Citation for the published paper:
Nilsson, Daniel., Rosenqvist, Håkan., Bernesson, Sven. (2015) Profitability of the production of energy grasses on marginal agricultural land in Sweden. *Biomass & Bioenergy*. Volume: 83, pp 159-168.
http://dx.doi.org/10.1016/j.biombioe.2015.09.007.

Profitability of the production of energy grasses on marginal agricultural land in Sweden

Daniel Nilsson[a*], Håkan Rosenqvist[b], Sven Bernesson[a]

[a]Department of Energy and Technology, P.O. Box 7032, Swedish University of Agricultural Sciences, SE-75007 Uppsala, Sweden. E-mail addresses: daniel.nilsson@slu.se (D. Nilsson), sven.bernesson@slu.se (S. Bernesson)

[b]Prästvägen 5, SE-26873 Billeberga, Sweden. E-mail address: hak.rosenqvist@telia.com

*Corresponding author. Tel.: +46 18 672669
E-mail address: daniel.nilsson@slu.se (D. Nilsson)

ABSTRACT

The objective of this study was to analyse the economic profitability of producing energy-grass fuels on marginal agricultural land in Sweden. Small and irregular-shaped fields, fields with less fertile soils, headlands and border strips were included, all located in four different regions representing different cultivation conditions. The grasses studied were reed canary grass (RCG) and ley, which were to be used as a solid fuel and biogas substrate, respectively. The economic profitability of these grasses was compared with the profitability of fallow land and the cultivation of winter wheat and spring barley. The results showed that all the alternatives studied, except winter wheat in southern Sweden, had a negative economic net gain (no subsidies included). Generally, the economic losses were greatest for small and irregular-shaped fields. Fallow had a higher economic competitiveness than RCG and ley for all marginal field categories and locations. RCG used as a solid fuel in boilers generally had a higher competitiveness than ley for biogas. However, when ley was used fresh without storage, its competitiveness improved considerably. Taking the direct payment subsidies and the economic value of reduced nutrient leakage into account, the economic net gain improved considerably. Nevertheless, fallow land still had a somewhat higher net gain than RCG for all field categories. Further cost reductions and higher revenues, including possible agro-environmental economic compensation, are required if RCG and ley are to be able to compete with fallow land.

Keywords: marginal land, energy grass, reed canary grass, ley, profitability, costs

1. INTRODUCTION

1.1. Background

In Sweden, thousands of hectares of agricultural land are not being actively used for agricultural production. Of the total agricultural land area of 2.60 million hectares in 2013, 0.16 million hectares were fallow land [1]. Hundreds of thousands of hectares of ley are also underutilised or cultivated at low intensity. In 2008, the excess cultivation area of this crop was estimated to be 0.2-0.3 million hectares [2]. Bearing in mind the ongoing rationalisation and closure of small farms, the current total acreage of such ‘marginal’ land in Sweden may be as high as half a million hectares.

The demand for renewable and carbon dioxide-neutral fuels for the production of heat, electricity and vehicle fuels is expected to increase. Therefore, instead of cultivating unprofitable ordinary crops or fallow or fields being abandoned and overgrown with brushwood, an alternative for ‘marginal’ land is the cultivation of dedicated energy crops [3]. Examples of suggested energy crops are poplar [4], short-rotation coppice willow [5] and herbaceous crops [6,7], *e.g.* perennial energy grasses. Some energy grasses, such as reed canary grass (RCG) (*Phalaris arundinacea* L.), can be used as a solid fuel for combustion in boilers [8,9], while ley grasses are suitable as substrates for the production of biogas [10-12]. Swedish studies have shown that the cultivation of ley on marginal land for the production of biogas may reduce greenhouse gas emissions by up to five tonnes of CO_2-equivalents per ha if the gas replaces petrol [13]. Cultivated on conventional agricultural land, both RCG and ley are beneficial from an energy and global warming perspective when replacing fossil fuels, although the net energy return and reductions in CO_2-emissions may differ considerably between different studies [8,14-17].

Cultivation of energy grasses on ‘marginal’ land also has many other advantages. For example, a limited number of field work operations is required since the crop is perennial. In comparison to annual crops, the soil structure is improved, the release of NO_x is reduced as annual ploughing is not required, and soil carbon is sequestered [8,10]. In contrast to growing poplar and short rotation coppice, the open landscape is preserved. A survey among Swedish farmers as regards their willingness to cultivate energy crops has shown that crops that can readily be terminated are preferred [18]. Furthermore, with regard to crop growth height, the crops should only have a small impact on the prevailing landscape image. The farmers also prefer to use conventional machines for cultivation and harvest instead of leasing specialist machines, which is the case for short rotation coppice [18]. In addition, they prefer crops for which work in the fields does not coincide with other hectic periods of farm work. RCG can be harvested in the early spring or in late summer/autumn [19,20], whereas ley can be harvested after the harvest of fodder ley when the yield in terms of quantity, and not in terms of fodder quality, is highest [21].

The term ‘marginal agricultural land’ is often used without being clearly defined [22]. Its meaning is vague in fact and it may be used in a “subjective sense for less-than-ideal lands without sufficient specificity” [23]. Generally, however, it is often used as an economic term for fields where it is difficult for economic revenues to balance the costs. Biophysical factors, such as field size, field shape, distantness, stoniness and wetness, as well as farm type have a significant impact on both costs and revenues. Therefore, the marginal land concept is relative with respect to location. As economic (and political) conditions may change considerably over time, marginality is also relative in time. The economic perspective of the term was used in this study, which also means that the land has the potential to contribute to future food and feed production. In this context, the marginal land concept did not include sub-marginal land, which is unsuitable for food production or has no possibility of being profitable in an agro-economic sense [23].

Existing small, outlying and irregular-shaped agricultural fields, as well as fields with less fertile soils, can be considered as marginal land from an agro-economic point of view [3,23]. For the former category of fields, cultivation costs are generally higher than in ‘normal’ cases as a result of lower in-field machine performance and higher transfer and transport costs [24-26]. For the latter field category, the revenues from sold products are lower, resulting in a break-even or even negative economic profitability. As the meaning of ‘small’, ‘irregular-shaped' and 'less fertile' is dependent on local cultivation conditions, it is important to consider geographical differences when calculating the profitability of energy grass production on marginal land.

Headlands can also be considered as a marginal land category as the crop yield is normally lower in comparison with other parts of the field due to soil compaction, run-over damages and non-optimal doses of fertilisers and pesticides [27-29]. Furthermore, border strips usually have lower crop yields because of no (or little or uneven) fertilisation and other edge effects, for example. In many cases, the machinery performance is also reduced at field borders [24]. For both headlands and border strips, the economic profitability is often negative, although the profitability for the field as a whole may be positive.

When annual crops are cultivated in the fields, cultivation of perennial energy grasses on headlands and border strips has positive environmental effects as it can significantly reduce the leakage of nitrogen, phosphorus and pesticides [30,31]. Fallon *et al*. [32] also point out that such field boundary management has other positive effects since it creates wildlife habitats, prevents and reduces soil erosion, creates new public access routes and sequesters considerable quantities of soil organic carbon (SOC). From a biodiversity point of view, cropping of perennial grasses on headlands and border strips, as well as in small and irregular-shaped fields, is beneficial to butterflies [33], ground flora, small mammals and birds [34].

1.2. Objectives

The objective of this study was to analyse economic profitability when energy-grass fuels were produced on marginal agricultural land. Small and irregular-shaped fields, fields with less fertile soils, headlands and border strips were included, all located in the municipalities of Svalöv, Ronneby, Vingåker and Skellefteå, representing different cultivation conditions in Sweden. A field category with ‘normal’ conditions was also included in the evaluations.

The grasses studied were RCG and ley, which were to be used as a solid fuel and biogas substrate, respectively. The economic profitability of these grasses was compared with the profitability of fallow land and of the cultivation of winter wheat and spring barley. Different calculation options were compared, *e.g.* taking into account different machinery sizes and the economic value of reduced nutrient leakage.

2. METHODOLOGY

2.1. Cost calculation options

The calculations were carried out for the crops, field types, locations and machinery sizes shown in Table 1. The cost calculations included costs of seed, fertilisers, pesticides, machine operations, transport to storage, storage, transport to user, labour, depreciation and interest charge (4%). An example of a cost calculation path, according to Table 1, is the cost of fuel bales (at the boiler plant gate) of RCG cultivated (*e.g.* with no N-fertilisation) in a small and irregular-shaped field (with its specific field shape) at Vingåker (with its specific field area, crop yield and transport distances) using a machinery system based on ‘large’ machines. These calculation options are described in greater detail in sections 2.2-2.5.

2.2. Crops and uses

RCG and ley are perennial grasses and it was assumed that they were re-sown after each crop rotation (ten and three years, respectively). The ley crop was assumed to consist of a mix of perennial grasses and clover. RCG and ley cultivated on headlands and border strips were not fertilised with N for environmental reasons, whereas there were two options in small and irregular-shaped fields and in fields with less fertile soils: with or without N-fertilisation. The RCG was used as a solid fuel in a boiler and the ley was used to produce biogas. Ley was harvested once or twice a year.

The yield of agricultural crops is dependent on many factors, *e.g*. the type of soil, geographical location (and thus weather, day length, seasonal length *etc.*), cultivation intensity, organic or conventional cultivation *etc*. A literature study [35] was undertaken to estimate crop yields for the field categories at each location.

The literature study showed that it was reasonable to assume that the crop yield in small and irregular-shaped fields was 10% lower than the average yields (*i.e.* for ‘normal’ fields) given in Table 2, for all crops at all locations. For less fertile soils, the yield was assumed to be 25% lower for ley and RCG, and 30% lower for cereals for all locations. For headlands, the corresponding values were 50% (no N-fertilisation) and 30%, respectively. With only one ley harvest per year, the yield was assumed to be 10 percentage points higher than the yield for the “1st harvest” in Table 2. For border strips, the yields were assumed to be 15% lower than the values in Table 2 for all crops and locations [35].

2.3. Type of fields

In the calculations, the results were related to a ‘normal’ field, which was assumed to have crop yields corresponding to average values for all locations (Table 2). The area of a ‘normal’ field was assumed to be 5.0 ha and rectangular in shape with a length:width-ratio of 2:1, irrespective of location. One reason for the area being the same was that the same machinery was assumed to be applicable for all locations.

All fields with less fertile soils were assumed to be rectangular with a length:width ratio of 2:1. The headlands and border strips were rectangular with a width of 16 m and 8 m, respectively.

There is no unambiguous definition of what is meant by an ‘irregular-shaped’ field. Normally, it can be used to describe a field with several corners, narrow tips and ‘islands’ with uncultivable land. One way of describing the irregularity is to divide the total area A (m^2) by the square of the total perimeter P (m) of the field. By relating this relationship to a circular area, a shape index $SI = P/(2\sqrt{(\pi A)})$ is obtained [36,37]. Thus, SI has its minimum value (=1) for a circular field. For a quadratic field, $SI = 1.13$, for a rectangular field with a length:width ratio of 4:1, $SI = 1.41$, and for a narrow rectangular field with a length:width ratio of 16:1, $SI = 2.40$. Note that for a given field shape, SI is independent of the size of the field. In this study, the field shape in Fig. 1 ($SI = 1.75$) was assumed to be representative for ‘small and irregular-shaped fields’ in all locations [38].

2.4. Locations studied

The municipality of Svalöv is located in the plain districts in Skåne, in the south of Sweden. Ronneby is also located in southern Sweden, but the main part of the municipality belongs to the agricultural production area “Central districts in Götaland”. Vingåker is located in the agricultural production area “Plain districts in Svealand”, whereas the municipality of Skellefteå is located in the north of Sweden.

There is a wide variety of crops grown at Svalöv, such as winter wheat, spring barley, ley, rapeseed, sugar beet and processing pea. Ley crops and extensive grass culture dominate at Ronneby, whereas ley, fallow, spring barley and winter wheat are common crops at Vingåker. Ley and extensive grass culture dominate at Skellefteå, but spring barley is also common.

There is quite a significant difference between the average parcel areas in the municipalities studied (Table 3). There is also a large number of small parcels in the municipalities, but their share of the total agricultural area is relatively small, especially at Svalöv. Investigations [38] have shown that Svalöv has the lowest SI values of the municipalities studied (Table 3) (a detailed description of the variations in SI for the different locations is described by Nilsson *et al*. [38]).

The areas for small and irregular-shaped fields were calculated as the average area of arable blocks that satisfied $A < 2.00$ ha and $SI > 1.75$ (all block and parcel data were obtained from the Swedish Board of Agriculture) (Table 4). The area of fields with less fertile soils was calculated as the average area for all arable blocks greater than 0.2 ha and smaller than the largest 10% of the blocks. The areas used for headlands were calculated as the average headland area in all arable blocks greater than 10.00 ha, assuming rectangular fields with a length:width ratio of 2:1 and a headland width of 16.0 m. Finally, the areas used for border strips were calculated as the average of the farmers’ subsidy application areas in 2012 (in the so-called SAM 2012 application system) [38].

All arable blocks in Sweden are identified by an 11-digit block number, with the first four digits describing the latitudinal position of the block centre, and the next three the longitudinal position. These positions refer to the national geographical grid system RT90. By counting the number of blocks with marginal land parcels within each grid (1 x 1 km), a better understanding of the field concentration can be obtained.

When all small and irregular-shaped blocks (*A* < 2.00 ha, *SI* > 1.75), all blocks with less fertile soils (parcels with *A* < 2.00 ha and fallow according to SAM 2012), headlands (in all blocks with *A* > 10.00 ha), border strips (in blocks according to the SAM 2012 applications) were counted, the results were as illustrated in Fig. 2.

The location (*i.e.* grid) with the highest concentration of marginal land was determined by using [38]:

$$\max\left|\sum_{k=1}^{m}(A_{i,j}/f_{i,j})_k\right|$$

where the *k*:th surrounding grid with coordinates *i,j* contains the marginal land area $A_{i,j}$, and where $f_{i,j}$ is a distance factor. The analyses showed, for example, that the best location for an energy conversion plant in the municipality of Svalöv, with a maximum transport distance of 6.0 km, was in the grid 6201-332 (Fig. 2) (note that neighbouring municipalities were not considered in the calculations). A maximum distance of 6.0 km at Svalöv corresponds to a quantity of about 1,000 tonnes DM of RCG delivered to a heating plant, or an area of about 180 ha. The resulting average distances, used in the cost calculations, for the transfer of machines and transportation of goods are presented in Table 5.

2.5. Machinery

The shape of agricultural fields, as well as the areas, may have an important impact on machinery performance [24,25,40-42]. In small and irregular-shaped fields, for example, the share of non-productive time for machine preparation, turnings and double passes of soil preparation work may be considerable. Furthermore, slower operating speeds due to curves, field obstacles, frequent accelerations and retardations also reduce the work efficiency.

To analyse the differences in machine performance between different field sizes and shapes, a dynamic discrete-event simulation model was developed. The model was built in the Arena software environment [43]. The model considered stochastic system properties, *e.g*. time between and duration of breakdowns/stoppages, as well as deterministic system properties, *e.g*. time for turnings, machine preparations and adjustments.

In the model, the driving patterns for different machinery widths were laid out in fields with different sizes and shapes. The machines then followed these ‘tracks’ and carried out their work, according to data specifications about optimal (or maximum) operation speed (depending on the type of work and machine width), turning times, stochastic stoppages, acceleration/retardation, preparation/adjustment times *etc*. (a detailed description of the model and its input data is presented by Nilsson *et al*. [38]). The results for rectangular fields (length:width ratio 2:1) with areas of 1.0 ha and 5.0 ha are shown in Fig. 3. As can be seen, field size inevitably had an important influence on total in-field operation time per ha. This was especially valid the smaller the fields were.

Rectangular fields with different shapes (1:1, 2:1 and 4:1), areas (from 0.5 ha to 15.0 ha), machinery work widths (from 1.0 m to 24.0 m) and optimal work speeds (from 4.0 km/h to 16.0 km/h) were simulated. Work in rectangular fields with a width of 8.0 m (border strips) and 16.0 m (headlands) were also simulated (note that ‘rectangular fields’ means fields with parallel but not necessarily straight sides). Furthermore, different irregular-shaped polygonal fields were compared in the simulations, including the field shape shown in Fig. 1. For example, the time for mowing grass in a polygonal field with an impediment (Fig. 1) was 66 minutes, whereas it took about 57 minutes in a rectangular 2:1 field (the area of both fields was 1.0 ha, the working width was 2.25 m and the maximum driving speed was 10 km/h). For ‘normal’ fields (5.0 ha, shape 2:1), machinery performance data were taken from Fig. 3.

The simulation results, *i.e*. the performance data expressed as work hours per hectare, were multiplied by the hourly costs [44] in order to calculate total machinery costs. An increased annual use of machines, due to their use in harvesting and handling ley for both fodder and energy purposes, was considered in the calculations. Timeliness costs, *i.e.* increased costs due to harvest work being undertaken at non-optimal times, were not considered, as it was assumed that these costs can be neglected for energy grass.

The RCG was harvested in the spring and handled as round bales in combination with self-loading bale transporters. Ley was harvested and handled as ensiled round bales. Another alternative was harvest by a self-chopping wagon (SCW) and direct use or storage in bunker silos. As the fields investigated were relatively small, a cost comparison was carried out for both ‘small’ and ‘large’ machines. For mowing, for example, the working width was 2.4 m and 3.0 m for a ‘small’ and a ‘large’ machine, respectively [35].

2.6. Revenues

Regarding the revenues, the price level for 2012 was used, which means that the price for RCG was € 94.1 per tonne DM, for ley € 119.4 per tonne DM, for winter wheat € 197.3 per tonne (moisture content 14%), for barley € 171.3 per tonne (moisture content 14%), (an exchange rate of € 1.00 = 9.63 SEK (2014-08-21) was used).

The direct payment to farmers in Sweden will change gradually up to the year 2020, according to the new EU support schemes within the framework of the Common Agricultural Policy (CAP) [45,46]. The current single payment scheme results in different payments depending on the values of the payment entitlements, which in turn are dependent on *e.g.* land uses and regions. In 2020, however, the payments will converge into a single value. This value will include payments from both the single payment scheme (€ 128.00 per hectare) and a new 'greening' support scheme (€ 70.40 per hectare), which will take both the CAP concepts of 'crop diversification' and 'ecological focus areas' (EFA) into account [46]. In this study, an optional subsidy income was included, amounting to € 200 per hectare.

Cultivation of energy grasses instead of cereals implies reduced leakage of phosphorous and nitrogen to lakes and the sea. It may be difficult to quantify the leakage reduction as it depends on local circumstances such as soil type, cultivation intensity, possible use of catch crops, retention and distance to rivers, lakes or the sea *etc*. In the project, a literature study [35] was undertaken to estimate reasonable leakage reduction levels when cereals were replaced by energy grasses in different types of marginal fields. These approximations were based on Swedish investigations on nutrient leakage from agriculture (see *e.g.* [47-50]). Furthermore, the economic consequences of the reductions can be calculated in different ways, *e.g.* as damage costs or abatement costs [51]. In this study, the economic benefits were mainly based on the costs of purification in wastewater treatment plants in Sweden: € 15.6 per kg N and € 105 per kg P, estimated from Swedish literature sources [35].

2.7. Profitability analyses

First, the costs and economic net gain were calculated for a system with basic options, *i.e.* with 'large' machines, ley harvested twice a year as ensiled round bales, fertilisation of N in small and irregular-shaped fields and in fields with less fertile soils where RCG and ley were cultivated, and with the income from sales as the only revenue. After that, the results for a sensitivity analysis regarding *e.g.* halved machinery and labour costs are presented, together with the results for alternative cost calculation options, including *e.g.* 'small' machines and harvesting of ley once a year. Thirdly, the profitability is presented when direct payment as a CAP subsidy and compensation for reduced nutrient leakage were taken into account.

3. RESULTS AND DISCUSSION

3.1. Basic calculation options

For the basic options, the economic net gain was negative for all the alternatives studied, except for winter wheat at Svalöv and Ronneby (Fig. 4). Fallow had a much higher competitiveness in comparison to energy grasses for all locations. RCG used as a solid fuel in boilers generally had a better competitiveness than ley did for biogas. One important reason was the higher handling and storage costs of ley. RCG also had a higher profitability than spring barley for all field categories at Vingåker and Skellefteå, for small and irregular-shaped fields, fields with less fertile soils and headlands at Ronneby, and for fields with less fertile soils at Svalöv. For 'normal' fields, the results were in accordance with calculation results presented by the Swedish Board of Agriculture [52].

Small and irregular-shaped fields, as defined in this study, generally resulted in the highest economic losses for all crops and locations. The only exceptions were winter wheat at Svalöv and Ronneby, where fields with less fertile soils had the lowest profitability.

Size and shape also had an influence on machinery performance (section 2.5.), which is usually not considered in conventional cost calculations. It should be noted, however, that a low *SI* value, *i.e.* a more circular area, does not necessarily facilitate machine operations. Machine performance may be better in an elongated rectangular field (with a high *SI* value) than in a circular field [24,26]. For example, if the width of a border strip is consistently exactly twice the machine working width, the machine can drive back and forth turning only once. More extensive analyses have shown that the smaller the block area, the lower the *SI* value [38]. This indicates that cultivation in small and irregular-shaped agricultural blocks has already been abandoned in many cases, and that a prerequisite for farmers to continue using small fields is that the arable block at least has a more 'regular' shape.

The net gain generally was highest at Svalöv and lowest at Skellefteå (Fig. 4). For a farmer at Svalöv, it was not profitable to cultivate RCG or ley on headlands or border strips when the field was cultivated with winter wheat or barley. At Vingåker and Skellefteå, however, the total profitability improved when RCG or ley was cultivated on headlands or border strips in fields with spring barley. This implies that yield level is an important factor in the choice of crops on headlands and border strips. For such fields as a whole, rotational grass/clover for biogas production, integrated with grain cultivation, can be an interesting alternative [53].

Marginal fields may comprise fields with crop yields from very low levels up to average levels. In this context, further insight may be provided by dividing the costs into area-related costs (€ ha^{-1}, *e.g.* cost for ploughing) and yield-related costs (€ $tonne^{-1}$ harvested material, *e.g.* costs for transport of the harvested material), where the total costs are the sum of the area-related costs and the yield-related costs multiplied by the yield. If the product price is about the same as or lower than the yield-related costs, increased yields will not result in greater profitability. Analyses of costs at Svalöv and Ronneby showed that the area-related costs of RCG were about one-third of the area-related costs of winter wheat and barley, whereas the yield-related costs of RCG were somewhat higher than the yield-related costs of these cereals (Fig. 5). Furthermore, for RCG the price was somewhat higher than the yield-related costs, whereas the price was about 3.5 times higher than the yield-related costs of cereals. Ley had an intermediate position. Although the total costs of RCG were much higher than the price (Fig. 6), this cost analysis indicated that RCG, followed by ley, may generally have a higher competitiveness than cereals in fields with low soil fertility.

3.2. Sensitivity analysis and alternative cost calculation options

A sensitivity analysis of product prices (chapter 2.6) showed that the price of RCG should increase from its current level by between 25% (‘normal’ fields) and 42% (small and irregular-shaped fields) in order to have the same profitability as fallow land (Svalöv) [35]. For ley, the respective values were between 31% (‘normal’ fields) and 76% (headlands).

In some cases it may be argued that only variable costs should be considered, and that full labour costs are not applicable. This may be true when the alternative value of work time and machinery is low. Therefore, a sensitivity analysis with halved machinery and labour costs was performed [35]. For Svalöv, the results showed that winter wheat and barley were the most profitable crops for all field categories. In addition, RCG was more profitable than fallow land and ley for all field categories. At Skellefteå, RCG had the highest profitability for all field categories, followed by fallow land, barley and ley for biogas. As expected [24], lower machinery and labour costs primarily favoured labour/machinery-intensive crops (*e.g.* spring barley) and field categories (*e.g.* small and irregular-shaped fields).

Fertilisation of N, in the cultivation of RCG and ley in small and irregular-shaped fields and in fields with less fertile soils, resulted in a similar or somewhat lower profitability at all locations in comparison to the omission of N fertilisation. The main reason was that the product price and yield-related costs were similar. Fertilisation of N in perennial grasses on marginal land may increase the yield [54] and the SOC sequestration rate [55], but the climate change mitigation potential may be outweighed by increased land-based emissions of N_2O and by greenhouse gas emissions from the manufacture of mineral N fertilisers [56].

The calculations showed that harvesting ley with a SCW and direct use, *i.e.* without intermediate storage, generally resulted in a higher profitability than round ensiled bales and harvest with SCWs and storage in bunker silos (Fig. 7). When the material was stored, the costs were similar for systems with round ensiled bales and SCWs, and bunker silo storage.

The net gain may be increased when ley is harvested later and only once a year, but with a higher yield (see section 2.5.). Calculations for Svalöv pointed out that the net gain was indeed improved for all field categories and handling systems (round bales, SCW stored, SCW fresh), except for 'normal' fields when the material was harvested with SCWs and used fresh. Thus, for this latter case, two harvests and immediate use of the material (as also pointed out by Gissén *et al*. [12]) were more profitable than one harvest. The highest gain improvement with one harvest occurred for small and irregular-shaped fields.

The comparison between 'smaller' and 'larger' machines showed that the latter were more profitable for all field categories, crops and locations. The largest difference occurred for crops with more frequent field operations, *i.e*. for winter wheat and barley, where the net gain was € 62-83 per ha higher for 'larger' machines. At Svalöv, for example, the increase in profitability for RCG varied from € 25 per ha ('normal' fields) to € 31 per ha (border strips), whereas it varied from € 35 per ha ('normal' fields) to € 46 per ha (border strips) for ley. Larger machines resulted in lower costs per hectare when they could benefit from their broader working widths, but when the time share of turnings, double passes *etc*. increased, their economic competitiveness was reduced. This is in accordance with the results presented by Søgaard and Sørensen [57] and de Toro [58] for example. A conclusion was drawn, that as long as the annual utilisation times were high (in most cases >100 hours) for larger machines, they were also more competitive in smaller fields. In contrast, for short annual utilisation times, smaller machines had a higher competitiveness than larger machines in smaller fields.

3.3. Area-related and environmental-related subsidies

As the direct payment is area-related and will converge into one value in 2020 (€ 200 per ha) for all crops and locations investigated, the net gain values (Fig. 4) will increase by € 200. In most cases, RCG and ley are still not profitable. If there were a special subsidy for energy crops, at least RCG would be profitable for most marginal land categories. However, such a subsidy could have an impact on production intensity and on the fields in which the crop is cultivated [59], leading to a risk of indirect land use change (iLUC) [60,61].

As Ronneby is located by the Baltic Sea and Svalöv is near Öresund, the economic value of reduced nutrient leakage (Table 6) was also taken into account for these locations. For RCG and fallow, the net gain was now positive for all field categories (Fig. 8, *cf*. Fig. 4). The net gain was also improved considerably for ley. However, fallow land nevertheless had a somewhat higher net gain than RCG and ley for all field categories.

The value of reduced nutrient leakage (Table 6) was an important factor in the net gain (Fig. 8). Debnath *et al*. [51] present a brief review of abatement costs for N and P runoff. In their study, they use a cost of € 8.5 per kg for N and € 34 per kg for P when estimating the environmental benefits of switchgrass cultivation in USA. However, their estimated loss reductions for N and P, when wheat production is converted to switchgrass production, are about two times and three to four times higher, respectively, than the values used in this study (Table 6) [51].

Cultivation of perennial energy grasses on marginal land may have considerable potential to sequester SOC when they replace annual crops [55,62-64]. However, as pointed out by Powlsen *et al*. [56], it is important to note that the quantity of carbon stored in the soil is finite and that the increase in SOC will cease when a new equilibrium is established. It often takes more than one hundred years to reach equilibrium, but the sequestration rate is much higher in the early years than in later years [56,65]. Furthermore, the process is reversible, as some of the SOC sequestered will be released when the field is ploughed again. In some situations, energy grasses on marginal land may also increase the release of nitrous oxide (N_2O) and methane [56], which counteracts the climate change mitigation potential of SOC sequestration.

The annual sequestration rate of SOC, due to perennial grass cultivation, is dependent on many factors, *e.g*. initial SOC content (*i.e*. earlier land use and management), soil type, fertilisation of N, temperature, precipitation *etc*. Studies have shown that the SOC sequestration by grasses may amount to about 1 tonne C ha^{-1} $year^{-1}$ in the early years [55,64]. For switchgrass produced in the USA, Debnath *et al*. [51] report an average SOC sequestration rate of 0.3 tonnes C ha^{-1} $year^{-1}$. The economic value of such an environmental benefit can be related to the price of carbon emission allowances in the European Union Emissions Trading System (EU ETS). This price has dropped from about € 30 per tonne CO_2 in 2008 to about € 6 per tonne in 2014 [66] (a price of € 6 per tonne CO_2 corresponds to about € 22 per tonne C). Thus, such an environmental-related compensation from society to farmers would be much lower than *e.g*. the direct payments according to CAP, including if emission reductions when replacing fossil fuels are to be considered. However, it can be argued that the newly introduced greening support scheme is aimed at encouraging such climate change mitigation steps, as well as the reduction of nutrient leakage [46].

Although it may be difficult to estimate ‘fair’ economic compensation for reduced nutrient leakage and a reduced climate change impact, there seems to be a common opinion that a certain proportion of the environmental and societal benefits should be passed on to the farmers [67]. From a societal perspective, it is advantageous in most cases if energy grass produced on marginal land, in contrast to fallow, can be used to replace fossil fuels. From a commercial point of view, however, Bryngelsson and Lindgren [61] claim that large-scale production of bioenergy on marginal land is unlikely. If the economic incentives were strong enough, farmers would cultivate bioenergy on more productive land and out-compete the more costly production on marginal land. However, as pointed out by Glithero *et al*. [68], farm-level decisions on the use of marginal land are complex and dynamic, and depend on relative crop yields, machinery costs and farmers' attitudes for example.

4. CONCLUSIONS

As marginal land often consists of small and irregular-shaped fields, it is important to take field size and shape into account in cost calculations. Therefore, a novel simulation model was developed to consider the time demand of different machine operations in fields with different sizes and shapes. Marginal fields are also often remote, and a simple method based on block identification numbers was developed to calculate transport distances. Furthermore, small fields and fields with less fertile soils are in most cases considered as marginal land. However, two possible field categories were added to this concept: headlands and border strips, which could contribute considerable arable land for energy grass production. At the same time, these field categories can contribute to the sequestration of SOC, reduced leakage of nutrients and pesticides, and the creation of wildlife habitats.

The results showed that all studied crops, except for winter wheat for all field categories at Svalöv and winter wheat in 'normal' fields and border strips at Ronneby, have a negative economic gain. Generally, the economic losses are highest for small and irregular-shaped fields. Fallow has a higher economic competitiveness than RCG and ley for all marginal field categories and locations. RCG used as a solid fuel in boilers generally has a higher competitiveness than ley for biogas. However, when the ley is used fresh without storage, its competitiveness improves considerably. Taking the direct payment subsidy and the economic value of reduced nutrient leakage into account, the economic net gain improves considerably. Nevertheless, fallow land has a somewhat higher net gain than RCG for all field categories.

For cultivation of energy grasses on agricultural marginal lands under Swedish conditions, further cost reductions and higher revenues, including possible agro-environmental economic compensations, are required if RCG in the first instance is to be able to compete with fallow land. At the same time, sustainable demands or local markets have to be established.

ACKNOWLEDGEMENTS

The authors would like to thank the Swedish Farmers' Foundation for Agricultural Research for its financial support.

REFERENCES

[1] Jordbruksverket (Swedish Board of Agriculture). Åkerarealens användning efter län/riket och gröda, hektar. År 1981-2013. Available from: http://statistik.sjv.se/PXWeb/Menu.aspx?px_db=Jordbruksverkets+statistikdatabas&px_language=sv&rxid=5adf4929-f548-4f27-9bc9-78e127837625 [cited 1.9.2014].

[2] Jonsson B. Kartläggning av mark som tagits ur produktion. Rapport 2008:7. Jönköping: Jordbruksverket; 2008.

[3] Liu TT, McConkey BG, Ma ZY, Liu ZG, Cheng, LL. Strengths, weaknesses, opportunities and threats analysis of bioenergy production on marginal land. Energy Procedia 2011;5:2378-86.

[4] Schweier J, Becker G. Economics of poplar short rotation coppice plantations on marginal land in Germany. Biomass Bioenerg 2013;59:494-502.

[5] McElroy GH, Dawson WM. Biomass from Short-rotation Coppice Willow on Marginal Land. Biomass 1986;10(3):225-40.

[6] Vaughan DH, Cundiff JS, Parrish DJ. Herbaceous Crops on Marginal Sites – Erosion and Economics. Biomass 1989;20(3-4):199-208.

[7] Wünsch K, Gruber S, Claupein W. Profitability analysis of cropping systems for biogas production on marginal sites in southwestern Germany. Renewable Energy 2012;45:213-20.

[8] Wrobel C, Coulman BE, Smith DL. The potential use of reed canary grass (*Phalaris arundinacea* L.) as a biofuel crop. Acta Agr Scand B-S P 2009;59(1):1-18.

[9] Prochnow A, Heiermann M, Plöchl M, Amon T, Hobbs PJ. Bioenergy from permanent grassland - a review: 2. Combustion. Bioresource Technol 2009;100:4945-54.

[10] Murphy JD, Power NM. An argument for using biomethane generated from grass as a biofuel in Ireland. Biomass Bioenerg 2009;33(3):504-12.

[11] Prochnow A, Heiermann M, Plöchl M, Linke B, Idler C, Amon T, Hobbs PJ. Bioenergy from permanent grassland - a review: 1. Biogas. Bioresource Technol 2009;100:4931-44.

[12] Gissén C, Prade T, Kreuger E, Nges IA, Rosenqvist H, Svensson S-E, Lantz M, Mattsson JE, Börjesson P, Björnsson L. Comparing energy crops for biogas production – yields, energy input and costs in cultivation using digestate and mineral fertilization. Biomass Bioenerg 2014;64:199-210.

[13] Lundegrén (ed.). Evalueringsrapport marginale jorder och odlingssystem. BioM Bæredygtig bioenergi. Available from:

http://agrotech.dk/sites/agrotech.dk/files/public_files/agrotech-dk/pdf/Evalueringsrapport_Marginale_light.pdf [cited 13.8.2014].

[14] Bullard MJ, Metcalfe P. Estimating the energy requirements and CO_2 emissions from production of the perennial grasses mischanthus, switchgrass and reed canary grass. London: ADAS Consulting Ltd; 2001.

[15] Berglund M, Börjesson P. Assessment of energy performance in the life-cycle of biogas production. Biomass Bioenerg 2006;30:254-66.

[16] Kimming M, Sundberg C, Nordberg Å, Baky A, Bernesson S, Norén O, Hansson P-A. Biomass from agriculture in small-scale combined heat and power plants - A comparative life cycle assessment. Biomass Bioenerg 2011;35:1572-81.

[17] Börjesson P, Tufvesson LM. Agricultural crop-based biofuels – resource efficiency and environmental performance including direct land use changes. J Clean Prod 2011;19:108-20.

[18] Paulrud S, Laitila T. Farmers’ attitudes about growing energy crops: A choice experiment approach. Biomass Bioenerg 2010;34(12):1770-9.

[19] Landström S, Lomakka L, Andersson S. Harvest in spring improves yield and quality of reed canary grass as a bioenergy crop. Biomass Bioenerg 1996;11:333-41.

[20] Hadders G, Olsson R. Harvest of grass for combustion in late summer and in spring. Biomass Bioenerg 1997;12:171-5.

[21] Gunnarsson C, Vågström L, Hansson P-A. Logistics for forage harvest to biogas production – timeliness, capacities and costs in a Swedish case study. Biomass Bioenerg 2008;32:1263-73.

[22] Shortall OK. “Marginal land” for energy crops: Exploring definitions and embedded assumptions. Energy Policy 2013;62:19-27.

[23] Richards BK, Stoof CR, Cary IJ, Woodbury PB. Reporting on marginal lands for bioenergy feedstock production: a modest proposal. Bioenerg Res 2014;7:1060-2.

[24] Witney B. Choosing and using farm machines. Edinburgh: Land Technology Ltd; 1995.

[25] Amiama C, Bueno J, Alvarez CJ. Influence of the physical parameters of fields and of crop yield on the effective field capacity of a self-propelled forage harvester. Biosyst Eng 2008;100:198-205.

[26] Gónzalez XP, Marey MF, Álvarez CJ. Evaluation of productive rural land patterns with joint regard to the size, shape and dispersion of plots. Agr Syst 2007;92:52-62.

[27] Sparkes DL, Jaggard KW, Ramsden SJ, Scott RK. The effect of field margins on the yield of sugar beet and cereal crops. Ann Appl Biol 1998;132(1):129-42.

[28] Sparkes DL, Ramsden SJ, Jaggard KW, Scott RK. The case for headland set-aside: consideration of whole-farm gross margins and grain production on two farms with contrasting rotations. Ann Appl Biol 1998;133(2):245-56.

[29] Kautz T, Stumm C, Kösters R, Köpke U. Effects of perennial fodder crops on soil structure in agricultural headlands. J Plant Nutr Soil Sc 2010;173(4):490-501.

[30] Mårtensson K, Johnsson H, Blombäck K. Läckage av kväve från svensk åkermark för år 2007 och 2008 beräknat med PLC5-metodik. Teknisk rapport 138. Uppsala: Dept of Soil and Environment, Swedish University of Agricultural Sciences; 2010.

[31] Jordbruksverket. Jordbruket och vattenkvalitén. Kunskapsunderlag om åtgärder. Rapport 2012:22. Jönköping: Swedish Board of Agriculture (Jordbruksverket); 2012.

[32] Falloon P, Powlson D, Smith P. Managing field margins for biodiversity and carbon sequestration: a Great Britain case study. Soil Use Manage 2004;20:240-7.

[33] Schneider C, Fry G. 2005. Estimating the consequences of land-use changes on butterfly diversity in a marginal agricultural landscape in Sweden. J Nat Conserv 2005;13:247-56.

[34] Semere T, Slater FM. Ground flora, small mammal and bird species diversity in miscanthus (Miscanthus giganteus) and reed canary-grass (Phalaris arundinacea) fields. Biomass Bioenerg 2007;31:20-9.

[35] Rosenqvist H, Nilsson D, Bernesson S. Kostnader och lönsamhet för odling av energigräs på marginell jordbruksmark. Rapport 073. Uppsala: Dept of Energy and Technology, Swedish University of Agricultural Sciences; 2014.

[36] de Clercq EM, Vandemoortele F, de Wulf RR. A method for the selection of relevant pattern indices for monitoring of spatial forest cover pattern at a regional scale. Int J Appl Earth Observ Geoinform 2006;8(2):113-25.

[37] Cousins SAO, Aggemyr E. The influence of field shape, area and surrounding landscape on plant species richness in grazed ex-fields. Biol Conservation 2008;141(1):126-35.

[38] Nilsson D, Rosenqvist H, Bernesson S. Tidsåtgång för maskinarbeten på små fält - en simuleringsstudie. Rapport 072. Uppsala: Dept of Energy and Technology, Swedish University of Agricultural Sciences; 2014.

[39] European Commission. COMMISSION REGULATION (EC) No 1122/2009. Available from: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009R1122 [cited 17.4.2015].

[40] Palmer RJ, Wild D, Runtz K. Improving the Efficiency of Field Operations. Biosyst Eng 2003;84:283-8.

[41] Spekken M, de Bruin S. Optimized routing on agricultural fields by minimizing maneuvering and servicing time. Precis Agric 2013;14:224-44.

[42] Rizzo D, Martin L, Wohlfahrt J. Miscanthus spatial location as seen by farmers: a machine learning approach to model real criteria. Biomass Bioenerg 2014;66:348-63.

[43] Kelton WD, Sadowski RP, Sturrock DT. Simulation with Arena. New York: McGraw-Hill; 2007.

[44] Maskinkalkylgruppen. Maskinkostnader 2013. Linköping: Hushållningssällskapen; 2013.

[45] European Commission. Direct payments. Available from: http://ec.europa.eu/agriculture/direct-support/direct-payments/index_en.htm [cited 17.4.2015].

[46] Jordbruksverket (Swedish Board of Agriculture). Jordbrukarstöd. Available from: http://www.jordbruksverket.se/amnesomraden/stod/jordbrukarstod.4.53b6e8e714255ed1fcc71bd.html [cited 17.4.2015].

[47] Naturvårdsverket. Åtgärder och kostnader för minskad fosforutlakning från jordbruksmark till sjön Glan, underlagsrapport (3) till Miljökvalitetsnormer för fosfor i sjöar - redovisning av ett regeringsuppdrag (NV rapport 5288). Rapport 5291. Stockholm: Swedish Environmental Protection Agency (Naturvårdsverket); 2003.

[48] Naturvårdsverket. Vidareutveckling av förslag till avgiftssystem för kväve och fosfor. Rapport 6345. Stockholm: Swedish Environmental Protection Agency (Naturvårdsverket); 2010.

[49] Andersson R, Kaspersson E, Wissman J. Slututvärdering av Miljö- och landsbygdsprogrammet 2000-2006 – vad fick vi för pengarna? Uppsala: Swedish University of Agricultural Sciences; 2009.

[50] Johnsson H, Larsson M, Lindsjö A, Mårtensson K, Persson K, Torstensson G. Läckage av näringsämnen från svensk åkermark – Beräkningar av normalläckage av kväve och fosfor för 1995 och 2005. Rapport 5823. Stockholm: Swedish Environmental Protection Agency (Naturvårdsverket); 2008.

[51] Debnath D, Stoecker AL, Epplin FM. Impact of environmental values on the breakeven price of switchgrass. Biomass Bioenerg 2014;70:184-95.

[52] Jordbruksverket (Swedish Board of Agriculture). Kalkyler för energigrödor. Available from: http://www2.jordbruksverket.se/webdav /files/SJV/trycksaker/Pdf_ovrigt/ovr304.pdf [cited 2.9.2014].

[53] Tidåker P, Sundberg C, Öborn I, Kätterer T, Bergkvist G. Rotational grass/clover for biogas integrated with grain production – a life cycle perspective. Agr Syst 2014;129:133-41.

[54] Shield IF, Barraclough TJP, Riche AB, Yates NE. The yield response of the energy crops

switchgrass and reed canary grass to fertiliser applications when grown on a low productivity sandy soil. Biomass Bioenerg 2012;42:86-96.

[55] Xiong S, Kätterer T. Carbon-allocating dynamics in reed canary grass as affected by soil type and fertilization rates in northern Sweden. Acta Agr Scand B–S P 2009;60:24-32.

[56] Powlson DS, Whitmore AP, Goulding KWT. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. Eur J Soil Sci 2011;62:42-55.

[57] Søgaard HT, Sørensen CG. A model for optimal selection of machinery sizes within the farm machinery system. Biosyst Eng 2004;89:13-28.

[58] de Toro A. Influences on timeliness costs and their variability on arable farms. Biosyst Eng 2005;92:1-13.

[59] Larsson S. Supply curves of reed canary grass (Phalaris arundinacea L.) in Västerbotten County, northern Sweden, under different EU subsidy schemes. Biomass Bioenerg 2006;30:28-37.

[60] Stürmer B, Schmidt J, Schmid E, Sinabell F. Implications of agricultural bioenergy crop production in a land constrained economy – the example of Austria. Land Use Policy 2013;30:570-81.

[61] Bryngelsson DK, Lindgren K. Why large-scale bioenergy production on marginal land is unfeasible: a conceptual partial equilibrium analysis. Energy Policy 2013;55:454-66.

[62] Anderson-Teixeira KJ, Davis SC, Masters MD, Delucia EH. Changes in soil organic carbon under biofuel crops. GCB Bioenergy 2009;1:75-96.

[63] Ma Z, Wood CW, Bransby DI. Carbon dynamics subsequent to establishment of switchgrass. Biomass Bioenerg 2000;18:93-104.

[64] Wang L, Qian Y, Brummer JE, Zheng J, Wilhelm S, Parton WJ. Simulated biomass,

environmental impacts and best management practices for long-term switchgrass systems in a semi-arid region. Biomass Bioenerg 2015;75:254-66.

[65] Johnston AE, Poulton PR, Coleman K. Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. Adv Agron 2009;101:1-57.

[66] Svensk energi (Swedenergy). Handel med utsläppsrätter. Available from: http://www.svenskenergi.se/Elfakta/Elpriser-och-skatter/Handel-med-utslappsratter/ [cited 15.4.2015].

[67] Wissman J, Berg Å, Ahnström J, Wikström J, Hasund KP. How can the Rural Development Programme's agri-environmental payments be improved? Experiences from other countries. Report 2013:21. Jönköping: The Swedish Board of Agriculture; 2013.

[68] Glithero NJ, Wilson P, Ramsden SJ. Optimal combinable and dedicated energy crop scenarios for marginal land. Appl Energ 2015;147:82-91.

Table 1 – Options in the cost calculations. An example of a calculation path (marked by bold letters) is: RCG cultivated in small and irregular-shaped fields at Vingåker using ‘large’ machines.

Crops and uses	Type of fields[a,b]	Locations[c]	Machinery[d]
RCG[e] – solid fuel[g]	‘Normal’ fields	Svalöv[k]	‘Small’
Ley[e,f] – biogas[h]	**Small and irregular-shaped fields**	Ronneby[k]	**‘Large’**
Winter wheat[i]	Fields with less fertile soils	**Vingåker**	
Spring barley[i]	Headlands	Skellefteå	
Fallow land[j]	Border strips		

[a] In the paper, ‘field’ is used as a general term for a non-specified piece of arable land, including land lying fallow (but not permanent pasture land).

[b] Each type of field was assumed to have a specific field shape.

[c] Distinctive features between the locations were field areas, transport distances and crop yields.

[d] The time demand for both small and large machinery was based on the dynamic simulation of machine operations in fields with different areas and shapes.

[e] In small and irregular-shaped fields and in fields with less fertile soils, no N-fertilisation was included as an alternative option. Energy grasses on headlands and border strips were not fertilised with N at all for environmental reasons.

[f] Two harvests per year was included as an alternative option.

[g] RCG was harvested as round bales. The costs included all operations up to the boiler plant gate.

[h] There were three harvest options: 1) harvest and handling as ensiled round bales, 2) harvest by a self-chopping wagon (SCW) and direct use, 3) harvest by a SCW and storage in bunker silos. The costs included all operations up to the biogas plant gate.

[i] Conventional cultivation and use. The costs included transports, drying and storage.

[j] ‘Green’-covered fallow.

[k] An option was calculated for these locations, taking the economic value of reduced nutrient leakage into account.

Table 2 – Average crop yields used for ‘normal’ fields in the calculations (m.c. – moisture content, DM – dry matter) [35].

	Svalöv	Ronneby	Vingåker	Skellefteå
RCG (spring harvest) (tonnes DM ha^{-1})	5.4	5.0	4.8	4.5
Ley (tonnes DM ha^{-1})	7.5	6.7	6.0	4.0
Share, 1st harvest (%)	53	56	65	68
Share, 2nd harvest (%)	47	44	35	32
Winter wheat (tonnes ha^{-1}, m.c. 14%)	7.3	5.5	4.8	-
Spring barley (tonnes ha^{-1}, m.c. 14%)	5.2	4.1	3.6	2.2

Table 3 – Arable land data for the municipalities investigated [38].

	Svalöv	Ronneby	Vingåker	Skellefteå
Total area of arable land (ha)	21 440	7 420	7 980	26 430
Total number of arable blocks[a]	2 260	3 480	2 140	12 100
Total number of arable parcels[b]	3 200	3 860	2 450	12 780
Average parcel area (ha)	6.71	1.92	3.25	2.07
Parcels < 1.00 ha, share of total number (%)	24.7	47.3	32.1	38.7
Parcels < 1.00 ha, share of total area (%)	1.8	12.7	5.3	10.3
Blocks with *SI* > 1.75, share of total number (%)	12.8	17.9	18.2	13.6

[a] A ‘block’ is a permanently demarcated area of agricultural land, which contains one or more parcels.
[b] A ‘parcel’ is a continuous area of land, declared by one farmer, which does not cover more than one single crop [39].

Table 4 – Field areas (ha) used in the economic calculations. Calculated from data obtained from Swedish Board of Agriculture.

	Svalöv	Ronneby	Vingåker	Skellefteå
Small and irregular-shaped fields	1.02	1.02	1.19	1.11
Low-fertility fields	5.79	1.42	2.35	1.62
Headlands	0.57	0.45	0.48	0.43
Border strips	0.51	0.59	0.75	0.75[a]

[a] No data available, therefore the same value as for Vingåker was assumed.

Table 5 – Average distances between blocks, and between blocks and a conversion plant located at the site with the highest concentration of blocks (with a total marginal land area of 180 ha). A tortuosity factor of 1.5 was used.

	Between blocks (km)	Between blocks and plant (km)
Svalöv	0.8	4.0
Ronneby	1.1	6.0
Vingåker	0.9	4.6
Skellefteå	1.0	5.0

Table 6 – Reduction of phosphorous (P) and nitrogen (N) leakage when cultivating energy grasses instead of cereals, and estimated economic value of the reduced leakage [35].

	Leakage reduction ($kg\ ha^{-1}$)		Economic value of leakage reduction (€ ha^{-1})[a]		
	P	N	P	N	Total
Normal fields	0.2	20	21	312	333
Small and irregular-shaped fields	0.2	20	21	312	333
Low-fertility fields	0.2	20	21	312	333
Headlands	0.6	25	62	389	451
Border strips	0.5	22	52	343	395

[a] Rate of exchange 2014-08-21: € 1.00 = 9.63 SEK.

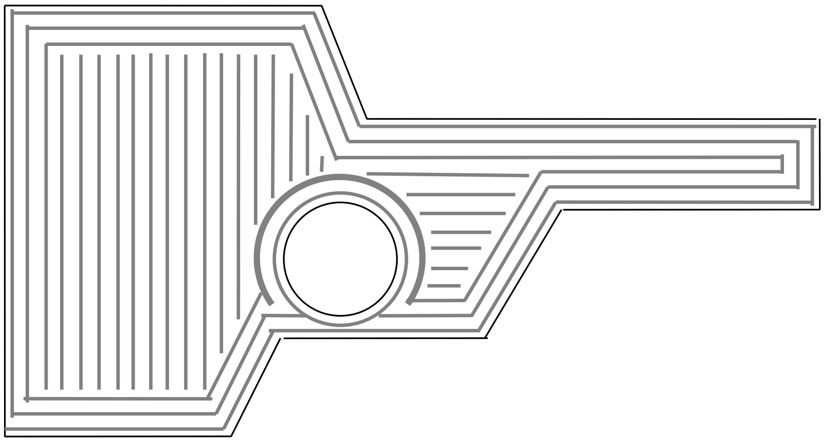

Fig. 1 – Shape of small and irregular-shaped fields. In this case, the driving pattern for mowing of grass with a working width of 2.25 m in a field with an area of 1.0 ha is shown.

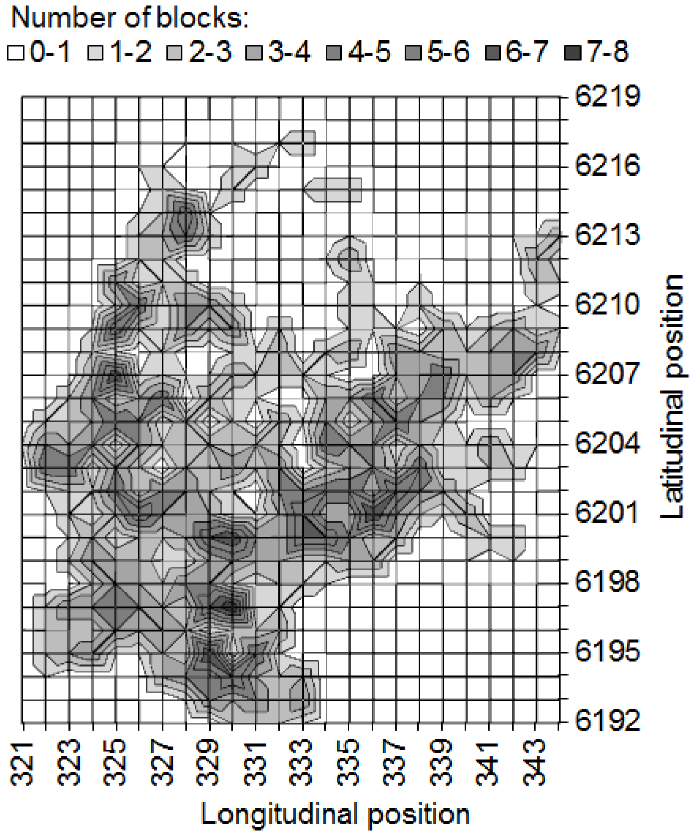

Fig. 2 – The number of agricultural blocks containing marginal land parcels in each 1x1 km-grid in the municipality of Svalöv. The town of Svalöv is located at coordinates 6201-331.

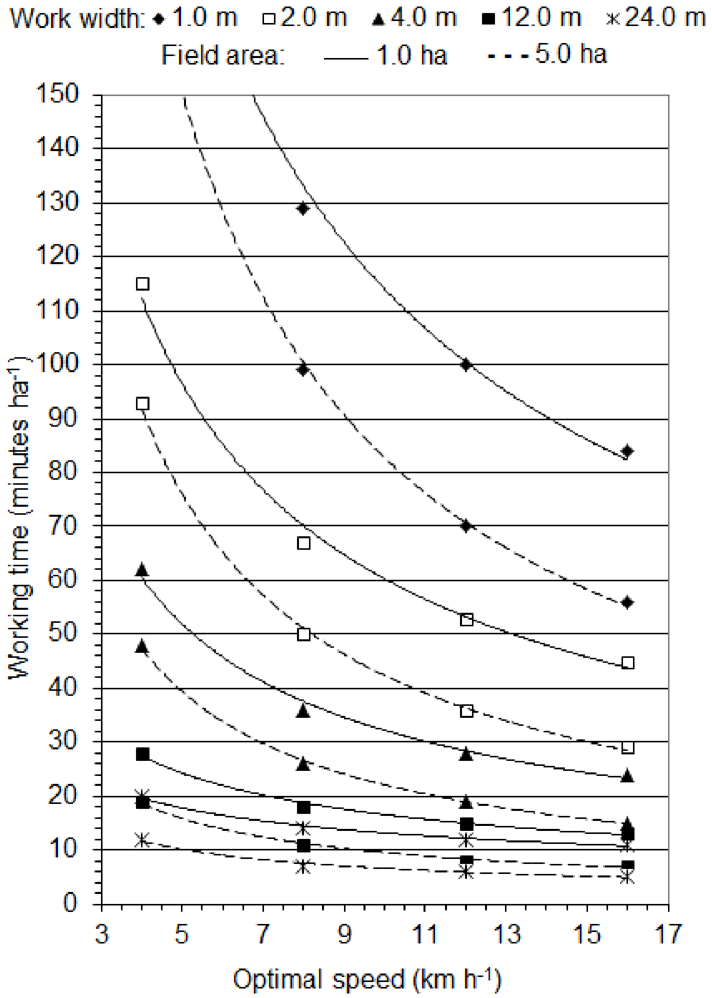

Fig. 3 – In-field working time for machine operations in rectangular fields (length:width ratio 2:1) with areas of 1.0 ha and 5.0 ha, as a function of optimal (maximum) driving speed and effective work width (1.0, 2.0, 4.0, 12.0 and 24.0 m).

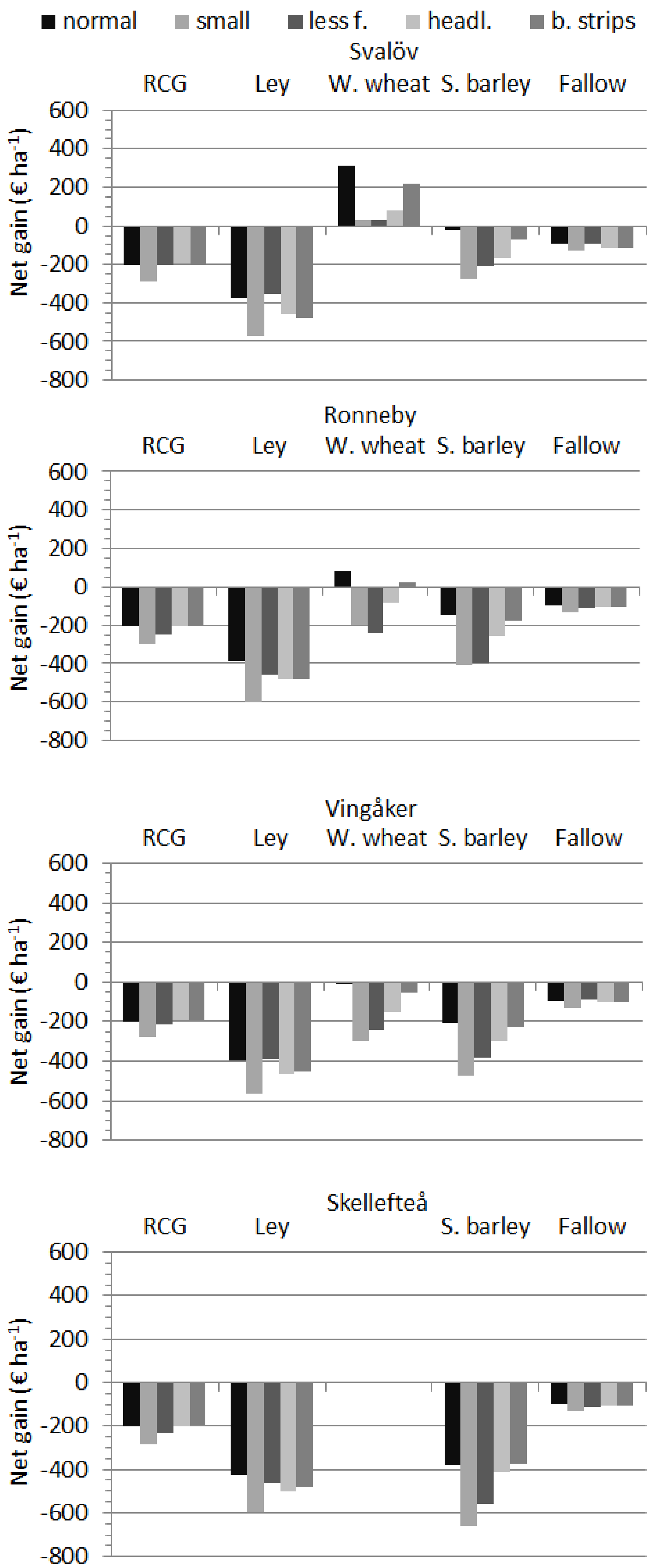

Fig. 4 – Net gain for the production of RCG, ley, winter wheat, spring barley and fallow in 'normal' fields, small and irregular-shaped fields, fields with less fertile soils, headlands and border strips in the municipalities investigated (winter wheat is not cultivated at Skellefteå).

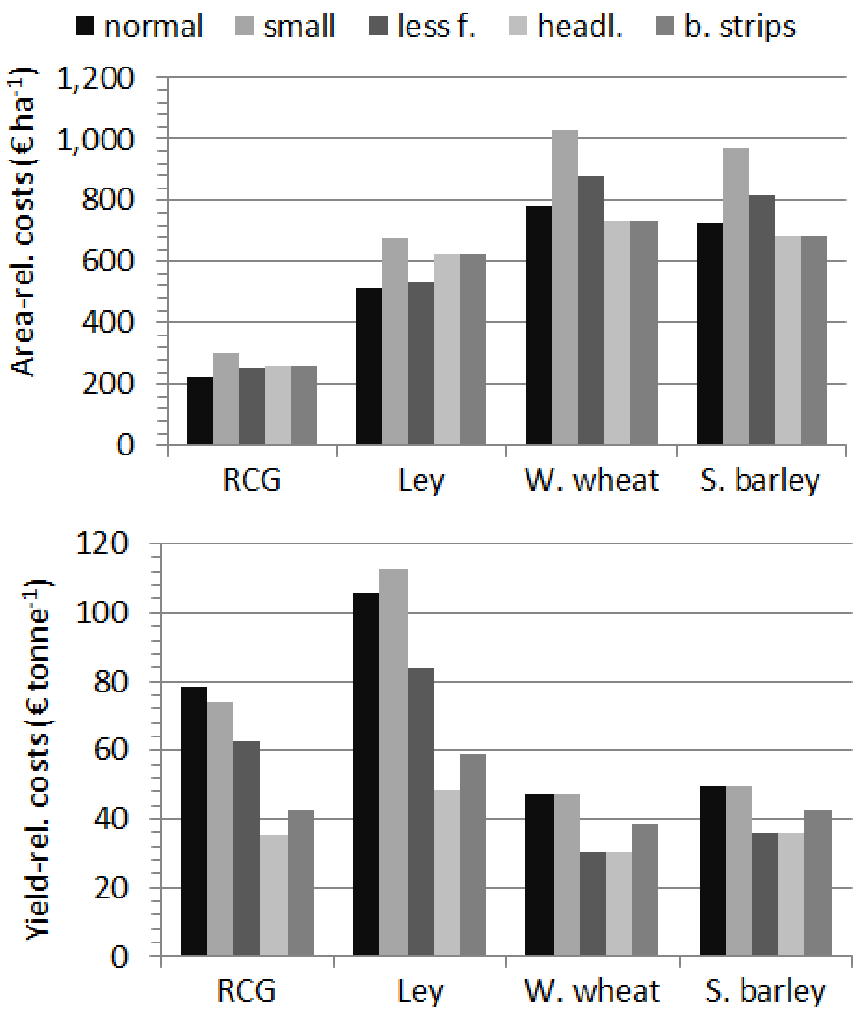

Fig. 5 – Area-related (in € per ha) and yield-related costs (in € per tonne DM for RCG and ley and € per tonne grain with 14% m.c. for winter wheat and spring barley) for cultivation at Ronneby.

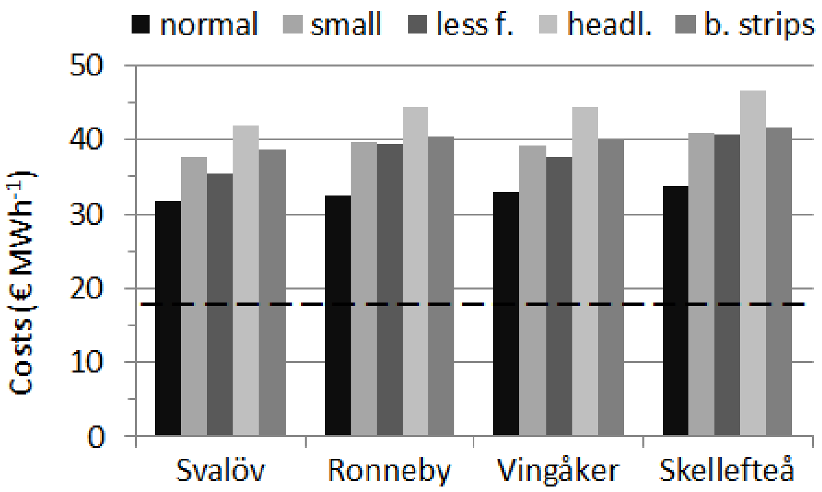

Fig. 6 – Costs for the production of RCG in 'normal' fields, small and irregular-shaped fields, fields with less fertile soils, headlands and border strips in the municipalities investigated. The dashed line shows the price for the product (17.6 € MWh^{-1}).

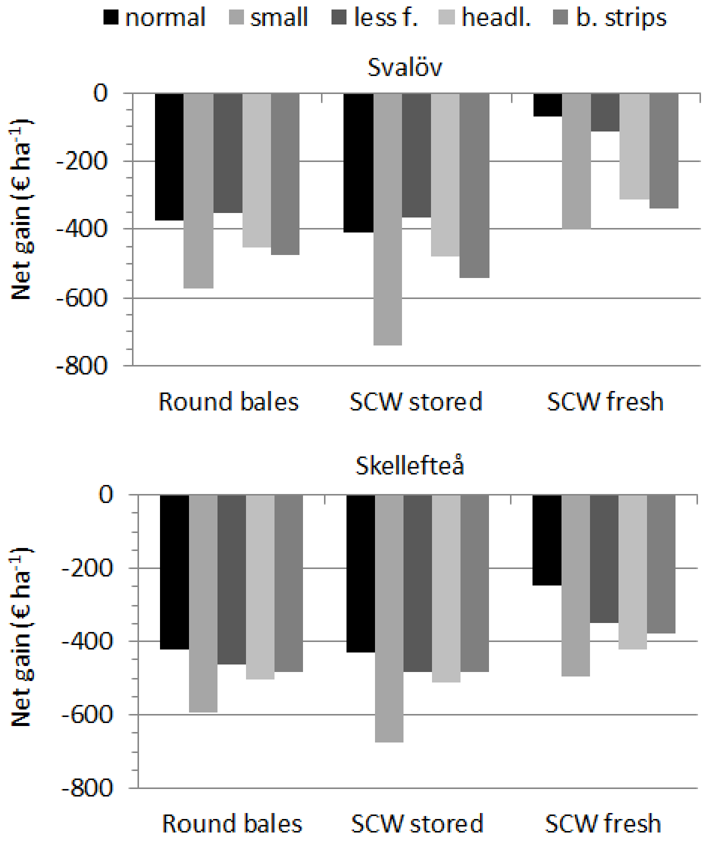

Fig. 7 – Net gain from different ways of harvesting and handling the ley crop for biogas production in 'normal' fields, small and irregular-shaped fields, fields with less fertile soils, headlands and border strips at Svalöv and Skellefteå (SCW – self-chopping wagon).

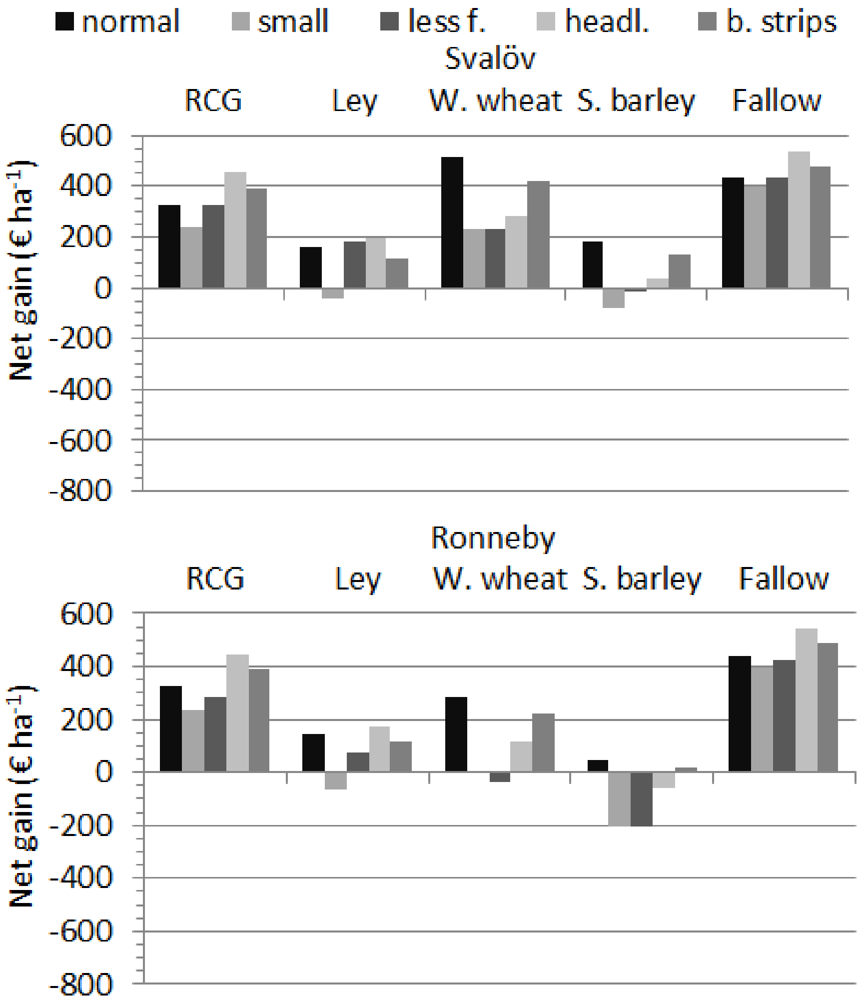

Fig. 8 – Net gain when direct payments and the value of reduced nutrient leakage is considered for the different crops in 'normal' fields, small and irregular-shaped fields, fields with less fertile soils, headlands and border strips at Svalöv and Ronneby.

Supplementary content

S1. MACHINERY COSTS

S1.1. Simulation of machinery performance in rectangular fields

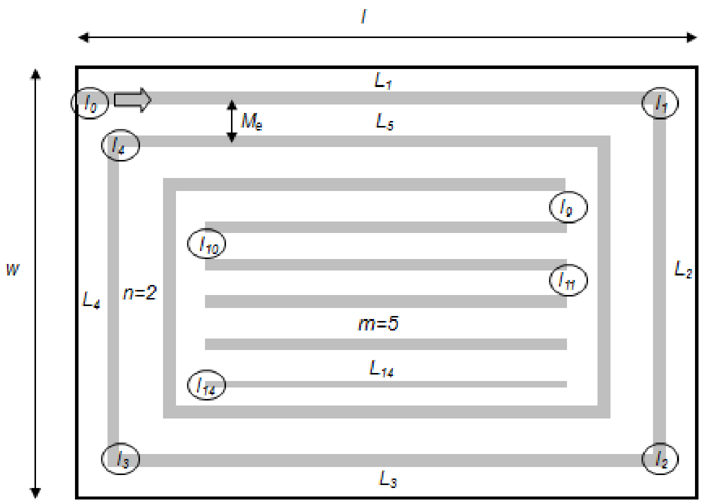

Fig. S1. Driving pattern in a rectangular field with length l and width w. A machine with an effective work width M_e tills the soil or processes the crop using n headland passes and m mainland passes. The driving pattern is implemented in the simulation model by using a number of intersections (I) and links (L) [1].

Table S1. Machine performance data used in the simulations (the number of simulation replications was 30 and the common random number technique was used to reduce the variance) [1-4]

Variable	Values used in simulations
Field shapes (for rectangular fields) (length:width)	1:1, 2:1, 4:1
Field areas *(A)*	0.5 ha, 1.0 ha, 1.5 ha, 2.5 ha, 5.0 ha, 15.0 ha
Effective operating width of machines (M_e)	1.0 m, 2.0 m, 4.0 m, 12.0 m, 24.0 m
Maximum (optimal) operating speed (v_a)	4.0 km/h, 8.0 km/h, 12.0 km/h, 16.0 km/h
Width of headlands	12.0 m, 16.0 m for A = 15.0 ha, 24.0 m for M_e = 24.0 m
In-field machine preparation time	2 min per parcel + 2 min per 5 ha
Operating speed, outer passes (following field boundaries)	0,75v_a
Operating speed, curves $\alpha < 60°$, machine in work	v_a (unchanged speed)
Operating speed, curves $60 \leq \alpha \leq 90°$, machine in work	0.5v_a
Time for curves $\alpha \geq 90°$, machine not in work	22 sec., reverse corner (excl. retardation and acceleration)
Time for turns, machine not in work	15 sec., loop turn (excl. retardation and acc.)
Retardation (d) (reduction of operating speed v_a)	$d = -\Delta v/(\Delta s/((v_a+v)/2))$, braking distance s = 5 m
Acceleration (a) (increase of operating speed v_a)	$a = \Delta v/(\Delta s/((v_a+v)/2))$, acc. distance s = 10 m
Driving speed when idle	8.0 km/h when operating speed 4.0 km/h, otherwise v_a
Time between stochastic stoppages (adjustments, blockages, breakdowns, etc.)	exponential distribution, expected value 30 min
Duration of stochastic stoppages	exponential distribution, expected value 3.0 min
Time for finishing up	3 min

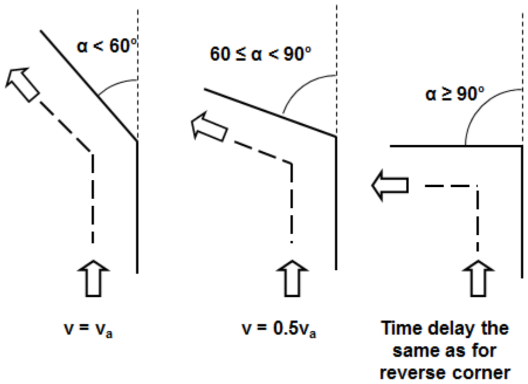

Fig. S2. Changes in operating speed for different types of curves. The same changes were assumed independent of the direction of the curves (left +α or right -α) [1].

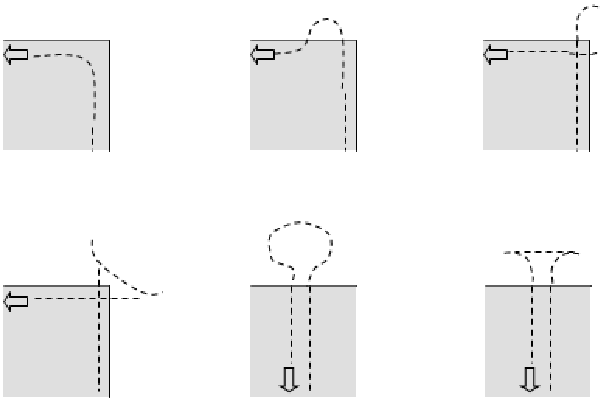

Fig. S3. Different types of corner and turn driving patterns: round corner, square corner and loop corner (upper; from left to right), reverse corner, loop turn and reverse turn (lower; from left to right) [1,4].

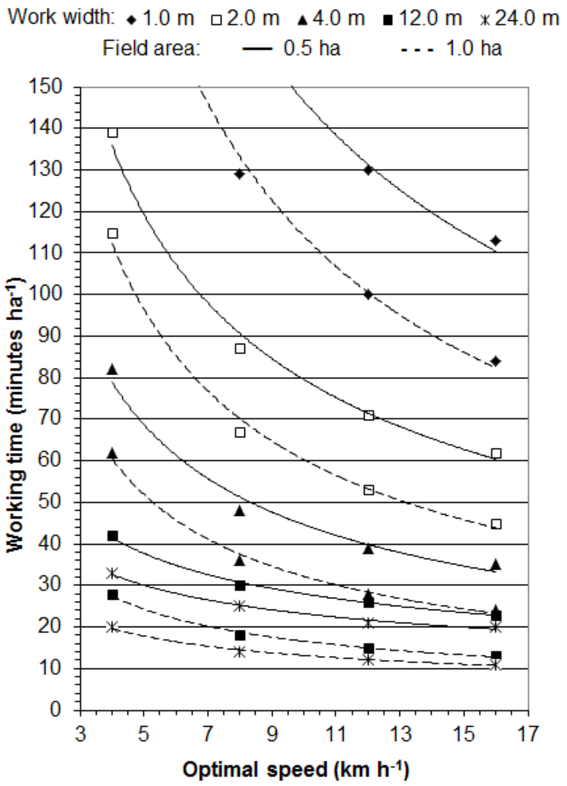

Fig. S4. Simulated in-field working time for machine operations in rectangular fields (length:width ratio 2:1) with areas of 0.5 ha and 1.0 ha, as a function of optimal (maximum) driving speed and effective work width (1.0, 2.0, 4.0, 12.0 and 24.0 m) [1].

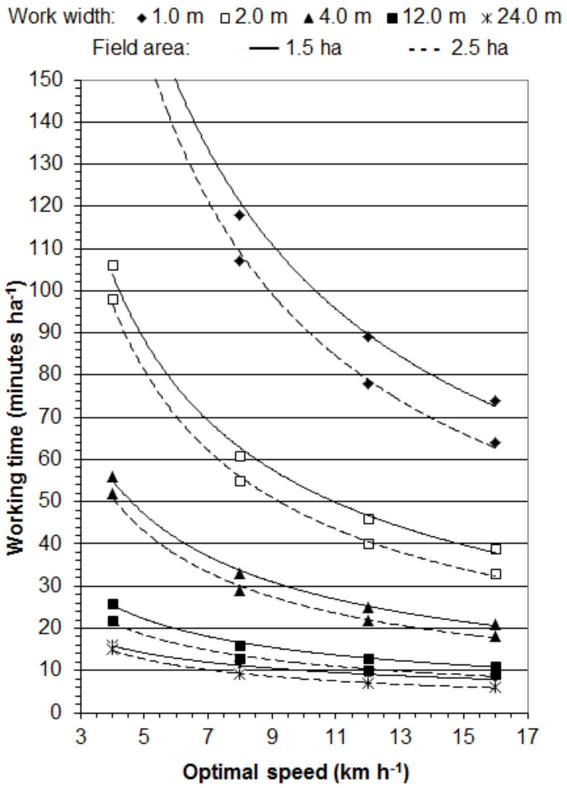

Fig. S5. Simulated in-field working time for machine operations in rectangular fields (length:width ratio 2:1) with areas of 1.5 ha and 2.5 ha, as a function of optimal (maximum) driving speed and effective work width (1.0, 2.0, 4.0, 12.0 and 24.0 m) [1].

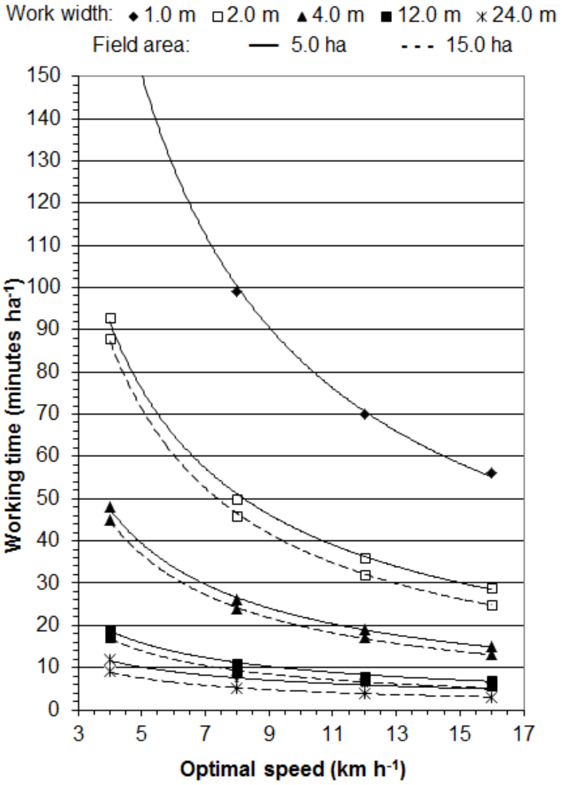

Fig. S6. Simulated in-field working time for machine operations in rectangular fields (length:width ratio 2:1) with areas of 5.0 ha and 15.0 ha, as a function of optimal (maximum) driving speed and effective work width (1.0, 2.0, 4.0, 12.0 and 24.0 m) [1].

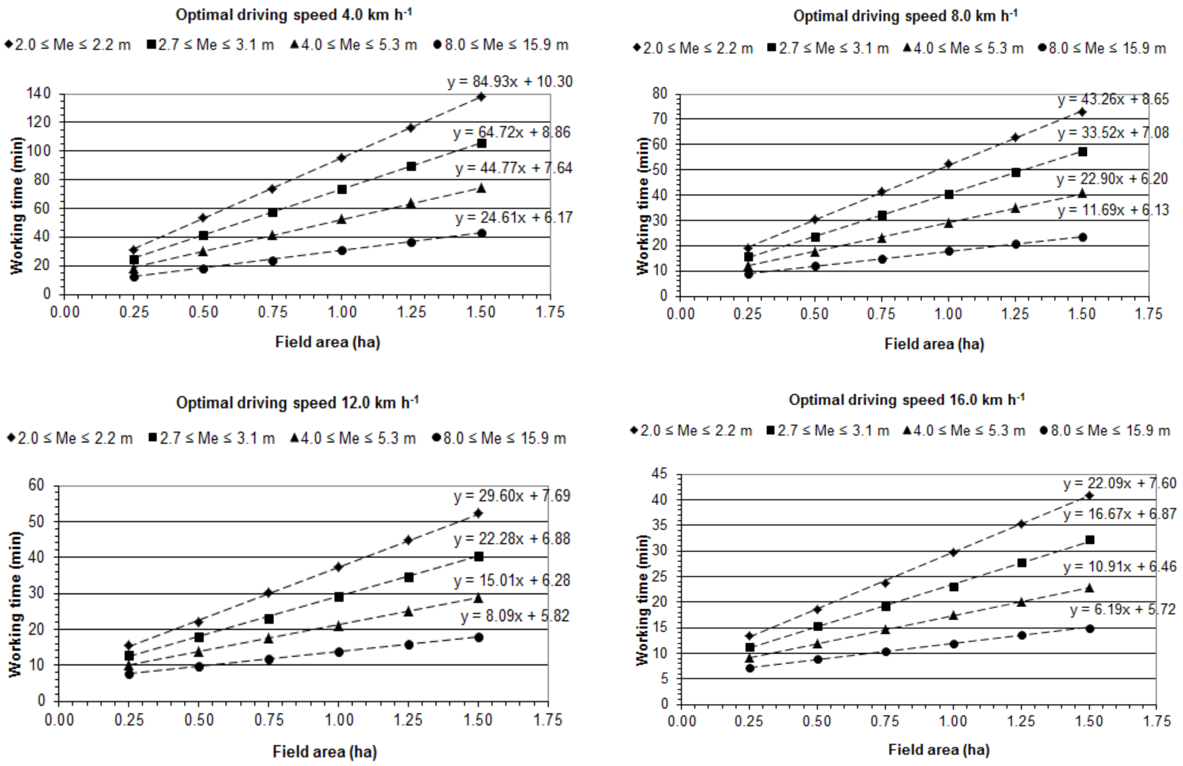

Fig. S7. Simulated time demand for operations in fields with a width of 16 m (e.g. headlands) for machines with M_e = 2.0-2.2 m (♦), 2.7-3.1 m (■), 4.0-5.3 m (▲) and 8.0-15.9 m (●), and optimal driving speeds of 4.0 km h^{-1} (upper left), 8.0 km h^{-1} (upper right), 12.0 km h^{-1} (lower left) and 16.0 km h^{-1} (lower right). The lengths of the fields were 156 m (0.25 ha), 312 m (0.5 ha), 469 m (0.75 ha), 625 m (1.0 ha), 781 m (1.25 ha) and 938 m (1.5 ha) [1].

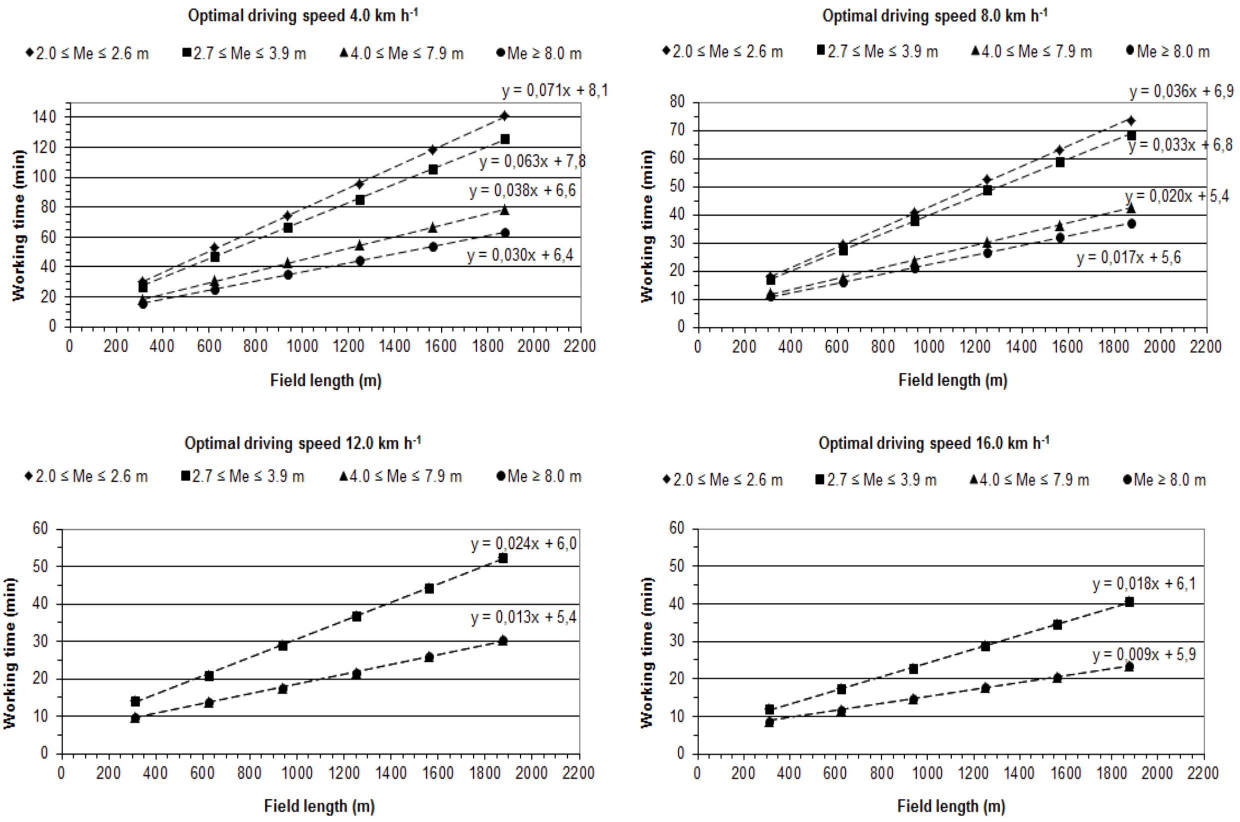

Fig. S8. Simulated time demand for operations in fields with a width of 8 m (e.g. border strips) for machines with M_e = 2.0-2.6 m (♦), 2.7-3.9 m (■), 4.0-7.9 m (▲) and ≥ 8.0 m (●), and optimal driving speeds of 4.0 km h^{-1} (upper left), 8.0 km h^{-1} (upper right), 12.0 km h^{-1} (lower left) and 16.0 km h^{-1} (lower right). The areas of the fields were 0.25 ha (313 m), 0.50 ha (625 m), 0.75 ha (938 m), 1.00 ha (1 250 m), 1.25 ha (1 563 m) and 1.50 ha (1 875 m) [1].

S1.2. Simulation of machinery performance in irregular-shaped fields

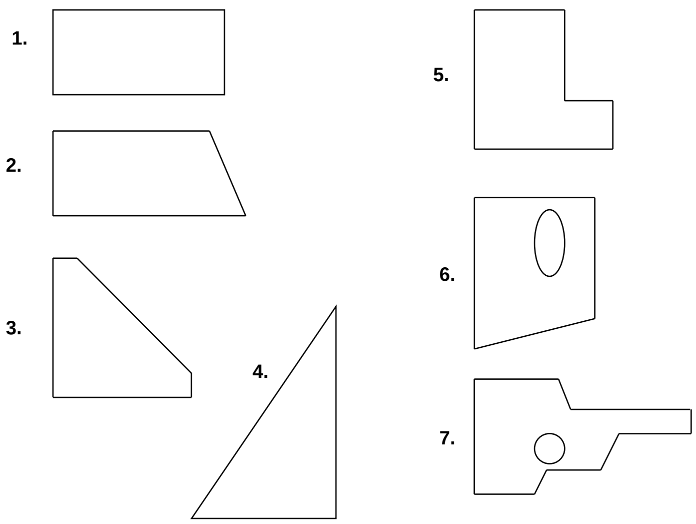

Fig. S9. 'Irregular' field shapes in the simulations (the rectangular shape (1) was used as a reference). The area was 1.00 ha [1].

Table S2. Perimeter, shape index and number of links (including a link for returning to the starting point) for the field shapes in Fig. S9 [1]

Field shape	1	2	3	4	5	6	7
Perimeter, m	424	443	433	495	455	554	620
Shape index	1.20	1.25	1.22	1.40	1.28	1.56	1.75
Total number of links	45	43	74	55	65	67	95

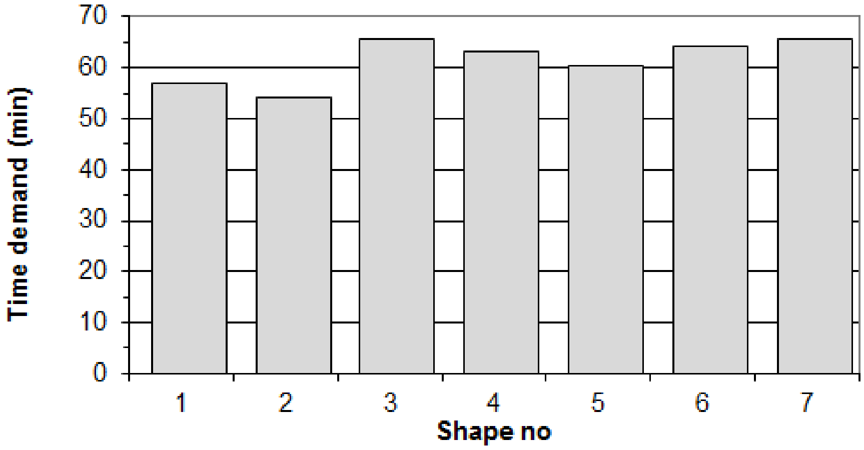

Fig. S10. Simulated time demand for mowing in different irregular-shaped fields (see Fig. S9). The area was 1.00 ha, the effective machine work width (M_e) was 2.25 m and the optimal driving speed was 10 km h^{-1} (according to FAT Berichte [5]) [1].

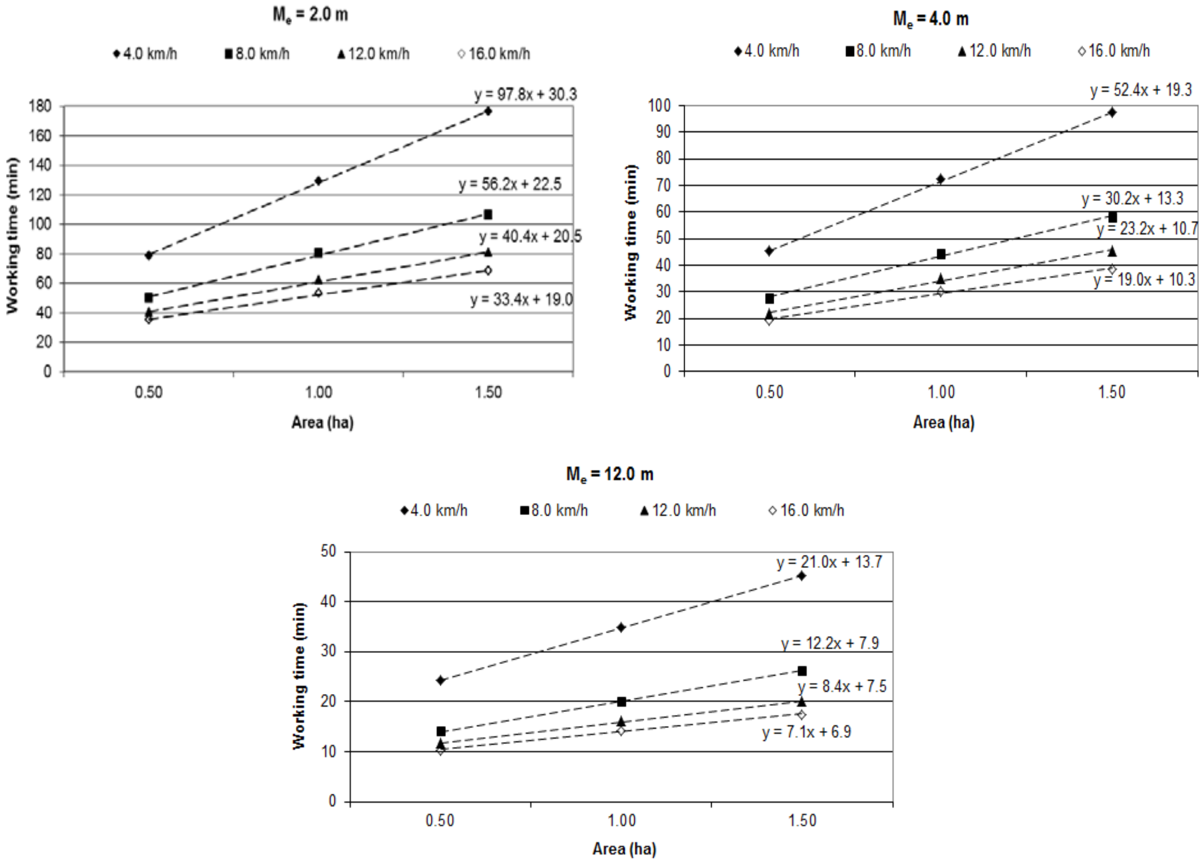

Fig. S11. Simulated time demand for different optimal driving speeds as a function of the area of small irregular-shaped fields (shape no 7 in Fig. S9) for M_e = 2.0 m (upper, left), 4.0 m (upper, right) and 12.0 m (lower) [1].

S1.3. Calculation of machinery costs

Table S3. Data for field operations with 'large' machines

Operation	Type of machine	Working width (m)	Optimal driving speed[a] (km h^{-1})	Hourly cost[b,c] (€ h^{-1})
Stubble tillage	Heavy disc harrow	4.2	8.3	109.2
Ploughing	Semi-mounted reversible plough, 5-furrow	5 x 0.4 = 2.0	6.7	89.3
Harrowing	Trailed implement	8.0	12.0	99.7
Sowing	2 200 l (no combi-drill)	6.0	7.4	95.6
Rolling	Roller	12.0	9.5	104.7
Fertiliser[d] application	Mounted implement, 2 500 l, computer	24.0	5.0	74.1
Pesticide application	Trailed sprayer, 2 500 l	24.0	5.7	105.4
Threshing	Combine harvester, 180 kW	5.4	4.5	209.5
Mowing	Mower conditioner	3.0	10.8	84.0
Tedding/windrowing	Rotary tedder/rotary windrower	6.5	7.7	78.5
Baling, dry grass	Round baler with bale collector	6.0	8.0	100.3
Baling, silage	Round baler with cutting knives and wrapper	3.0	6.0	131.3
In-field chopping	Self-chopping wagon (with compactor), 50 m^3	3.0	12.0	194.7
Fallow management	Mower	3.0	10.8	84.0
Transporter for bales				12.5[e]
Bale storage building				20.8[e]
Concrete slab				7.3[e]

[a] Effective optimal speeds calculated from data by Maskinkalkylgruppen [6], assuming a field area of 5.0 ha, and the use of the data in Fig. S6.

[b] According to Maskinkalkylgruppen [6], incl. labour costs (25.4 € h^{-1}) and costs of tractor, diesel fuel (1.0 € l^{-1}) and off-field preparations and pauses (15%), but excl. transports (€ 1.00 = 9.63 SEK; 2014-08-21).

[c] The total costs for each operation were calculated as the time demand (obtained from Figs. S4-S8, S11) multiplied by hourly costs, plus transport costs.

[d] Costs of P, K and N fertilisers were 2.39 € kg^{-1}, 0.83 € kg^{-1} and 1.14 € kg^{-1}, respectively.

[e] Costs per tonne dry matter (DM).

Table S4. Data for field operations with 'small' machines[a]

Operation	Type of machine	Working width (m)	Optimal driving speed[b] (km h^{-1})	Hourly cost[b,c] (€ h^{-1})
Stubble tillage	Heavy disc harrow	2.5	5.3	72.9
Ploughing	Mounted plough, 4-furrow	4 x 0.4 = 1.6	6.5	71.4
Harrowing	Trailed implement	6.0	10.4	79.8
Sowing	Mounted, no combi-drill	4.0	5.3	51.0
Rolling	Roller	6.0	7.2	52.3
Fertiliser[e] application	Mounted implement, 1 500 l	12.0	5.3	49.4
Pesticide application	Mounted implement, 1 000 l	12.0	5.3	60.2
Threshing	Combine harvester, 60 kW	3.0	3.0	86.3
Mowing	Mower conditioner, mounted	2.4	9.5	66.9
Tedding/windrowing	Rotary tedder/rotary windrower	4.5	7.1	54.2
Fallow management	Mower	2.4	9.5	66.9

[a] The machines for baling and in-field chopping were assumed to be the same as for 'large' machines.

[b] Effective optimal speeds calculated from data by Maskinkalkylgruppen [6], assuming a field area of 5.0 ha, and the use of the data in Fig. S6.

[c] According to Maskinkalkylgruppen [6], incl. labour costs (25.4 € h^{-1}) and costs of tractor, diesel fuel (1.0 € l^{-1}) and off-field preparations and pauses (15%), but excl. transports (€ 1.00 = 9.63 SEK; 2014-08-21).

[d] The total costs for each operation were calculated as the time demand (obtained from Figs. S4-S8, S11) multiplied by hourly costs, plus transport costs.

[e] Costs of P, K and N fertilisers were 2.39 € kg^{-1}, 0.83 € kg^{-1} and 1.14 € kg^{-1}, respectively.

S2. SOME RESULTS (ALL RESULTS ARE PRESENTED IN [1] AND [7])

S2.1. Basic calculation options

Table S5. Results for the basic calculation options for Svalöv. SCW –self-chopping wagon. For all options, RCG was used as solid fuel and ley was used for biogas production [7]

Crop	Harvested quantity (tonnes ha^{-1})[a]	Energy[b] (MWh ha^{-1})	Price[c] (€ tonne^{-1})[a]	Costs[c] (€ tonne^{-1})[a]	Costs[c] (€ MWh^{-1})[b]	Net gain[c] (€ ha^{-1})
Normal fields						
RCG	5.4	21	94.1	139.8	31.8	-202.9
Ley, round bales	7.5	19	119.4	169.2	67.7	-373.4
Ley, SCW, stored	7.5	19	119.4	174.0	69.6	-409.3
Ley, SCW, fresh	7.5	19	119.4	128.8	51.5	-69.9
Winter wheat	7.3	28	197.3	154.5	39.9	312.5
Spring barley	5.2	20	171.3	175.0	45.2	-18.9
Fallow	-	-	-	-	-	-96.5
Small irregular-shaped fields						
RCG with N-fert.	4.9	19	94.1	166.5	37.8	-289.5
RCG without N-fert.	3.4	13	94.1	166.6	37.8	-202.7
Ley with N-fert., round bales	7.5	19	119.4	195.8	78.3	-573.1
Ley without N-fert., round bales	5.3	13	119.4	201.2	80.5	-429.7
Ley with N-fert., SCW, stored	7.5	19	119.4	218.3	87.3	-741.6
Ley without N-fert., SCW, stored	5.3	13	119.4	223.5	89.4	-546.0
Ley with N-fert., SCW, fresh	7.5	19	119.4	173.1	69.3	-402.3
Ley without N-fert., SCW, fresh	5.3	13	119.4	158.7	63.4	-206.2
Winter wheat	7.3	28	197.3	192.9	49.8	31.6
Barley	5.2	20	171.3	224.5	58.0	-276.3
Fallow	-	-	-	-	-	-132.4
Fields with less fertile soils						
RCG with N-fert.	4.1	16	94.1	155.8	35.4	-205.5
RCG without N-fert.	2.8	11	94.1	159.2	36.1	-151.9
Ley with N-fert., round bales	5.6	14	119.4	182.2	72.9	-353.4
Ley without N-fert., round bales	3.9	10	119.4	190.8	76.3	-280.9
Ley with N-fert., SCW, stored	5.6	14	119.4	184.6	73.8	-366.8
Ley without N-fert., SCW, stored	3.9	10	119.4	191.0	76.4	-281.9
Ley with N-fert., SCW, fresh	5.6	14	119.4	139.4	55.8	-112.1
Ley without N-fert., SCW, fresh	3.9	10	119.4	145.8	58.3	-112.1
Winter wheat	5.1	20	197.3	191.5	49.5	29.6
Barley	3.6	14	171.3	229.6	59.3	-212.1
Fallow	-	-	-	-	-	-96.5
Headlands						
RCG	2.6	10	94.1	184.1	41.8	-196.0
Ley, round bales	3.7	9	119.4	243.2	97.3	-454.7
Ley, SCW, stored	3.7	9	119.4	249.5	99.8	-478.3
Ley, SCW, fresh	3.7	9	119.4	204.4	81.7	-312.0
Winter wheat	5.1	20	197.3	181.6	46.9	80.0
Spring barley	3.6	14	171.3	216.6	56.0	-164.9
Fallow	-	-	-	-	-	-116.2
Border strips						
RCG	3.2	13	94.1	169.9	38.6	-200.4
Ley, round bales	4.5	11	119.4	225.9	90.3	-474.9
Ley, SCW, stored	4.5	11	119.4	240.7	96.3	-541.2
Ley, SCW, fresh	4.5	11	119.4	195.4	78.2	-339.3
Winter wheat	6.2	24	197.3	161.6	41.7	221.4
Spring barley	4.4	17	171.3	186.8	48.3	-68.3
Fallow	-	-	-	-	-	-114.2

[a] Tonnes of dry matter (DM) for RCG and ley, and tonnes of grain with a moisture content of 14% for wheat and barley.

[b] Refers to the net calorific value of RCG, winter wheat and spring barley, and of biogas (ley).

[c] € 1.00 = 9.63 SEK (2014-08-21).

Table S6. Results for the basic calculation options for Ronneby. SCW –self-chopping wagon. For all options, RCG was used as solid fuel and ley was used for biogas production [7]

Crop	Harvested quantity (tonnes ha^{-1})[a]	Energy[b] (MWh ha^{-1})	Price[c] (€ tonne^{-1})[a]	Costs[c] (€ tonne^{-1})[a]	Costs[c] (€ MWh^{-1})[b]	Net gain[c] (€ ha^{-1})
Normal fields						
RCG	5.0	20	94.1	143.3	32.6	-202.5
Ley, round bales	6.7	17	119.4	176.8	70.7	-384.6
Ley, SCW, stored	6.7	17	119.4	181.2	72.5	-413.8
Ley, SCW, fresh	6.7	17	119.4	135.9	54.4	-110.6
Winter wheat	5.5	21	197.3	182.1	47.0	83.5
Spring barley	4.1	16	171.3	208.1	53.8	-150.8
Fallow	-	-	-	-	-	-96.5
Small irregular-shaped fields						
RCG with N-fert.	4.5	18	94.1	174.9	39.8	-299.0
RCG without N-fert.	3.2	12	94.1	176.3	40.1	-213.0
Ley with N-fert., round bales	6.7	17	119.4	208.7	83.5	-598.4
Ley without N-fert., round bales	4.7	12	119.4	216.9	86.8	-457.3
Ley with N-fert., SCW, stored	6.7	17	119.4	228.5	91.4	-730.5
Ley without N-fert., SCW, stored	4.7	12	119.4	236.2	94.5	-548.1
Ley with N-fert., SCW, fresh	6.7	17	119.4	183.2	73.3	-427.3
Ley without N-fert., SCW, fresh	4.7	12	119.4	171.5	68.6	-244.5
Winter wheat	5.5	21	197.3	233.2	60.2	-197.5
Barley	4.1	16	171.3	270.9	70.0	-408.2
Fallow	-	-	-	-	-	-132.4
Fields with less fertile soils						
RCG with N-fert.	3.8	15	94.1	173.8	39.5	-246.0
RCG without N-fert.	2.6	10	94.1	180.6	41.0	-186.7
Ley with N-fert., round bales	5.0	13	119.4	210.3	84.1	-456.5
Ley without N-fert., round bales	3.5	9	119.4	225.2	90.1	-372.2
Ley with N-fert., SCW, stored	5.0	13	119.4	216.3	86.5	-486.8
Ley without N-fert., SCW, stored	3.5	9	119.4	230.0	92.0	-389.1
Ley with N-fert., SCW, fresh	5.0	13	119.4	171.0	68.4	-259.4
Ley without N-fert., SCW, fresh	3.5	9	119.4	184.7	73.9	-259.4
Winter wheat	3.9	15	197.3	259.2	67.0	-238.4
Barley	2.9	11	171.3	311.4	80.5	-402.1
Fallow	-	-	-	-	-	-110.3
Headlands						
RCG	2.5	10	94.1	194.9	44.3	-203.1
Ley, round bales	3.3	8	119.4	265.2	106.1	-478.6
Ley, SCW, stored	3.3	8	119.4	273.2	109.2	-504.8
Ley, SCW, fresh	3.3	8	119.4	227.9	91.2	-356.2
Winter wheat	3.9	15	197.3	219.4	56.7	-85.0
Spring barley	2.9	11	171.3	260.6	67.3	-256.2
Fallow	-	-	-	-	-	-105.3
Border strips						
RCG	3.0	12	94.1	177.6	40.4	-204.4
Ley, round bales	4.0	10	119.4	240.0	96.1	-480.8
Ley, SCW, stored	4.0	10	119.4	247.5	99.0	-510.4
Ley, SCW, fresh	4.0	10	119.4	202.2	80.9	-329.9
Winter wheat	4.7	18	197.3	192.1	49.6	24.4
Spring barley	3.5	13	171.3	222.9	57.6	-179.9
Fallow	-	-	-	-	-	-107.5

[a] Tonnes of dry matter (DM) for RCG and ley, and tonnes of grain with a moisture content of 14% for wheat and barley.

[b] Refers to the net calorific value of RCG, winter wheat and spring barley, and of biogas (ley).

[c] € 1.00 = 9.63 SEK (2014-08-21).

Table S7. Results for the basic calculation options for Vingåker. SCW –self-chopping wagon. For all options, RCG was used as solid fuel and ley was used for biogas production [7]

Crop	Harvested quantity (tonnes ha^{-1})[a]	Energy[b] (MWh ha^{-1})	Price[c] (€ $tonne^{-1}$)[a]	Costs[c] (€ $tonne^{-1}$)[a]	Costs[c] (€ MWh^{-1})[b]	Net gain[c] (€ ha^{-1})
Normal fields						
RCG	4.8	19	94.1	145.4	33.0	-202.3
Ley, round bales	6.0	15	119.4	185.2	74.0	-394.4
Ley, SCW, stored	6.0	15	119.4	189.0	75.6	-417.7
Ley, SCW, fresh	6.0	15	119.4	143.7	57.5	-146.1
Winter wheat	4.8	19	197.3	199.2	51.5	-9.0
Spring barley	3.6	14	171.3	229.9	59.4	-210.8
Fallow	-	-	-	-	-	-96.5
Small irregular-shaped fields						
RCG with N-fert.	4.3	17	94.1	172.8	39.3	-279.8
RCG without N-fert.	3.0	12	94.1	173.8	39.5	-198.2
Ley with N-fert., round bales	6.0	15	119.4	214.0	85.6	-567.4
Ley without N-fert., round bales	4.2	11	119.4	223.7	89.5	-438.0
Ley with N-fert., SCW, stored	6.0	15	119.4	233.4	93.4	-683.9
Ley without N-fert., SCW, stored	4.2	11	119.4	242.4	97.0	-516.5
Ley with N-fert., SCW, fresh	6.0	15	119.4	188.2	75.3	-412.4
Ley without N-fert., SCW, fresh	4.2	11	119.4	178.7	71.4	-248.9
Winter wheat	4.8	19	197.3	258.9	66.9	-295.7
Barley	3.6	14	171.3	303.3	78.4	-475.0
Fallow	-	-	-	-	-	-132.9
Fields with less fertile soils						
RCG with N-fert.	3.6	14	94.1	166.6	37.8	-214.5
RCG without N-fert.	2.5	10	94.1	171.3	38.9	-160.2
Ley with N-fert., round bales	4.5	11	119.4	206.3	82.6	-391.2
Ley without N-fert., round bales	3.2	8	119.4	220.4	88.2	-317.9
Ley with N-fert., SCW, stored	4.5	11	119.4	211.2	84.4	-413.0
Ley without N-fert., SCW, stored	3.2	8	119.4	223.4	89.3	-327.4
Ley with N-fert., SCW, fresh	4.5	11	119.4	165.9	66.4	-209.2
Ley without N-fert., SCW, fresh	3.2	8	119.4	178.1	71.2	-209.2
Winter wheat	3.4	13	197.3	270.0	69.8	-244.3
Barley	2.5	10	171.3	323.5	83.6	-383.4
Fallow	-	-	-	-	-	-91.9
Headlands						
RCG	2.4	9	94.1	195.0	44.3	-195.3
Ley, round bales	2.9	7	119.4	277.7	111.1	-465.2
Ley, SCW, stored	2.9	7	119.4	283.2	113.3	-481.4
Ley, SCW, fresh	2.9	7	119.4	237.9	95.1	-348.4
Winter wheat	3.4	13	197.3	242.5	62.6	-151.6
Spring barley	2.5	10	171.3	289.5	74.8	-297.7
Fallow	-	-	-	-	-	-103.5
Border strips						
RCG	2.9	11	94.1	176.5	40.1	-193.8
Ley, round bales	3.6	9	119.4	245.9	98.3	-451.7
Ley, SCW, stored	3.6	9	119.4	252.6	101.0	-475.7
Ley, SCW, fresh	3.6	9	119.4	207.4	83.0	-314.1
Winter wheat	4.1	16	197.3	210.8	54.5	-55.1
Spring barley	3.1	12	171.3	246.7	63.8	-230.6
Fallow	-	-	-	-	-	-102.9

[a] Tonnes of dry matter (DM) for RCG and ley, and tonnes of grain with a moisture content of 14% for wheat and barley.

[b] Refers to the net calorific value of RCG, winter wheat and spring barley, and of biogas (ley).

[c] € 1.00 = 9.63 SEK (2014-08-21).

Table S8. Results for the basic calculation options for Skellefteå. SCW –self-chopping wagon. For all options, RCG was used as solid fuel and ley was used for biogas production [7]

Crop	Harvested quantity (tonnes ha^{-1})[a]	Energy[b] (MWh ha^{-1})	Price[c] (€ tonne^{-1})[a]	Costs[c] (€ tonne^{-1})[a]	Costs[c] (€ MWh^{-1})[b]	Net gain[c] (€ ha^{-1})
Normal fields						
RCG	4.5	18	94.1	148.7	33.7	-202.1
Ley, round bales	4.0	10	119.4	225.0	90.0	-422.4
Ley, SCW, stored	4.0	10	119.4	226.6	90.7	-428.7
Ley, SCW, fresh	4.0	10	119.4	181.3	72.6	-247.7
Spring barley	2.2	9	171.3	343.9	88.9	-379.8
Fallow	-	-	-	-	-	-96.5
Small irregular-shaped fields						
RCG with N-fert.	4.1	16	94.1	180.0	40.9	-286.0
RCG without N-fert.	2.8	11	94.1	182.3	41.4	-205.8
Ley with N-fert., round bales	4.0	10	119.4	268.0	107.3	-594.6
Ley without N-fert., round bales	2.8	7	119.4	291.7	116.6	-482.2
Ley with N-fert., SCW, stored	4.0	10	119.4	288.4	115.4	-675.7
Ley without N-fert., SCW, stored	2.8	7	119.4	311.3	124.5	-537.4
Ley with N-fert., SCW, fresh	4.0	10	119.4	243.1	97.2	-494.6
Ley without N-fert., SCW, fresh	2.8	7	119.4	246.4	98.5	-355.7
Barley	2.2	9	171.3	473.0	122.2	-663.6
Fallow	-	-	-	-	-	-133.5
Fields with less fertile soils						
RCG with N-fert.	3.4	13	94.1	179.2	40.7	-236.3
RCG without N-fert.	2.4	9	94.1	188.6	42.9	-183.6
Ley with N-fert., round bales	3.0	8	119.4	273.8	109.6	-463.3
Ley without N-fert., round bales	2.1	5	119.4	310.8	124.3	-402.0
Ley with N-fert., SCW, stored	3.0	8	119.4	280.7	112.3	-483.8
Ley without N-fert., SCW, stored	2.1	5	119.4	315.6	126.3	-411.9
Ley with N-fert., SCW, fresh	3.0	8	119.4	235.4	94.2	-348.0
Ley without N-fert., SCW, fresh	2.1	5	119.4	270.3	108.1	-348.0
Barley	1.5	6	171.3	535.3	138.3	-560.5
Fallow	-	-	-	-	-	-110.3
Headlands						
RCG	2.2	9	94.1	205.7	46.7	-202.4
Ley, round bales	2.0	5	119.4	376.3	150.6	-503.5
Ley, SCW, stored	2.0	5	119.4	380.5	152.2	-511.6
Ley, SCW, fresh	2.0	5	119.4	335.2	134.1	-422.9
Spring barley	1.5	6	171.3	440.6	113.8	-414.6
Fallow	-	-	-	-	-	-105.3
Border strips						
RCG	2.7	11	94.1	183.6	41.7	-197.2
Ley, round bales	2.4	6	119.4	322.0	128.9	-482.2
Ley, SCW, stored	2.4	6	119.4	322.9	129.2	-484.4
Ley, SCW, fresh	2.4	6	119.4	277.7	111.1	-376.7
Spring barley	1.9	7	171.3	371.1	95.8	-373.5
Fallow	-	-	-	-	-	-102.9

[a] Tonnes of dry matter (DM) for RCG and ley, and tonnes of grain with a moisture content of 14% for wheat and barley.

[b] Refers to the net calorific value of RCG, winter wheat and spring barley, and of biogas (ley).

[c] € 1.00 = 9.63 SEK (2014-08-21).

S2.2. Cost distribution for different crops at Svalöv

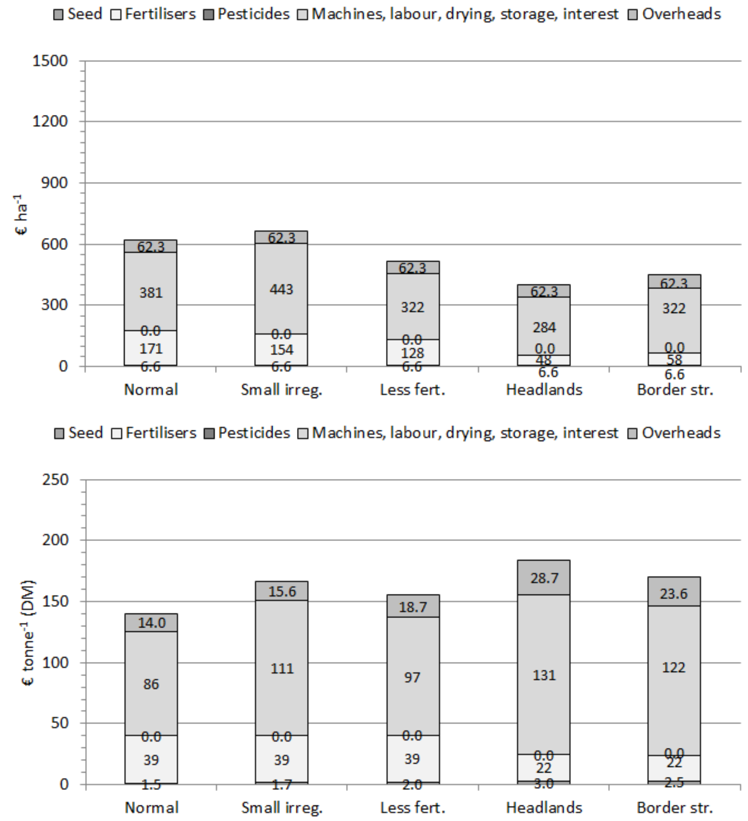

Fig. S12. Costs per hectare (upper) and per tonne dry matter (DM) (lower) for RCG at Svalöv [7].

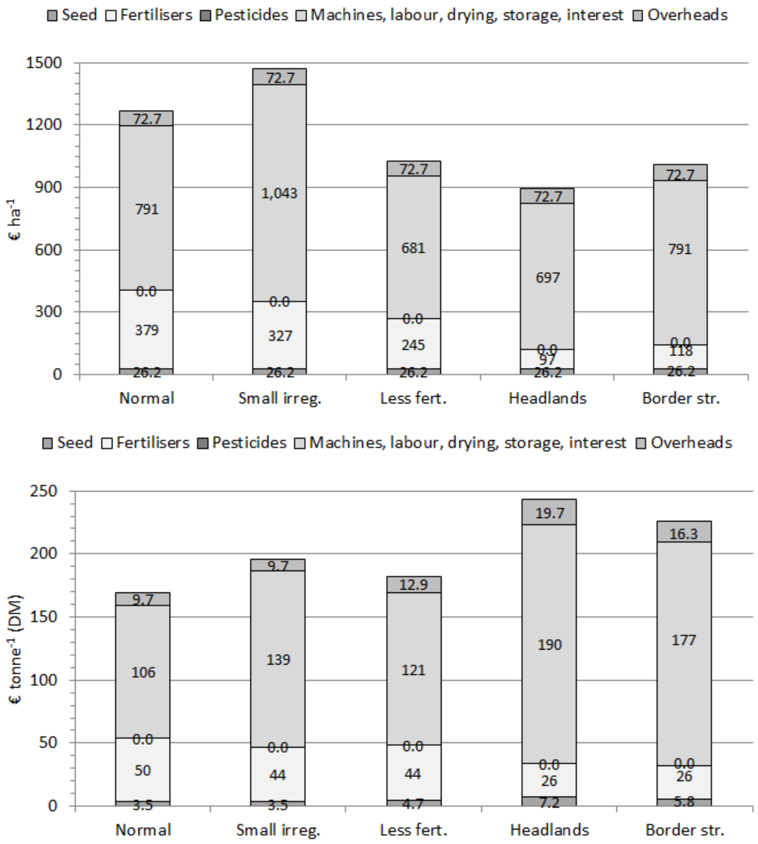

Fig. S13. Costs per hectare (upper) and per tonne dry matter (DM) (lower) for ley at Svalöv [7].

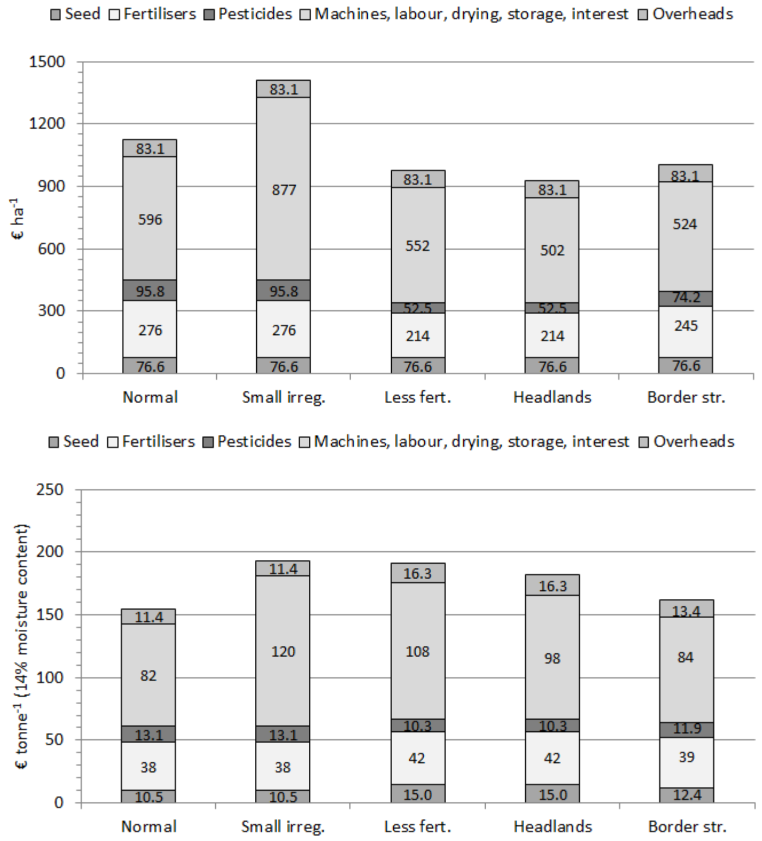

Fig. S14. Costs per hectare (upper) and per tonne (14% moisture content) (lower) for winter wheat at Svalöv [7].

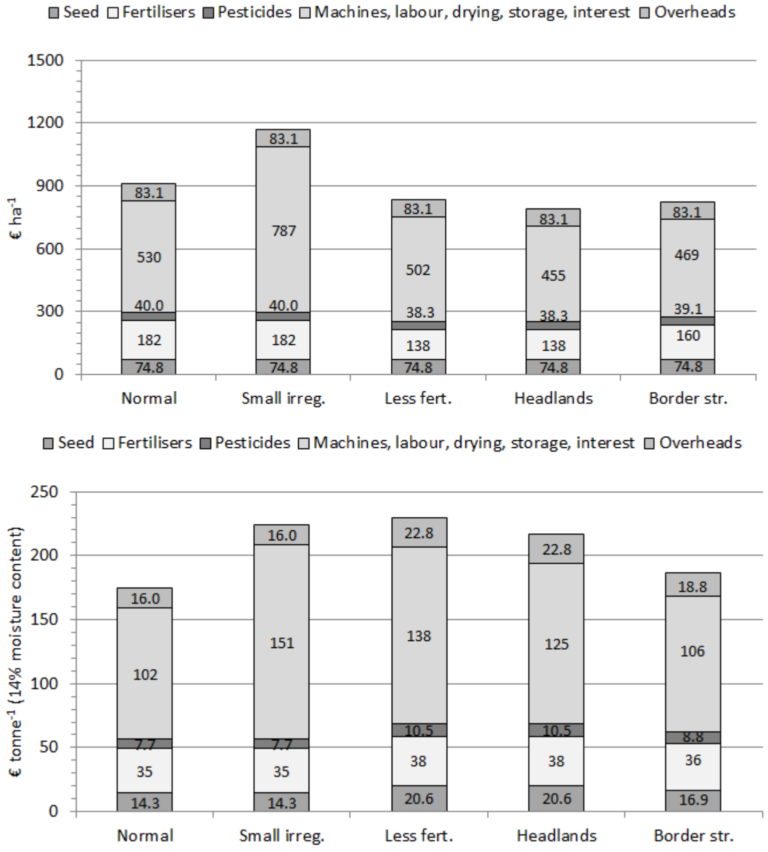

Fig. S15. Costs per hectare (upper) and per tonne (14% moisture content) (lower) for spring barley at Svalöv [7].

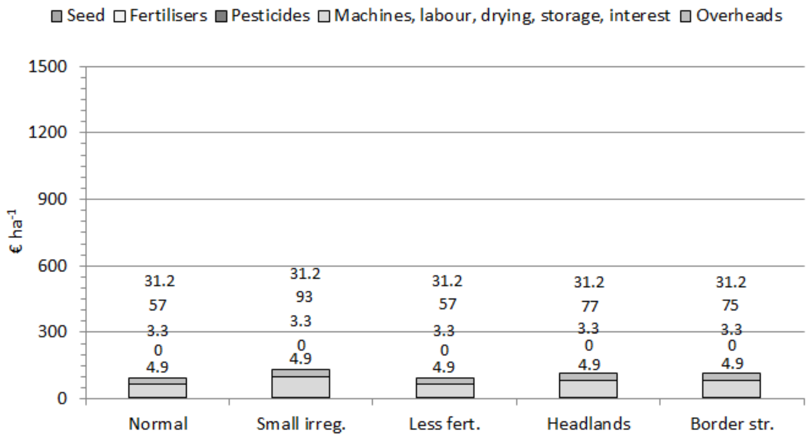

Fig. S16. Costs per hectare for fallow at Svalöv [7].

REFERENCES

[1] D. Nilsson, H. Rosenqvist, S. Bernesson, Tidsåtgång för maskinarbeten på små fält - en simuleringsstudie [Time demand for machine operations in small fields – a simulation study], Rapport 072, Dept of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala, Sweden, 2014 [in Swedish, with English summary]. Available at: http://pub.epsilon.slu.se/11860/11/nilsson_et_al_150206%20.pdf.

[2] I. Eriksson, G. Zetterberg, Fältmaskiner i jordbruket, LTs förlag, Stockholm, 1984 [in Swedish].

[3] D. Hunt, Farm power and machinery management, Iowa State University Press, 2001.

[4] B. Witney, Choosing and using farm machines, Land Technology Ltd, Edinburgh, 1995.

[5] FAT Berichte, Arbeitswirtschaftliche Kennzahlen zur Raufutterernte, Nr. 588/2002, Forschungsanstalt für Agrarwirtschaft und Landtechnik (FAT), Ettenhausen, Switzerland, 2002 [in German].

[6] Maskinkalkylgruppen, Maskinkostnader 2013, Hushållningssällskapen, Linköping, Sweden, 2013 [in Swedish].

[7] H. Rosenqvist, D. Nilsson, S. Bernesson, Kostnader och lönsamhet för odling av energigräs på marginell jordbruksmark [Costs and economic profiatbility of energy grass cultivation on marginal agricultural land], Rapport 073, Dept of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala, Sweden, 2014 [in Swedish, with English summary]. Available at: http://pub.epsilon.slu.se/11857/7/rosenqvist_h_etal_150206.pdf.