermore, small machines, i.e., machines with narrower effective working width, do not necessarily result in lower total costs per ha, because they have lower operational capacity and often fewer utilisation hours per year than more expensive larger machines [23]. Optimal machine size is dependent on the total acreage cultivated.

Another reason for the lower profitability in small fields was the higher proportion of headland (Table 1), and thus higher headland yield losses. Headland width could probably be narrowed by using smaller machines and tractors, which would result in lower total yield losses. Using smaller machines and tractors would probably also result in lower yield losses because of less overlapping and gaps in the in-field driving pattern. However, the approach in this study was to perform calculations for a typical middle-sized Swedish farm with some small, irregular-shaped fields, rather than for a small farm with mainly small fields.

For small and 'normal'-shaped fields (type A), with the current direct payment support (scenario 2), fallow and extensive cultivation of ley (for harvest of hay) were the most competitive alternatives (excluding the tree options) (see Figure 5). Analysis of data from the Swedish Board of Agriculture showed that ley was cultivated in 40% of all fields smaller than 0.75 ha at Svalöv (in 2016), while 43% of such fields were under fallow. The corresponding proportions for Ronneby were 77% and 10%, respectively. According to farmers' applications for direct payments in 2016, 36% of the fields smaller than 0.75 ha with ley at Svalöv (20% at Ronneby) could be classified as "extensive cultivation". Thus, it is clear that farmers already utilise most of their small fields in a 'profitable' way, given that they are still keeping these fields open (with no tree plantations).

Cultivation intensity and yield were important factors in profitability. For spring barley and winter wheat, intensive cultivation was more profitable than extensive cultivation in all field types (see Figure 3). For SRCW, intensive cultivation was more profitable in larger, 'normal'-shaped fields (3.00A, 6.00A and 12.00A). Extensive cultivation was more profitable for all grass crops (ley and RCG) in all field types. The net gain for fields at Ronneby, with lower yields than at Svalöv, was worse for all alternatives studied (Figure 4). The largest difference between the sites was estimated for winter wheat (€100–150 ha^{-1} yr^{-1}), whereas there were no or negligible differences for fallow and RCG.

4.2. Impact of Payments for Environmental Benefits on Profitability

With no public support, all land use alternatives at Svalöv had negative net gains except for Norway spruce and for winter wheat and hybrid aspen in large fields (Figure 3). At Ronneby, with lower yields (Table 3), the net gains were even more negative (Figure 4). From a purely economic perspective, if no subsidies are available, most fields at the sites should be planted with spruce (or used for purposes not considered here). Thus, the results clearly show that the profitability of farming is highly dependent on subsidies at present (see also e.g., [24]). At the same time, agriculture plays a key role in the transition to a more sustainable society, according to e.g., United Nations' global Sustainable Development Goals and Swedish Environmental Quality Objectives [77]. In current efforts to reform the CAP, it is of the utmost importance that farm subsidisation systems are designed in such a way that they benefit both provisioning ecosystem services (i.e., production of food, feed and bioenergy) and regulating and maintenance ecosystem services.

Field perimeter-based support is a novel and interesting option to increase biodiversity in the agricultural landscape. A study by Cederberg et al. [78] showed that this support can benefit ecosystem services in grass-based milk and beef production. In contrast to the current area-based CAP direct payment support, small, irregular-shaped fields would be favoured by perimeter-based support over large, 'regular'-shaped fields. Thus, such support would benefit small farms in forested areas and in areas with mixed agriculture and forestry, where the cultivation costs are often higher than in plains areas. Perimeter-based support would reflect and compensate for the higher costs in these areas, and could replace both the current direct payment and the so-called "compensatory payment" systems.

Perimeter-based support would be quite easy to administer, as basic data on field perimeter are already available in agricultural block databases. However, more research is needed to investigate the economic, legal, and administrative consequences at field, farm, regional, national, and EU farm policy levels. Questions to be answered concern support amount per linear metre, maximum amount per hectare, the legal definition of 'perimeter', differentiations between crops and regions, etc. As pointed out by Clough et al. [8], there is a large potential for reducing the economic–biodiversity trade-off associated with small fields by using new technologies such as small fossil-free autonomous vehicles.

The present analysis showed that, with soil carbon sequestration support, the net gain would increase considerably for crops that sequester SOC, provided that the level of support is sufficiently high (Figures 10 and 11). However, it was assumed in the calculations that the sequestration rates used applied for a starting position with previous cultivation of annual crops. As mentioned earlier, most small fields at the study sites are used for ley production or are under fallow, so they may already have quite a high SOC content, resulting in lower sequestration rates. This is one of many questions that should be investigated further before possible introduction of soil carbon sequestration support. Release of nitrous oxide and methane, which counteracts the climate change mitigation potential of SOC sequestration [14], should also be investigated in greater detail for different crop, fertilisation, and tillage options. Support related to climate impact would be more accurate when adjusted to crops, fertilisation rates, and tillage requirements, rather than being based solely on potential SOC sequestration rate.

Another difficulty is to determine an appropriate monetary value for SOC sequestration. Values based on CO_2 taxes reflect political negotiations, while the price of EU ETS allowances to a certain degree reflects policy rather than real abatement costs. The cost of capture and storage of CO_2 from combustion of biomass (Bio-CCS) in combined heat and power (CHP) plants and in the wood pulp industry in Sweden is estimated to be

€80–90 t^{-1} CO_2 [79], corresponding to around €300 t^{-1} C. At this level of support, SRCW, poplar, and hybrid aspen would be profitable in 'normal' fields (types 3.00A, 6.00A, 12.00A).

The combined area of SRCW, poplar, and hybrid aspen in Sweden in 2017 was around 11,000 ha [1]. Assuming a soil carbon sequestration rate of 0.45 t C ha^{-1} yr^{-1}, the total quantity sequestered in SRCW, poplar, and hybrid aspen plantations in Sweden in that year was around 5000 t C yr^{-1}, or 18,000 t CO_2 yr^{-1}. This corresponds to only 0.03% of total national emissions of greenhouse gases in 2018 (51.8 Mt CO_2-eq) [80]). Thus, even a 10-fold increase in the total area of these crops would have a minor influence on the total CO_2 balance in Sweden. The sequestration rates of these crops can be compared with the amount of carbon bound in harvestable biomass, which is 3.5–4 t ha^{-1} yr^{-1} for SRCW [52] and around 3 t C ha^{-1} yr^{-1} for poplar (calculated from [81]). More optimal utilisation of the products from a climate impact point of view, in combination with Bio-CCS, would further strengthen the ability of these crops to act as net carbon sinks.

5. Conclusions

- Small and irregular-shaped fields had higher crop production costs as a result of more costly machine operations and higher headland yield losses. A perimeter-based support would outweigh higher costs in such fields. With a perimeter-based support, the profitability of e.g., ley for fodder production, would increase, which in turn would benefit biodiversity and sequestration of SOC.
- In larger fields, different food, fodder, and energy crops were profitable with currently available area-based supports. With a sufficiently high area- and crop-based SOC sequestration support, stocks of SOC and soil fertility could increase for these fields.
- Our recommendation for future studies is to investigate a well-balanced combination of perimeter-based support and soil carbon sequestration support that benefits biodiversity, climate, and soil fertility under different field and cultivation conditions.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su132313354/s1, Figure S1: Reduction of speed through bends was assumed to be 0% if $\alpha < 30°$, 33% if $30° \leq \alpha < 60°$, and 67% if $60° \leq \alpha < 90°$; Figure S2: Half turns (upper: round corner, square corner, loop corner, reverse corner) and full turns (lower: loop turn, reverse turn); Table S1: Example of programming code (for simulation of rolling in field 0.75B); Table S2: Maximum operational speed in row/pass, install time (in-field preparation), finishing-off time, and stoppage time used in simulations (after calibration to data presented in [36] for a field assumed to have an area of 6.00 ha and shape A); Table S3: Costs of cultivation commodities, etc., for the crops studied; Table S4: Total costs for different machine operations, incl. costs of machines, tractors, fuel, and driver; Table S5: Net gain (€ ha^{-1} yr^{-1}) for the crops investigated at Svalöv without financial support; Table S6: Net gain (€ ha^{-1} yr^{-1}) for the crops investigated at Ronneby without financial support; Table S7: Net gain (€ ha^{-1} yr^{-1}) at Svalöv with direct payment (€200 ha^{-1} yr^{-1}) support for all crops except Norway spruce, and with establishment (€580 ha^{-1}) and fence-in (€1000 ha^{-1}) support for poplar and hybrid aspen; Table S8: Net gain (€ ha^{-1} yr^{-1}) at Svalöv with perimeter-based support (€0.5 m^{-1} yr^{-1}) for all crops except poplar, hybrid aspen, and Norway spruce, and with establishment (€580 ha^{-1}) and fence-in (€1000 ha^{-1}) support for poplar and hybrid aspen; Table S9: Net gain (€ ha^{-1} yr^{-1}) for the crops investigated at Svalöv with soil carbon sequestration support of €400 t^{-1} C; Table S10: Net gain (€ ha^{-1} yr^{-1}) for ley (silage), short rotation coppice willow (SRCW), poplar, fallow, Norway spruce, and winter wheat with carbon sequestration support of €0–1000 t^{-1} C in fields of type 12.00A (best case); Table S11: Net gain (€ ha^{-1} yr^{-1}) for poplar, fallow, ley (silage), short rotation coppice willow (SRCW), Norway spruce, and winter wheat with carbon sequestration support of €0–1000 t^{-1} C in fields of type 0.75B (worst case).

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