Timeliness Costs in Grain and Forage Production Systems

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Doctoral Thesis
Swedish University of Agricultural Sciences
Uppsala 2008

Acta Universitatis agriculturae Sueciae
2008:102

ISSN 1652-6880
ISBN 978-91-86195-35-9

Tryck: SLU Service/Repro, Uppsala 2008

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Abstract

With increasing prices for energy, fertiliser and feed concentrates, it is becoming increasingly important for farmers to produce high quality feed while minimising costs. For a Swedish farm, costs for machinery make up about 25% of the production costs. The economic consequences of performing a field operation at non-optimal time are called timeliness costs. They are caused by reductions in crop value and can be reduced by increasing machine capacity. To improve the basis for optimal selection of field machinery in agriculture, methods were developed and applied for calculation of timeliness costs in terms of crop quality and quantity losses at non-optimum operation times.

Timeliness costs for grain that accounted for crop quantity and quality losses at delayed sowing and harvesting were higher per kg for organic grain than for conventional. The main differences in timeliness costs resulted from two counteracting factors – lower yields and higher product prices in organic production. Higher timeliness costs resulted in a larger combine harvester with higher capacity being economically optimal for the organic system.

A method was developed for valuing forage for milk production with respect to crop yield increases and feed value decreases due to delayed time of harvesting. The results showed significantly higher timeliness cost factors in € per ha and day for the first cut compared with regrowth. Timeliness cost factors also varied greatly between years. Harvesting costs in terms of timeliness were calculated for different machinery systems and capacities. Harvesting costs decreased with increasing forage area up to a certain threshold area, beyond which decreasing machine costs were outweighed by increasing timeliness costs due to longer duration of harvest. Using machine contractors or machine cooperatives decreased harvesting costs, particularly for small forage areas, due to increased annual use of the machines. However, to avoid high timeliness costs delays in harvesting must be avoided.

Forage was also valued in terms of biogas production by accounting for changes in yield and methane production with varying cutting date. Timeliness costs were small as long as harvesting was not delayed. Matching capacity to requirements is important in avoiding costly overcapacity and minimising costs.

Keywords:, Crop valuation, machinery selection, harvest, quality, milk, biogas, organic production, annual variation, linear programming

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Till Stephan, Felix och Fredrik

Contents

List of Publications

This thesis is based on the work contained in the following papers, which are referred to in the text by their Roman numerals:

I Gunnarsson, C. & Hansson, P-A. (2004). Optimisation of field machinery for an arable farm converting to organic farming. *Agricultural Systems* 80, 85-103.

II Gunnarsson, C., Spörndly, R. & Hansson, P-A. (2005). Timeliness costs for silage harvest in conventional and organic milk production. *Biosystems Engineering* 92(3), 285-293.

III Gunnarsson, C., Vågström, L. & Hansson, P-A. (2008). Logistics for forage harvest to biogas production - Timeliness, capacities and costs in a Swedish case study. *Biomass and Bioenergy* 32, 1263-1273.

IV Gunnarsson, C., Spörndly, R., Rosenkvist, H., de Toro, A. & Hansson, P-A. (2008). A method to calculate timeliness costs in forage harvesting illustrated using harvesting systems in Sweden (submitted to Grass and Forage Science).

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The studies presented in Papers I-IV were planned by Gunnarsson and Hansson and carried out by Gunnarsson with input from the co-authors. In Papers II and IV Spörndly constructed the feed rations. Gunnarsson wrote Papers I-IV with comments from the co-authors.

Abbreviations

DM	Dry matter
ha	Hectare
FV	Forage value, € ha^{-1}
M	Yield, kg DM ha^{-1}
V	Feed value, € kg^{-1} DM
W	Harvested biomass, g m^{-2}
R_s	Relative growth rate, g g^{-1} day^{-1}
AGE	Age function
GI	Growth index
d	Timeliness cost before operation starts, € day^{-1}
l	Timeliness factor, kg ha^{-1} day^{-1}
p	Price, € kg^{-1}
A	Area, ha
n	Average number of days to perform an operation
k	Average area harvested per day, ha day^{-1}
S	Timeliness costs during the operation, €
B	Number of work hours per day
P	Workday probability
C	Capacity of the machine, ha h^{-1}
Z	Total machinery, labour and timeliness costs, € yr^{-1}
c	Annual cost for a machine, €
x	Binary decision variable
y	Continuous decision variable
D, **E**	Constraint matrices
b	Constraint vector
PCFT	Precision chop forage trailer
PCFH/T	Precision chop forage harvester with separate trailers
RBI	Round baler with integral wrapping

1 Introduction

1.1 Background

Increasing international competition is putting pressure on farming in Europe, including Sweden, to increase productivity and decrease production costs (Ekman & Gullstrand, 2006; SLF, 2006). For a Swedish farm producing cereals or milk, costs for machinery together with costs for fertilisers, seed and pesticides (requisites) make up a large part of the production costs (Fig. 1). Costs for purchased services such as machinery contractors are included in operating costs, a large item in Fig. 1.

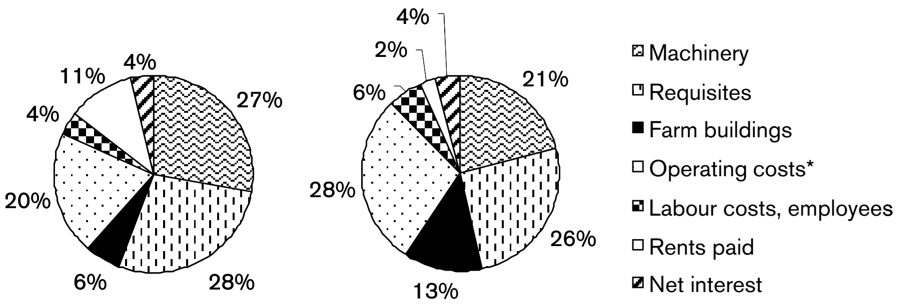

Figure 1. Costs for production of cereal (left) and milk (right) in Sweden according to statistical data from SCB (2008a). *Operating costs: electricity, insurance, leasing of equipment, purchased services such as machinery, veterinary etc.

Productivity can be increased by a structural change towards larger farming units, adoption of new technology and larger and more effectively used machinery for crop production (Kutzbach, 2000; Norell, 2007). Larger farming units are often created through cooperation between farmers, shared enterprises and hiring machine contractors instead of having in-house machines for field work (Norell, 2007). Machine cooperation can reduce mechanisation costs and also allows farmers to apply advanced technology and environmentally friendly production techniques (Camarena *et al.*, 2004; de Toro A. & Hansson, 2004).

The increasing price of energy in recent years has had direct effects on production costs in agriculture through increased prices for fuel and indirect effects through increased costs for manufacture of fertilisers and chemicals (Mitchell, 2008; Jordbruksverket, 2008b). According to Jordbruksverket (2008a), purchased feed makes up 20% of total costs on Swedish dairy farms. Since prices of feed and concentrates have also increased during the past year (Jordbruksverket, 2008b), it is becoming increasingly important for farmers to ensure production of high quality feed crops instead of having to buy concentrates.

In organic farming, regulations restrict the use of concentrates and purchased feed, and producing high quality feed is therefore particularly important (KRAV, 2008). Organic farming strives for high self-sufficiency of farms, using local and renewable sources for feed and nutrients (Cahlin *et al.*, 2008). Therefore, when converting to organic farming the farm system has to be restructured to replace external inputs such as chemical fertilisers and pesticides (Stockdale *et al.*, 2001). It has been reported that timing of operations is particularly important in organic farming systems (Stonehouse *et al.*, 1996). However although a great number of farms have converted, or are about to convert, to organic farming, there is limited knowledge of how the optimal machinery system for these farms is affected by conversion (Soerensen *et al.*, 2005).

1.2 Timeliness costs

When a field operation is performed there is normally an optimal time for this operation with respect to the value of the crop. If the operation is performed earlier or later, the value of the crop may decrease due to changes in quantity and/or quality (Fig. 2) (ASABE, 2006b). The economic consequences of performing a field operation at non-optimal time are called timeliness costs. If an operation starts after the optimal time, timeliness costs occur on the whole area before the operation starts and thereafter on a decreasing area depending on the capacity of the operation. Since these costs are partly dependent on planning and scheduling of the field operation and on machine capacity, they are also referred to as indirect machine costs. If timeliness costs are not considered there is a risk of overall costs and machinery capacity requirements being under-estimated. Timeliness costs are important to consider for efficient crop management and machinery selection, particularly for crop establishment, spraying, harvesting and soil compaction (Manby, 1984; Witney, 1995; Ekman, 2000; Stockdale *et al.*, 2001; ASABE, 2006b; Chapman *et al.*, 2008). Significant timeliness costs can occur in regions with short periods available for sowing and harvesting, and since they are affected by the weather such costs are specific for regions and are subject to annual variations (de Toro A., 2004).

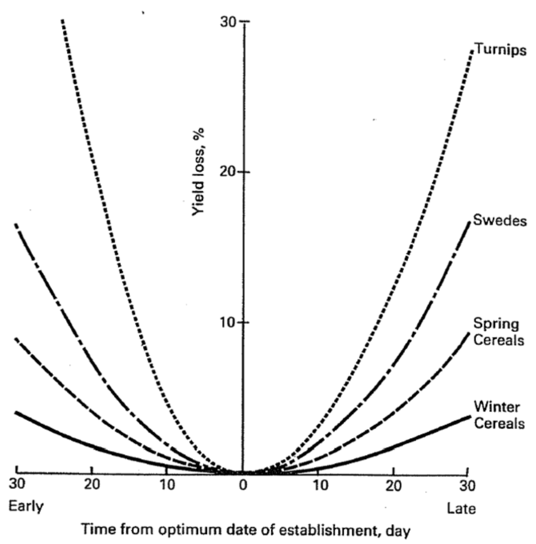

Figure 2. Yield losses as a function of time of crop establishment (Witney, 1995).

To achieve satisfactory accuracy, particularly in forage production, it is necessary to calculate timeliness losses in terms of changes in both quantity and quality, since in addition to yield changes, quality parameters such as the nutrient content change with time of harvest and affect the feed value and price of the crop (Witney, 1995). Timing of harvest has an impact on the nutritional value, voluntary intake and milk yield potential of the forage (Bertilsson & Burstedt, 1983; Rinne *et al.*, 1999; Bernes *et al.*, 2008). However, few data are available on timeliness losses due to quality, while timeliness costs, especially for grain production, are often based only on yield decreases (Axenbom *et al.*, 1988; Sörkvist *et al.*, 2000; de Toro, 2005). ASABE (2006b) cites timeliness coefficients expressing the change in crop return for sowing and harvesting for different states in the USA.

Timeliness costs for a specific area or operation are normally calculated using timeliness factors expressing the loss for each day's delay of an operation. Furthermore, timeliness costs are dependent on farm-specific parameters influencing the length of the operation, such as transport distances, labour availability and length of working day. Delays due to weather conditions also affect the length of the operation. When calculating machine capacity, the actual time spent carrying out the operation as well as the time spent on non-productive activities such as turning and adjustment need to be considered (Soerensen, 2003).

Srivastava *et al.* (2006) mention increasing machine capacity as one way to decrease timeliness costs, as larger machines with greater capacity can accomplish more timely work. In addition, optimal work organisation and machinery utilisation are important in achieving cost reductions (Soerensen, 2003). Another way to decrease timeliness losses is to plant different crops or varieties with different dates of maturation (Nilsson, 1987).

When planning an operation, two alternatives exist for when to start, referred to as balanced and delayed scheduling, illustrated in Fig. 3. By starting the operation before the optimum time, timeliness losses can be reduced compared with the losses at delayed scheduling (see the marked area in Fig. 3). Given an optimum sowing date, the sowing period can normally be balanced around this optimum date (Srivastava *et al.*, 2006). On the other hand, in some areas excessive moisture content in the soil prevents spring sowing operations from starting before the optimum time and consequently the fields are sown as they dry (de Toro A. & Hansson, 2004). For most harvesting operations, it is not feasible to begin harvesting until the crop is mature (Srivastava *et al.*, 2006).

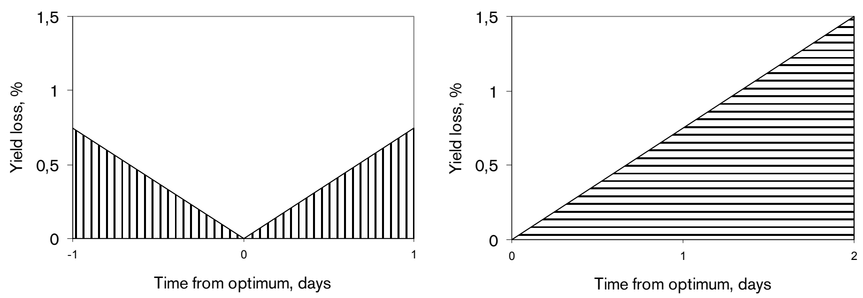

Figure 3. Illustration of balanced (left) and delayed (right) scheduling.

When farmers have to invest in new machinery, they have the choice of buying in-house machines or using contractors or machine cooperatives. Timeliness costs are important in this decision. One common perception about contractor work or machine cooperatives is that the operation may not start on the optimal day, leading to increased timeliness losses, especially during seasons with difficult weather conditions (de Toro & Hansson, 2004; Wilkinson, 2005). On the other hand, machine capacity may be higher due to larger machines being viable for contractors and cooperatives.

1.3 Crop valuation

To calculate timeliness factors, knowledge of how the value of the crop changes with the time of performing the operation is required (Schneeberger & Bär, 1997). Timeliness factors are calculated by determining the value of the crop at different times of performing an operation. Therefore parameters that change with time of the operation and that influence the value of the crop need to be explored.

For a cash crop such as grain, which is a common commodity sold on a market, the value is easy to decide and depends on whether the crop is used for human consumption, feed or other purposes. Estimating the value of forage is more difficult, as it is commonly used within the farm and its value is very dependent on its quality and end-use (Witney, 1995; Doyle & Topp, 2004).

Another difference between harvest of forage and grain is that when the harvest is delayed the forage yield increases, whereas the grain yield is not affected or may decrease to the extent that grain is lost through shed seed. Another complication that needs to be accounted for when valuing forage is that in contrast to grain, it is harvested repeatedly during the growing season. The time of the first cut has implications not only on the yield and nutrient concentration of that cut but also on those of the following cuts.

When forage is used for methane production, the value of the crop change. Although the biogas yield per kg dry matter (DM) decreases when harvest is delayed, the increased yield contributes to greater total biogas production. In contrast, in milk production late-harvested forage with lower nutrient content must be supplemented by feeding grain or concentrates, giving rise to higher feed costs and possibly lower milk yield, which has a negative influence on the overall value of the forage (Witney, 1995).

1.4 Machinery systems in crop production

1.4.1 Grain production

During 2007, 32% of the agricultural land in Sweden was used for cereal production and 37% for forage and green fodder. Of the remaining land, 16% was used for grazing and 9% was set-aside (SCB, 2008a). The agricultural area being used for grain production is increasing in Sweden and in the rest of the world (FAO, 2008; SCB, 2008b). Wheat and barley are the most commonly grown crops in Sweden, followed by oats (SCB, 2008a). In 2006, 4% of the cereals produced in Sweden were organically grown (SCB, 2007).

Grain is usually cultivated using a tillage system including mouldboard ploughing and harrowing before drilling (Ekman, 2000), but replacing the mouldboard plough with alternative tillage systems is reported to be economically beneficial due to lower operating costs (Sijtsma *et al.*, 1998). The generally low product prices until recently (de Toro A., 2004) combined with increased costs for fertilisers, fuel and machinery have resulted in increased interest in reduced tillage practices and machines that perform a combination of operations (Lexmon & Andersson, 1998; Soerensen & Nielsen, 2005). However, during the last two years (July 2006-July 2008), cereal prices in Sweden have increased by about 70% (Jordbruksverket, 2008b) but the price of fertilisers has also increased so the focus is now on measures to increase yield and maximise fertiliser use, *e.g.* precision fertilisation (Halldorf, 2007).

1.4.2 Forage production

According to SCB (2008b), the area used for growing forage and green fodder is currently increasing in Sweden. In 2006 almost 27% of the total amount of forage harvested in Sweden was organically produced (SCB, 2007). Most forage is used for feeding animals but with the growing interest in producing bioenergy from field crops, forage is also used for biogas production. One of the first attempts in Sweden to use forage for biogas production on a large scale was within the Växtkraft project in Västerås (see Paper III).

In forage production, harvesting technique is important in achieving high fodder quality and low levels of nutrient and DM losses (Neuman, 2002). The clover content in the forage is often higher in organic production than in conventional. This leads to increased demand on the harvesting machinery to minimise losses of DM and nutrients since the thin clover leaves dry faster than the stems, become brittle and fall off during handling (Weinberg & Ashbell, 2003). Since field losses are usually lower for conservation as silage compared with hay (Lingvall & Spörndly, 1996), ensiling is more suitable for forages containing clover and other legumes.

Forage is normally preserved as hay or silage, with hay-making restricted to crops that can dry quickly and to areas with little or no rainfall during harvest (Weinberg & Ashbell, 2003). A number of harvesting and machinery systems exist for forage, each placing different demands on machinery, labour, logistics and management. Silage is preserved in clamps, bunker silos, tower silos, plastic bags/sleeves or round/square bales (Weinberg & Ashbell, 2003; Orosz *et al.*, 2008).

Forage harvesting includes mowing the crop, wilting in the field, harvesting and transport to storage. The length of the wilting period depends on the conservation method and the climate (Weinberg & Ashbell, 2003). In baled silage the herbage is generally unchopped, compared with a particle length of approximately 5-20 cm when using a forage harvester (McEniry *et al.*, 2007). Mowers and forage harvesters can be tractor-mounted, trailed or self-propelled (Weinberg & Ashbell, 2003; Forristal & O´Kiely, 2005). In continuous harvesting systems using *e.g.* a forage harvester, forage collection in the field, transport and ensiling must follow in direct conjunction with each other, whereas with a round baler, harvesting in the field and transport can be separated in time (Schick & Stark, 2002). Continuous systems generally place higher demands on labour and planning of harvesting to match capacity and avoid costly delays and waiting times (Schick & Stark, 2002). Because contractors typically prefer continuous harvesting systems, the use of the forage wagon has been in decline (Forristal & O´Kiely, 2005). According to Wilkinson (2005), baled silage is one of the most popular systems on farms, accounting for about 25% of total silage production in Europe.

1.5 Field machinery models

In general, two main modelling approaches are available for selection or estimation of machinery capacity and costs; static models based on mathematical programming and dynamic models based on simulation techniques (de Toro A., 2004). A wide range of models for calculating machinery costs exist, varying in range from specifically studying the field machinery on a single farm up to covering machinery cooperation for an entire region (Klein & Narayanan, 1992; Higgins *et al.*, 1998; Ekman, 2000; de Toro & Hansson, 2004).

Models based on mathematical programming typically solve a problem, *i.e.* maximise or minimise a function while other constraints are satisfied. They are generally based on linear, integer or mixed integer programming (MIP). Weather uncertainties are generally accounted for using a workday probability and the result is an optimal set of machinery for an average season (de Toro A., 2004). When using a MIP model, each machine included in the model can be defined with specific data for price, size and capacity. An example of an applied mathematical model is the farm level model presented by Ramsden *et al.* (1999), which uses linear programming to establish optimum utilisation of machinery and labour depending on the time available for field operations. Soegaard & Soerensen (2004) developed a non-linear programming model specifically for optimisation of machinery size but also intended for use as part of a whole-farm planning model. In the study presented in Paper I, a MIP model developed by Nilsson (1976) was used for selecting the size of the seed drill and combine harvester that minimised annual costs including timeliness. Camarena *et al.* (2004) presented a MIP model for multi-farm use of machinery that selects the machinery sets used in a shared form on a number of farms corresponding to the lowest mechanisation costs. Mapemba *et al.* (2008) used a MIP model to determine the least-cost harvest and delivery system for plant biomass on a large scale.

In dynamic models, techniques such as discrete event simulation are used to simulate operations day-by-day. Because the effects of parameter variations such as weather are better accounted for in discrete event simulation models, they are a good complement to static models to test the feasibility of the solutions obtained (de Toro A., 2004). Furthermore, work organisation, resource matching and stochastic events can easily be examined using dynamic models. De Toro & Hansson (2004) used discrete event simulation to study the daily field operations for grain production on a farm during a number of years. Discrete event simulation has also been used to analyse a harvesting and transport system for sugarcane (Arjona *et al.*, 2001). Nilsson (1999) developed a model studying a straw fuel delivery system and consisting of a dynamic simulation part for analysis of the systems performance and a static part for cost and energy analysis.

2 Objectives

The general objective of this thesis work was to develop and apply methods for calculation of timeliness costs in terms of quality and quantity losses of the crop at non-optimal time of the operation, with the overall aim of improving the basis for optimal selection of field machinery in agriculture.

More specific objectives were:

- To develop timeliness factors valid for calculating timeliness costs for organic farming and to examine how the optimal machinery system is affected when an arable farm converts to organic farming (Paper I).
- To value forage for calculation of timeliness costs associated with harvesting of forage for milk production and to analyse factors influencing the timeliness costs (Paper II).
- To value forage used for biogas production, and to examine how the resulting timeliness costs vary with varying harvesting capacity and harvesting time (Paper III).
- To develop a method to calculate timeliness cost factors by valuing forage in terms of changes in yield and feed value with delayed harvesting, to examine annual variations in timeliness losses and to investigate the effect of considering timeliness on different harvesting systems and sizes (Paper IV).

3 Scope of the work

The thesis is based on Papers I-IV, which are briefly described below. Figure 4 illustrates how the papers are connected to each other.

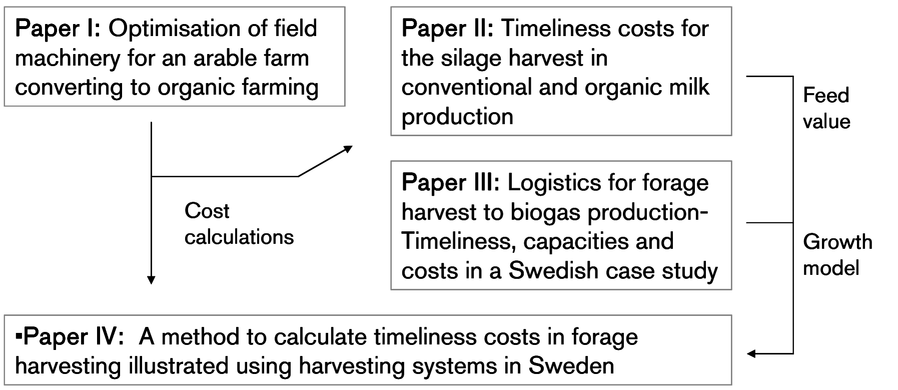

Figure 4. Papers included in the thesis and how they are connected to each other.

As an introduction to the project, the first study (Paper I) concentrated on the machinery system and costs for an arable farm before and after conversion to organic farming. An initial field study was carried out to organic arable farms in the Uppsala area (central Sweden) and timeliness factors accounting for quantity and quality losses were developed. In addition, timeliness factors valid for organic production were calculated based on differences in crop value and cultivation conditions. All field operations carried out on the crop were investigated using an optimisation model based on mixed integer programming. The machine capacity for sowing and harvesting that minimised the machine costs for an arable farm in central Sweden was determined.

Papers II, III and IV concentrated on valuation of forage for calculation of timeliness costs in forage harvesting and the effect on the machinery system when timeliness costs were taken into account. In the study presented in Paper II, timeliness factors were calculated for two harvests per season in conventional and organic production. Machine, labour and timeliness costs were then calculated for a typical dairy farm in the Uppsala area harvesting silage for 60 cows using a precision chop forage trailer. Factors influencing the capacity at harvest, such as labour availability and transport distance, were analysed.

Paper III analysed how timeliness losses were affected when the forage was used for biogas production instead of milk production. The value of the forage was determined by the amount of methane produced, which was dependent on the quality of the forage and the yield. Harvesting costs were calculated for an existing system harvesting approximately 300 ha forage for a full-scale biogas plant in Västerås in Sweden. The focus of this study was on how costs could be reduced by matching harvest and transport capacities when machine contractors harvested the forage with a self-propelled precision chopper and trucks with trailers for transport of the forage to the biogas plant.

The study presented in Paper IV examined the timeliness costs for forage harvest in a more detailed way covering three harvests per season, varying harvest systems, annual variations and two geographical locations. Building on experiences from the previous papers, a method was developed to calculate timeliness cost factors with respect to quality and quantity for forage harvest. The value of the forage in terms of the quality was calculated following the method developed in Paper II. The forage yield was calculated using a forage growth model based on daily weather parameters as used in Paper III. The result of the valuation was timeliness cost factors expressing quantity and quality losses in economic terms as € per ha and day. Timeliness cost factors were calculated for ten subsequent years using daily weather data for calculation of forage growth. Harvesting costs were then calculated for different sizes of harvest machine chain and for different harvest systems by varying forage area and transport distance. The effect on costs of hiring contractors for the harvest was also investigated.

4 Methods

The aim of this project was to develop methods to calculate timeliness factors by valuing crops with respect to quality and quantity losses. Knowing the timeliness factors, timeliness costs were calculated for specific farms or areas depending on farm-specific parameters influencing the capacity of operations, *e.g.* machines used, length of working day, transport distance, *etc.*

4.1 Calculation of timeliness factors

Timeliness losses due to yield losses are typically expressed as timeliness factors for quantity reduction, in kg ha^{-1} day^{-1}. The timeliness cost factors presented in Paper IV expressed the combined quality and quantity reductions occurring due to delayed operations in economic terms, in € ha^{-1} day^{-1}.

In Papers I and II, the quality losses were expressed in kg ha^{-1} day^{-1} as the economic value of the quality loss was expressed as a crop quantity. These timeliness factors expressed in kg ha^{-1} day^{-1} were also divided by the yield and thus presented as percentage yield loss per day (day^{-1}). This allowed timeliness factors for fields with different yields to be compared.

4.1.1 Valuation of grain crops

Timeliness factors considering quantity losses as a function of time of sowing or harvesting were modified to also consider costs due to quality decreases. Timeliness factors for wheat due to quality at harvesting were developed by considering the price difference between grain for human consumption and for animal feed. Wheat for human consumption commands a higher price than wheat for animal feed, with the protein content and falling number being used to separate the two qualities. The correlation between falling number and time of harvest was identified from field trials.

Timeliness factors for late sowing in organic production were developed from the increased risk of yield losses at delayed sowing. In conventional farming, pests are normally treated with pesticides, whereas no such effective method exists for controlling pests in organic farming. If sowing is delayed in spring, there is a higher risk of pest attacks when the crop is at a sensitive stage. The potential yield losses due to pest attacks at normal and delayed sowing time were estimated (Sigvald *et al.*, 2001).

4.1.2 Valuation of forage for milk production

When forage harvest is delayed, the feed value of forage is affected through DM yield increasing and nutrient concentration decreasing with time (Witney, 1995). The fact that the yield of the first cut affects the second cut was accounted for in Paper II by the assumption that the increased yield occurring when the first cut was delayed resulted in a corresponding decrease in yield of the second cut, the total annual yield being constant. A study by Hall *et al.* (2005) concluded that for a mixture of early, medium and late-heading cultivars of timothy, the total DM yield is not influenced by the initial harvest date. Statistical yield data were used, with 60% of the annual yield in the first of the two cuts per season.

The feed value of the forage at two cutting dates was calculated from the nutrient concentration (content of energy and protein) by making complete rations with forage and concentrates and considering fodder costs and milk yield. The additional yield of lower quality forage at the later cutting date was assumed to have no alternative value and was therefore not included in the valuation.

In Paper IV, timeliness losses at forage harvest were studied in a more detailed way. This study included three cuts per season and the effect of the increased yield at the later cutting date was accounted for in a more accurate way by using the forage growth model employed previously in the study of forage for biogas production (Paper III).

A model was constructed that calculated the forage value for different cutting dates for each cut. The model consisted of two parts, one that calculated the DM production of grass-clover forage at different cutting dates using a forage production model, and another that estimated the change in feed value of forage harvested on different dates. Using the growth model enabled the increasing yield at later cutting dates to be assigned a feed value relating to its nutrient content. The feed value was calculated in the same manner as in Paper II. By multiplying the yield by the feed value, the forage value in € per ha was calculated for different days in the harvest period.

An optimisation was made to find the cutting dates for each cut that resulted in maximum total value of the forage from all three cuts. The objective function describing the total forage value (FV_{tot}) of the three cuts was described as:

$$FV_{tot} = M1 \times V1 + M2 \times V2 + M3 \times V3 \quad (1)$$

where M denotes the yield in kg DM ha^{-1}, V denotes the feed value of the forage in € kg^{-1} DM, and the numbers 1, 2 and 3 denote first, second and third cut. The optimal forage harvest time was determined by finding the dates for each cut that maximised the total forage value (in € ha^{-1}) of all cuts. This was done for different cutting days of each cut by finding the cutting dates of the following cut/s that resulted in the highest total forage value. In this way, account was taken of the fact that delays in a cut also affected the following cuts. When the dates of the second and third cuts were optimised, it was assumed that the preceding cut/s occurred on the optimal day.

For each cut, the cutting day resulting in maximum forage value (FV_{tot}) was set as the optimal day for harvest. This value was compared with the total forage value a number of days later, allowing timeliness cost factors to be calculated based on the difference in value between these two dates. A linear decrease in value of the harvest was assumed between the cutting dates, *i.e.* timeliness cost factors were assumed to be linear. To examine annual variations, the calculations were repeated with weather data for 10 years.

Feed value

The feed value of the forage was calculated by making complete rations with forage and concentrates and considering fodder costs and milk yield, using a method developed in Paper II:

1. Regression analyses of field experiments were used to calculate cutting date and protein content relating to two specified energy contents of the forage.
2. By setting a relevant monetary value (feed value) on the early harvested forage in the first cut, the feed value of the forage harvested later was calculated. By using the same price for milk and for all feeds except the forage and by setting the same value on the total sum of milk income minus total fodder costs for each ration, the feed value of each forage was calculated.

3. The daily change in feed value was calculated from the difference in feed value between the two forage qualities in each cut and the number of days between the two cutting dates.

The forage growth model

The forage DM yield at different cutting dates was calculated using a growth model developed by Torssell and Kornher (1983) and Torssell *et al.* (1982) requiring daily weather data as input and a set of model parameters specific for the sward and site.

Daily increase in DM yield was calculated as the product of the current amount of biomass and the relative growth rate R_s. The model can be summed up by Eqn. 2 where W (g m^{-2}) describes the harvested biomass. R_s (g g^{-1} day^{-1}) was modified by a growth index (GI) and an age function (AGE). GI summarised the effects on plant growth of temperature, radiation and plant-available soil water, while the AGE function accounted for the impact of crop ageing, quantified as a function of the leaf area index (LAI).

$$W_t = W_{(t-1)} + W_{(t-1)} \times R_s \times AGE \times GI \qquad (2)$$

The initial amount of biomass and the initial R_s at the start of each growth period accounted for the influence of botanical composition and management practices such as nitrogen fertilisation, number of cuts per season and geographical location. The initial values of R_s and the initial amount of biomass were taken from Fagerberg *et al.* (1990).

4.1.3 Valuation of forage for biogas production

Paper III presented timeliness costs for forage harvest when the forage was used for production of biogas. The value of the forage was decided by accounting for the biogas production per kg forage and the yield. Hence, finding the optimal time for harvest meant finding the maximum value of the forage considering both the methane yield per kg DM decreasing with time and the yield increasing with time. The forage value per ha was calculated as the yield (kg DM ha^{-1}) multiplied with the feed value (methane value, € kg^{-1} DM), summed up for both cuts.

The DM yield was calculated using the forage growth model described in Eqn. 2. The yield calculations were repeated using weather data for 15 years and the average yield was then used in the calculations of the forage value. The methane yield was calculated from the forage content of crude protein, crude fat, crude fibre and nitrogen-free extracts using an equation derived by Amon *et al.* (2003). The content of the forage deciding the methane yield came from trials by Kivimäe (1959). The feed value per kg DM was calculated from the methane yield, the energy content of the methane and the price of methane.

4.2 Calculation of timeliness costs

In Papers I, II and IV, timeliness costs were calculated following a method developed by Nilsson (1976) and used in the mixed integer programming (MIP) model for optimisation of machinery costs in Paper I. Timeliness costs in € per day before the operation started were calculated using Eqn. 3:

$$d_i = l_i \times p_i \times A_i \tag{3}$$

where l_i is the timeliness factor in kg ha^{-1} day^{-1} for crop i, p_i is the price in € kg^{-1} of the crop involved and A_i is the total area in ha of the crop grown.

Timeliness costs during the operation were calculated differently depending on delayed or balanced scheduling. For delayed scheduling when the operation starts at the optimal time, the timeliness cost *S* (in €) was calculated using Eqn. 4 and summarised for each crop *i* handled with the machine where *m* is the number of crops grown.

$$S = \sum_{i=1}^{m} \left(\frac{n_i - 1}{2} \right) \times k_i \times p_i \times l_i \times n_i \tag{4}$$

where n_i is the average number of days available to perform the operation (including days that are not workable) on crop *i* and k_i is the average area in ha of crop *i* harvested per day. The parameter n_i is calculated by:

$$n_i = \frac{A_i}{B \cdot P \cdot C} \tag{5}$$

where B is the number of work hours per day, P is the workday probability (%) and C is the capacity of the machine (ha h^{-1}).

For balanced scheduling, when the operation starts before the optimal time and the timeliness losses are divided on both sides of the optimum, the timeliness costs (in €) were calculated according to Eqn. 6:

$$S = \sum_{i=1}^{m} \left(\frac{n_i}{2} - 1 \right) \times k_i \times p_i \times l_i \times n_i \times 0.5 \tag{6}$$

When calculating timeliness costs during the operation (Eqns. 4-6) the duration of the operation was prolonged according to the workday probability, *i.e.* the probability that sowing or harvesting can be performed on a certain day in the period for performing the operation with respect to the weather.

The workday probability for sowing and harvesting of grain presented in Paper I was decided with regard to soil property parameters calculated with a soil model described in de Toro & Hansson (2004). For harvest of forage, the workday probability was decided from weather data and varied depending on the desired DM content of forage for a specific cut and conservation system. The desired DM content influences the time needed for drying the forage in the field, with higher DM content resulting in shorter available harvesting period (Venturi *et al.*, 1998). Since the weather and therefore also the number of workable days varies between years, the calculation of the workday probability was repeated for a number of years and average probability values were used.

In Paper IV, when the timeliness loss was expressed in economic terms as a timeliness cost factor, the product of parameters l_i (in kg ha^{-1} day^{-1}) and p_i (the price in € kg^{-1}) in Eqn. 3,4 and 6 was replaced by the timeliness cost factor in € ha^{-1} day^{-1}.

In Paper I, timeliness costs for sowing in the spring were calculated assuming delayed scheduling, since it is not possible to start before the optimal time due to excessive moisture content in the soil. Timeliness costs for sowing in the autumn and grain harvesting were calculated using balanced scheduling. For the harvest of forage for milk production, timeliness costs were calculated using delayed scheduling where harvesting was assumed to start on the day when the specified quality was reached. It was assumed that due to excessively low structural effect of the fibre and excessively high protein concentration in the forage, harvesting did not start before the optimal day.

Timeliness costs for harvesting of forage for biogas production (Paper III) were calculated as the difference in forage value between when all forage was assumed to be harvested at maximum forage value per ha and the forage value using a specific harvesting capacity. The forage value per ha was calculated for every field harvested, and the starting date of both cuts was optimised for all fields with the aim of maximising the total forage value.

4.3 Machinery optimisation

The analysis of the machinery costs and capacities presented in Paper I was carried out using the MIP model developed by Nilsson (1976) that selected the machinery capacity by minimising the machinery, labour and timeliness costs.

The size of the seed drill and the combine harvester was optimised to minimise the total cost by including machines of varying sizes and letting an algorithm choose the machine size resulting in the lowest costs. The objective function Z to be minimised included the average annual machinery, labour and timeliness costs and was defined by:

$$Z = \mathbf{cx} + \mathbf{dy} \quad \mathbf{x} = \left[x_1 x_2 \ldots x_n\right] \quad \mathbf{y} = \left[y_1 y_2 \ldots y_j\right] \tag{7}$$

where **x** is a vector with binary decision variables indicating whether a machine is included in the studied solution (x_i=1) or not (x_i=0), and *n* is the number of machines to choose among for the optimal solution. The **y** vector contains continuous decision variables, defined for each crop, indicating the delay of sowing and harvesting dates compared with the optimal dates for each crop and *j* is the total number of such events. The **c** vector defines the annual costs, including labour and the part of the timeliness costs depending on the machine capacity (Eqn. 4 or 6), in € for each machine if included in the optimal solution. The **d** vector defines the timeliness costs in € day^{-1} for each day's delay in either sowing or harvesting date.

Constraints for the optimal solution were then defined in the form:

$$\mathbf{Dx} + \mathbf{Ey} \leq \mathbf{b} \tag{8}$$

where the values in **D** and **E** (constraint matrices) and **b** (vector) were decided by constraints ensuring for example that at least one seed drill was included in the optimal solution. Another type of restriction comprised the time and timeliness restrictions ensuring that the farming operations were done in the correct order and with delays that were as small as possible for the machine set studied. The definition of the constraints is described in greater detail in Paper I.

4.4 Machinery cost calculations

Machine costs were calculated for using in-house machines and for contracting machine operations. The studies presented in Papers I and II calculated costs using in-house machines, whereas the harvest costs presented in Paper III were calculated for forage harvest to biogas using machine contractors. For the harvesting systems studied in Paper IV, cost calculations were made both for in-house machines and for hiring contractors. When harvest costs using contractors were calculated, a cost per hour or ha including driver and fuel was used.

Machine costs were calculated according to ASABE (2006a) and (2006b) and included costs for depreciation, capital interest, maintenance, tax and insurance, shelter and fuel.

- Machine depreciation was calculated using the straight line method by dividing the difference between the sales price and the salvage value by the estimated life, or for shorter annual use by the economic lifetime times the annual use. The salvage value was calculated depending on the economic life and the annual use of the machine.
- Capital interest was real (nominal inflation) and was calculated on the average value of the sales price and the salvage value.
- Maintenance costs were calculated based on factors of total repair and maintenance costs from ASABE (2006b) and adjusted if total use was shorter than the physical life of the machine.
- Tax and insurance costs were calculated as part of the sales price; for tractors 0.3%, for combine harvesters 0.2% and for other machines/implements 0.1%.
- Shelter costs were calculated per area required for the particular machine.
- Fuel consumption costs were calculated based on values from Danfors (1989) or for forage harvesters with consideration of the forage yield and cutting length.

The capacity for performance of the operations was calculated from the capacity of the machine working in the swath by considering the field efficiency. A field efficiency factor from ASABE (2006b) was used to account for time when the machine was performing productive work such as overlapping, turnings, interruptions for adjustments and maintenance and personal time. The capacity of the machine in the swath was decided from the working width, the speed and the yield. The speed was adjusted to avoid the theoretical capacity of the machine being exceeded.

In Paper III, the costs and capacities were calculated for harvest of a number of existing fields of varying sizes, shapes and transport distances from the biogas plant. In addition to adapting the harvesting capacity to time for unproductive work, the capacity and the time required for harvest of each field was calculated with adjustments for field size and shape. The time needed to transport the forage from each field to storage was calculated from the real transport distance. The capacity of the harvest then depended on whether the capacity of the harvester or the transport limited the operation.

5 Results and discussion

5.1 Timeliness and machinery costs in grain production (Paper I)

Timeliness factors accounting for quantity losses were adjusted for late sowing in organic production and for quality losses at harvesting according to Table 1. The resulting timeliness factors (see Sowing total and Harvesting total rows in Table 1) were used in the cost calculations. Higher prices in organic production and larger price differences between wheat for human and animal consumption resulted in higher timeliness factors for quality at harvesting compared with wheat in conventional production.

Table 1. *Timeliness factors for organic and conventional production expressed as percentage loss per day (day^{-1}) and as kg ha^{-1} day^{-1} for quantity losses, for adjustment made for sowing in organic production and for quality at harvesting, and total for sowing and harvesting*

Timeliness factors	Oats	Barley	Winter wheat	Winter wheat	Spring wheat
	Organic	Conv.	Organic	Conv.	Organic
Sowing, quantity, (day^{-1})	0.007	0.010	0.011	0.011	0.013
Sowing organic (day^{-1})	0.0018	–	–	–	0.0021
Sowing total (day^{-1})	0.009	0.01	0.011	0.011	0.015
Sowing total (kg ha^{-1} day^{-1})	23	40	44	55	59
Harvesting, quantity, (day^{-1})	0.019	0.019	0.009	0.009	0.017
Harvesting, quality, (day^{-1})	–	–	0.0039	0.0014	0.0092
Harvesting total (day^{-1})	0.019	0.019	0.013	0.010	0.026
Harvesting total (kg ha^{-1} day^{-1})	48	76	52	50	78

The timeliness factors were then applied to a hypothetical 120 ha arable farm to calculate costs for all operations performed on the crops from spring to autumn. Since one operation sometimes delayed the next operation, timeliness costs were calculated both before the operation started (Eqn. 3) and during the operation (Eqns. 4, 6). The annual machinery, labour and timeliness costs for the entire farm were higher in conventional production. However, when expressed per ha or kg grain grown, costs were higher in organic production due to lower yields and smaller area used for grain (Fig. 5). Timeliness costs were the same size as labour costs.

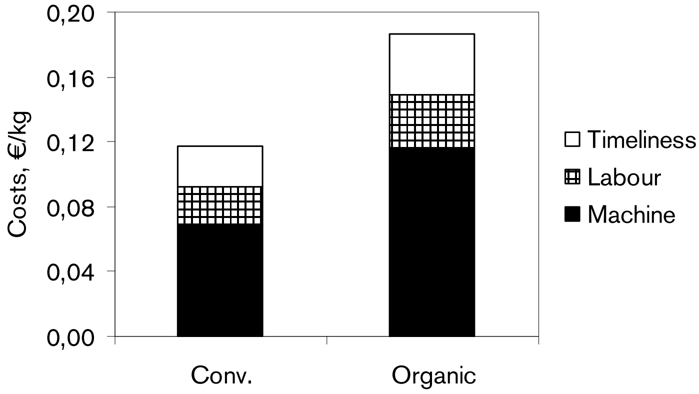

Figure 5. Machine, labour and timeliness costs per kg grain for conventionally and organically grown grain.

The majority of timeliness costs were caused by delays in the start of sowing or harvesting, with only a smaller proportion arising during sowing or harvesting. Compared with organic production, conventional production had higher timeliness costs for sowing of winter wheat. This could be explained by the larger acreage of winter wheat in conventional production. In contrast, timeliness costs for harvesting in organic production were higher than in conventional production due to several crops with similar optimal harvest dates, leading to delays.

In the results presented in Paper I, a small error was later detected in calculation of the average area harvested per day (k) when calculating timeliness costs during the operation. This means that the results for optimisation presented in Paper I should be somewhat adjusted. However, since the majority of the timeliness costs resulted from delays to the start of sowing or harvesting, the effect on the resulting total costs (Fig. 5) was less than 1%. The machine optimisation showed that the optimum size of combine harvester (that which minimised costs) was larger for organic production, although the cultivated area was smaller in organic production due to cultivation of green manure. The timeliness factors calculated for quality were able to explain the larger combine harvester requirement in organic production. However, the decrease in total costs when changing to the larger combine harvester that was optimal in organic production was very small (0.3%) compared with keeping the machine optimal in conventional production. Consequently, this change could be made when the machine is due to be replaced.

5.2 Forage harvesting costs in milk production (Papers II and IV)

The initial study of forage harvest (Paper II) included two cuts per season in central Sweden. The harvest was performed using a mower-conditioner, a precision chop forage trailer, and a wheel loader for loading and packing the bunker silo.

Paper IV presented a method to calculate timeliness costs for forage harvest based on the experiences and results from the studies presented in Papers I-III. The number of cuts was increased to three and the annual variation in timeliness losses was studied for southern and central Sweden. Furthermore, choice of machinery size was explored by calculating harvesting costs for three machine chain sizes in different harvesting systems: a precision chop forage trailer (PCFT) or a precision chop forage harvester with separate trailers (PCFH/T), when ensiling in bunker silos or a round baler with integral wrapping (RBI). Harvesting costs included the costs of machinery, labour and timeliness.

5.2.1 Timeliness cost factors

Analysis using standard ANOVA techniques showed that for the three cuts included in the study presented in Paper IV, timeliness cost factors (in € ha^{-1} day^{-1}) were significantly higher ($p<0.05$) in the first cut compared with the second or third cut (Table 2, Fig. 6). There was no significant difference between the timeliness cost factors of the second and third cut.

Table 2. *Timeliness cost factors (€ ha^{-1} day^{-1} and € kg^{-1} DM day^{-1}) as mean values (standard deviation in brackets) for three cuts of forage in southern Sweden (1984-1993) and central Sweden (1978-1987)*

Timeliness cost factor	Southern Sweden			Central Sweden		
Cut	1	2	3	1	2	3
(€ ha^{-1} day^{-1})	8.7 (5.5)	3.0 (1.4)	2.1 (0.9)	6.4 (3.5)	2.5 (1.1)	1.5 (0.7)
(€ kg^{-1} DM day^{-1})	0.0024	0.00064	0.00054	0.0020	0.00075	0.00054

As is clearly obvious in Figure 6, timeliness losses per ha and day's delay of harvest varied greatly between years. This is also apparent in Table 2 as high standard deviation. For the first cut, timeliness cost factors varied between €1 and €19 per ha and day in southern Sweden and between €2 and €14 per ha and day in central Sweden. High timeliness cost factors in some years, *e.g.* the first cut in 1989 in southern Sweden or in 1986 in central Sweden, were due to differences in the value per ha caused by different daily forage growth rates. When timeliness cost factors were high, the value of each cut was higher for the optimal cutting dates of first, second and third cut compared with the value of each cut when the first cut was delayed by seven days. In comparison, in years with low timeliness cost factors, the value of each cut did not decrease much when harvest was delayed by seven days.

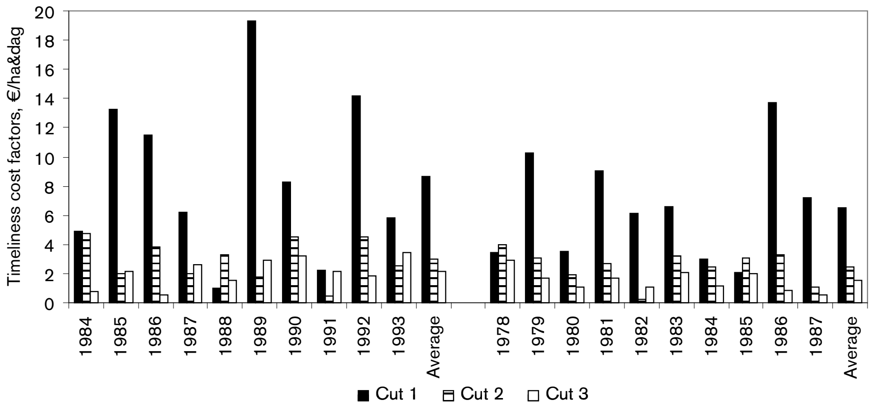

Figure 6. Timeliness cost factors (€ ha^{-1} day^{-1}) for southern Sweden for the period 1984-1993 (left) and central Sweden for the period 1978-1987 (right).

While the yield was calculated for each year based on daily weather data, the feed value depending on change in nutrient content was based on average values for a number of years. The change in protein and energy content with time was therefore the same for each of the 10 years for which calculations were made. Consequently the variation in timeliness cost factors was dependent on differences in DM growth between years but not on annual variation in change in nutrient content. Using average values of nutrient content in the forage, derived from regression analysis of trials from different years, results in slower changes in content with respect to time compared with the results for individual years (Witney, 1995). Faster changes in nutrient content would have resulted in higher timeliness factors.

The large annual variation emphasised the importance of basing the calculation of timeliness costs and choice of machinery capacity on weather data for more than one year. Timeliness costs may be strongly over- or under-estimated if based on weather data for only one year. Basing the choice of harvesting capacity on average values of the timeliness cost factors will nevertheless result in overcapacity in some years and high timeliness losses in other years.

The statistical analysis also showed that there was no significant difference between timeliness cost factors in southern and central Sweden ($p<0.16$). One reason for this could be that differences in crop quality development between the two places were not accounted for, as the energy and protein contents were calculated from experimental data presented as average values for southern and central Sweden. However, the yield was calculated separately for southern and central Sweden.

In the study presented in Paper II, timeliness factors describing the daily loss per ha and day were higher for the first cut compared with the second. This can be explained by faster crop development early in the season and higher yield in the first cut compared with the second. Timeliness factors were also higher in organic production compared with conventional, mainly due to the greater difference in value of the organic forage between the two cutting dates depending on feeding restrictions and decreased milk yield for the later forage harvest date in organic production.

5.2.2 Harvesting costs

As Figure 7 shows, the harvesting costs (Paper IV) using the precision chop forage harvester with separate trailers (PCFH/T) were influenced by the scale of the operation and for small forage areas the machine cost was the dominant harvesting cost, as noted previously by Sijtsma *et al.* (1998) and de Toro & Rosenqvist (2005). A general result irrespective of machinery system and size was that if timeliness costs were not considered, harvesting costs per ha continued to decrease as the forage area increased, since the annual use of the machines increased. However, as timeliness costs increased with increasing forage area since the harvest took a longer time to carry out, at a certain forage area the increasing timeliness costs outweighed the decreasing machine costs. Thus, for the harvesting system presented in Figure 7, harvesting costs began to increase after reaching a minimum cost at 120 ha. Labour costs per ha were independent of the area harvested. Without timeliness costs being included, harvesting costs would be under-estimated, especially for large forage areas.

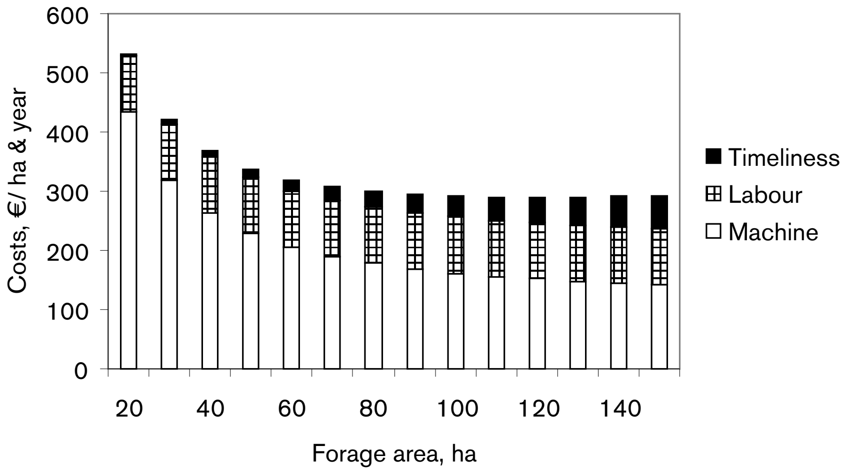

Figure 7. Harvesting costs for a medium machine chain size using a precision chop forage harvester with separate trailers in central Sweden.

The harvesting systems studied reacted differently to changes in transport distance. The harvesting capacity in the field using a round baler (RBI) did not decrease when the transport distance increased, since the bales could be transported after the harvest period. Consequently timeliness costs did not increase with increasing transport distance for the RBI system. The harvesting system using the precision chop forage trailer (PCFT) lost capacity when the transport distance increased, which resulted in timeliness costs increasing with transport distance. When harvesting with a PCFH/T harvesting capacity was decided by either the harvesting capacity in the field or the transport capacity. At increasing transport distance the timeliness costs increased as soon as the transport capacity limited the capacity of the whole harvest.

The study presented in Paper II showed that the timeliness costs were sensitive to changes that influenced the capacity of the harvest, *e.g.* number of workers available. The calculations were based on two people carrying out the harvest work; one person driving the precision chop forage trailer and the other person the wheel loader. When one person harvested alone the capacity for harvesting decreased, leading to harvesting costs increasing by 8% since longer duration of harvest increased timeliness losses. A machine optimisation by Soegaard & Soerensen (2004) also showed that availability of labour is critical and that lack of labour results in increased optimal machine size, since timeliness costs can only be reduced in that case by larger machines decreasing the duration of the operation. Another solution when available labour is restricted is to switch to contractor harvesting (Ramsden *et al.*, 1999).

For harvesting of forage using a precision chop forage trailer (PCFT) the possibility of hiring contractors to carry out the work instead of buying a system of machinery in-house was examined in Paper IV. For contractor harvest the cost per hour was fixed and the reason for the costs increasing with forage area (Fig. 8) was the increasing timeliness costs. A general result depending only on the timeliness cost factors and the forage area was the timeliness costs occurring at delayed start of the harvest. They are well illustrated in Figure 8 as the difference between the parallel lines showing costs for contractor harvest starting on the optimal day or with three or seven days' delay.

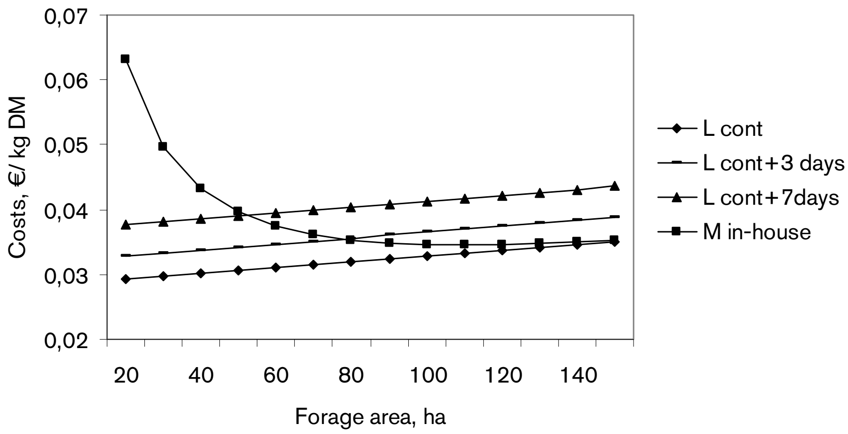

Figure 8. Harvesting costs using a in-house precision chop forage trailer with a medium (M) machine chain size in central Sweden compared with using a contractor with a large machine chain. L cont = contractor harvest starting on the optimal day; L cont +3days = contractor harvest starting 3 days after the optimal day; L cont +7days = contractor harvest starting 7 days after the optimal day.

As Figure 8 demonstrates, hiring contractors resulted in lower harvesting costs compared with in-house machines for forage areas less than about 130 ha when harvesting using the medium size PCFT in central Sweden, as long as harvest was not delayed. Already at about 80 ha forage area, having in-house machines was a cheaper alternative than contractor harvest with three days' delay. The smaller the forage area, the greater the benefits of machine cooperatives, a finding also reported in a study of machine cooperation in grain production (de Toro & Rosenqvist, 2005). However, to minimise the timeliness costs it is important that harvesting starts on the optimal day.

5.3 Costs of harvesting forage for biogas production (Paper III)

The costs of harvesting a total of 316 ha forage for a full-scale biogas plant were calculated by developing a static calculation model. Machine contractors were assumed to harvest the forage (two cuts) with a self-propelled precision chop forage harvester and trucks with trailers to transport the forage to the biogas plant, where it was ensiled in plastic bags.

The optimal time for harvest was defined as the date of each cut that maximised the forage value of both cuts in all fields (Fig. 9). The outcome was that the harvest started before the harvest value per ha had its maximum value and timeliness losses were divided on both sides of the optimal date, *i.e.* balanced scheduling. Figure 9 shows how costs and forage value varied when the harvest started before or after the optimal day.

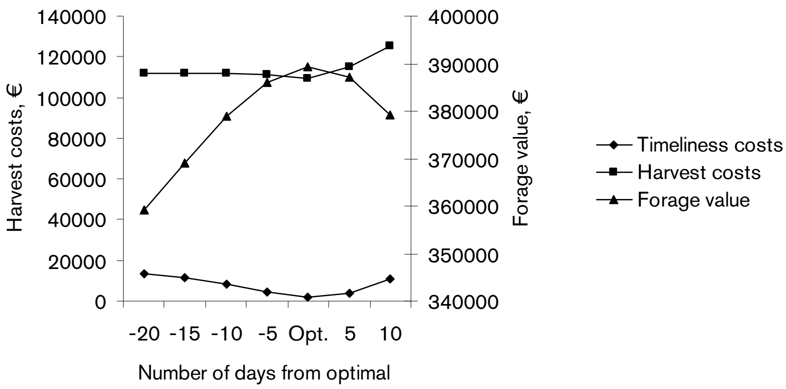

Figure 9. Timeliness costs, harvest costs (including machinery, labour and timeliness) and forage value for two harvests of 316 ha forage, using a transport system with two trucks with trailers, when both cuts were performed on the optimal dates and when both cuts deviated from 20 days before to 10 days after the optimal cutting dates.

Timeliness costs were lowest at the optimal cutting dates, as they were defined as the difference in forage value between when all fields were harvested at maximum value and when they were harvested with a specific capacity (Fig. 9). When the harvest was carried out before the optimal cutting date the machine costs decreased due to lower yields and less material to handle but since timeliness costs are included in the harvest costs in Figure 9, harvest costs increased when the cutting dates deviated from the optimal date.

Although the timeliness costs were almost four-fold larger for the transport system with the lowest capacity (1 truck with trailer) compared with that with the highest capacity (3 trucks with trailers), they constituted at most 3.5% of the total costs (Fig. 10). As also shown in Figure 10, matching chopping and transport capacity was essential for minimising the time and costs for the harvest. Since the harvest was carried out by contractors, the costs per hour were the same regardless of whether the machines were active or idle.

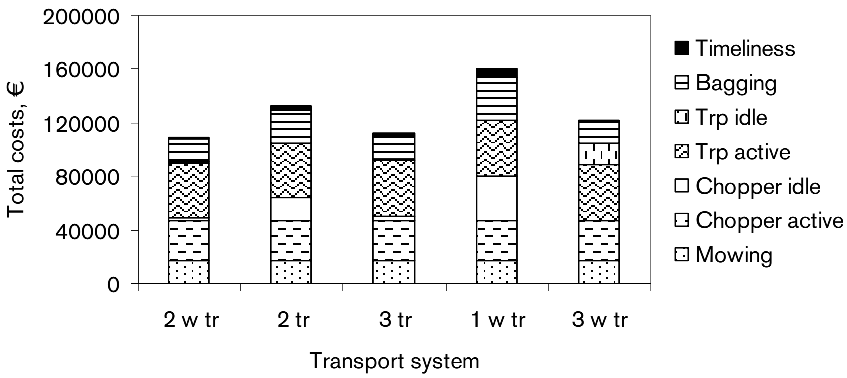

Figure 10. Harvesting costs, divided into costs for different operations, for first and second cut for the transport systems studied: two or three trucks (2 tr, 3 tr) and one, two or three trucks with trailers (1 w tr, 2 w tr and 3 w tr).

5.4 General discussion

Timeliness losses are dependent on biological systems, weather parameters that cannot be controlled and the price of crops, feed, machinery, *etc.*, which rely on the market and change over time and place. Modelling these systems for valuation of crops and calculation of costs therefore requires assumptions to be made. It is important to emphasise that the results depend on the assumptions made. Sensitivity analyses of parameters that influence the results or that are subject to uncertainties are therefore important. Costs and capacities for the systems studied in this thesis were calculated by constructing static models but the results of these models have not been verified against real systems. Except for the study of forage harvest for biogas

(Paper III), which was based on an existing system, the studies were performed on systems intended to be typical for an area rather than for a single farm. Therefore validation against an existing farm or system could not easily be done.

Although the cost calculations were made for systems intended to be typical for an area, results such as differences between systems based on the same assumptions and effects of changes in the system can be of more general interest. The cost calculations were based on prices in Sweden but when focusing on changes and differences rather than absolute values, the results are still relevant in countries with different price levels. The crop valuation in the calculation of timeliness factors due to quality is dependent on crop prices, the prices of all feed ingredients and the milk price. Since prices change over time, the methods presented in this thesis can also be used to adjust timeliness factors to such changes in prices.

The calculations of plant growth, yields and nutrient contents presented in this thesis were generally based on older field trials or statistical data. The use of new varieties and new crop management methods may influence these data, leading to uncertainty in the results. The trend over the years since the growth model was first developed (1982-83) has been towards an increasing number of forage cuts and thus towards ley species adapted to an increased number of cuts. However, the data used in this study were based on a large number of trials and it is uncertain whether newer field data are available to the same extent. Validations of the growth model used for calculating forage yields against observed growth in the field showed that the model accounted for variations in test material with great accuracy (Torssell & Kornher, 1983). Variation in forage production over time is partly due to environmental factors that cannot be controlled and partly to management factors that can be controlled (Brown *et al.*, 1986). Therefore the large annual variation in yields calculated with the forage growth model is most likely due to variations in the weather since management practices, accounted for in the model by input parameters, were the same for all years.

Calculating timeliness factors for forage requires an approach that considers not only changes in price and yield but also the value of livestock output. Therefore Witney (1995) claims that compared with grain, the loss in value of forage crops is more subjective as it involves ration formulation and feed conversion rates. Kuoppala *et al.* (2008) showed that cutting time of the forage affects forage intake and milk production. In this study the rations were constructed and milk yields estimated from the knowledge that a silage with higher energy content, achieved through earlier harvesting, is consumed by cows in larger amounts than silage with a lower energy content (Bertilsson & Burstedt, 1983). The lower consumption of later harvested silage could be partly compensated for by higher amounts of concentrates and barley. In the organic production system, feeding regulations restricted the possibilities to compensate for lower forage quality by feeding concentrates, which resulted in decreased milk yield. Decreased milk yield in turn had a large impact on the value of the feed and resulted in higher timeliness factors in organic production compared with conventional.

The fact that forage yield increases with delayed harvest time was treated differently in Papers II and IV, both of which studied forage for milk production. In Paper II, the influence of the first cut on regrowth was considered by assuming that increased yield at delayed first cut resulted in a corresponding decrease in yield of the second cut, the total yield being constant. In Paper IV, which studied a three-cut system, this assumption was not viable. Instead the yield for each cut was calculated in a more exact way using a forage growth model. The value of the additional yield obtained when the date of each cut is delayed depends on the planning situation on the farm. If the farmer plans the forage requirement according to the nutrient content and yield achieved at the desired cutting date, the value of the additional low quality forage resulting from late cutting is limited. However, Savoie *et al.* (1985) report that a profit may sometimes be made by substituting quantity for quality when feeding low-producing animals. Furthermore, the market for selling forage is uncertain since it is not a common commodity. Unless preserved in bales, trading of silage is also difficult for practical reasons (Wilkinson, 2005). In Paper II, the value of the additional yield at late harvest was not included in the valuation of the forage, whereas it was included in the study presented in Paper IV. Valuation of the forage considering changes in feed value and changes in DM yield with delayed time of harvesting results in lower timeliness factors compared with when the additional DM yield at delayed harvest is not considered.

The optimisation of cutting dates presented in Paper IV resulted in the three cuts being fairly equal in size, whereas the first cut was the largest when looking at statistical data (Paper II). One reason for the relatively small first yield calculated as optimal in Paper IV could be that the rapid decrease in nutrient concentration early in the season promotes an early low-yielding first cut. The slower decrease in nutrient content in the regrowth could explain the higher yields in the later cuts. In a study of alfalfa forage harvest it was concluded that an early harvest to get a high quality feed was generally most profitable considering milk income and costs for supplemental feed and harvesting (Savoie *et al.*, 1985). Higher yield of an individual cut results in higher timeliness factors. The differences mentioned here between the studies presented in Papers II and IV make it difficult to compare the results of the two. However, the method presented in Paper IV is considered to handle the DM yield more accurately than the method used in Paper II.

It is important to know when the harvest of forage has its maximum value with respect to both yield and quality, since delaying the start of harvesting increased timeliness costs irrespective of harvesting capacity. Moreover, because timeliness losses were highest in the first cut it is particularly important to avoid delays in this cut. However, deciding the optimal date is difficult, especially in the real farming situation when the weather for the coming cuts is unknown. It is therefore difficult to choose cutting times that consider the effect on the following cuts in the same way as in the calculations in Paper IV. If the effects on the following cuts were not considered when optimising the first cut, it was optimal to cut later.

When optimising the cutting date of the last cut, no restrictions were placed on the date set as regards the effect on overwintering and on yield in the following year. In the study presented in Paper IV, the last cut was made at the end of September. Theoretically, for best overwintering the forage should either be harvested early enough for the crop to have time to store nutrients for consumption during the coming winter or late to avoid regrowth (Andersson, 1997). In field trials in northern Sweden, Andersson (1997) showed that the effects of harvest time on overwintering is often moderate and varies between years and forage species, and it is therefore important to also base the choice of cutting time on the nutrient content of the forage.

The optimal time to harvest changes depending on the use of the forage. When harvesting a crop for biogas production Lehtomäki *et al.* (2008) reported that it is important to consider the energy yield per ha. Compared with normal harvesting dates for forage for milk production, the study presented in Paper III indicated that the optimal harvest date for forage for biogas was later. One explanation could be that although biogas production per kg DM decreases when harvest is delayed, the DM yield increases and still contributes to the biogas production per ha. In milk production, the lower quality at later harvest was compensated for by increased use of concentrates and possible decreased milk yield. The methane yield was based on results from trials in laboratory scale and costs such as increased size of the digester needed due to possible increased retention time when digesting older material harvested later were not considered.

When calculating timeliness costs it was assumed that the whole forage area had the same optimal harvesting date but in reality there are differences between fields and due to ley age. The R_s-values used to calculate forage yield were average values for first, second and third year leys. If different optimal harvesting dates were set for first, second and third year leys, timeliness costs would decrease. A study of grain harvesting has shown that timeliness costs can be determined more exactly if they are calculated individually for smaller areas with different maturation dates instead of the whole area as one unit (de Toro & Hansson, 2004).

In a study of a large-scale harvesting system, Mapemba *et al.* (2008) found that harvesting costs are sensitive to the number of harvest days. The method used here accounted for delays due to weather interruptions by prolonging the length of the harvest with an average workday probability factor. Since the annual variation in weather is large, the method of using average values will overestimate the length of the operation and the timeliness costs in some years and underestimate them in others. Furthermore, no account was taken of a possible decrease in forage quality due to rain.

In this project timeliness costs were used to calculate field machinery costs and select machinery capacities. Timeliness costs could also be estimated for non-economic factors such as biodiversity in order to recompense farmers for protecting the environment. For example Aschenbrenner *et al.* (2006) presents calculations of premiums based on the value of forage used for milk production to cover the loss in forage value when harvesting is delayed for nature conservancy purposes.

5.5 Future research

In future studies on harvesting of forage it would be interesting to use a growth model developed for the particular species and number of cuts commonly used today. One improvement of the results presented in Paper IV would also be to simulate changes in both yield and quality from daily weather data. Therefore the possibility of using models such as the FOPROQ (Kornher *et al.*, 1991; Herrmann *et al.*, 2005a) should be examined.

Another interesting project for the future would be to study the harvest of forage for biogas production in greater detail. The estimation of biogas yield in Paper III was based on international trials on plant material. In further studies of the forage for biogas, efforts should be made to base the biogas yield estimations on forage grown in Sweden. Determining the effects of different harvest dates on biogas production would require experimental results on the methane yields from plant material harvested on different dates.

The sharp changes in the price of cereals, fertilisers and fuel that occurred during the last year have changed the conditions for cereal production and it would be interesting to examine how these changes affect the cost and optimal capacities for sowing and harvesting.

The method presented here for valuation of forage and calculation of timeliness cost by considering changes in both feed value and yield could also be used on maize, a crop interesting for energy purposes. Maize is a relatively new crop in Sweden and the strategic knowledge for harvesting, handling and storage, in particular when used for energy production, is limited. Analysis of optimal harvest capacity and time for maize when used for feed or energy purposes would therefore be valuable.

In this project machinery systems were studied with the aim of minimising costs. Optimisation of machinery systems with respect to aspects such as power and fuel efficiency, emissions, *etc.* would be interesting in order to reduce the impact on the environment.

6 Conclusions

- The main differences in timeliness costs between conventional and organic farming can be attributed to two counteracting facts – the lower yields and higher product prices in organic production. Timeliness costs in harvesting of organic forage are also affected by feeding restrictions and the expected decrease in milk yield resulting from later harvested forage.
- The method presented here for valuation of forage and calculation of timeliness cost factors by considering changes in both feed value and yield (Paper IV) is recommended for use in further studies. The method could be used in other regions by adapting the calculations on forage growth and feed value, and could also be adapted for valuing forage for other uses such as biogas production.
- The timeliness factors presented in this thesis can be used to calculate timeliness costs for specific farms or operations by also considering more farm-specific parameters affecting the capacity of the operation. Adjustment of the timeliness factors to changing prices may be necessary since they are dependent on the price of crops, feed and milk.
- The majority of the timeliness costs for sowing and harvesting of grain resulted from delays to the start of the operations, with only a minor proportion occurring during sowing and harvesting. It is therefore important to choose crops and varieties with different optimal times for sowing and harvesting.
- Higher timeliness costs resulted in a larger combine harvester being economically optimal in organic grain production than in conventional. However, the difference in total costs was very small.
- Timeliness cost factors for forage harvest expressing quality and quantity losses in economic terms were significantly higher for the first cut compared with the second and third cuts, one reason being faster crop

development early in the summer. Timeliness cost factors for second and third cut did not differ significantly from each other. Therefore it is most important to avoid delays in the first cut.

- Timeliness cost factors for forage harvest varied greatly between years, and therefore it is important to base timeliness cost calculations on weather data for more than one year.
- It is important to know when the forage has its maximum value with respect to both yield and quality, since delaying the start of harvest increases timeliness costs irrespective of harvesting capacity. Nevertheless, deciding the cutting date, particularly concerning effects on the following cut/s, is difficult.
- Harvesting costs decreased with increasing forage area up to a certain threshold area, beyond which decreasing machine costs were outweighed by increasing timeliness costs due to longer duration of harvest. Therefore, the importance of including timeliness costs when calculating harvesting costs and choosing harvesting capacity increases with increasing forage area.
- Timeliness costs were independent of the transport distance when using a round baler since the bales could be transported after the harvest period. Harvesting using the precision chop forage trailer lost capacity when the transport distance increased, which resulted in timeliness costs increasing with transport distance. When harvesting with a precision chop forage harvester with separate trailers, the timeliness costs increased with increasing transport distance as soon as the transport capacity limited the capacity of the whole harvesting system.
- Using machine contractors or machine cooperation decreases harvesting costs, particularly for small forage areas, since increased annual use of the machines lowers machine costs and allows larger machines with higher capacity to be used. However, to avoid high timeliness costs it is important to avoid delays in harvesting.

7 Sammanfattning

Med ökande priser på energi, gödselmedel och foderkoncentrat ökar vikten av att producera foder av hög kvalitet till minimala kostnader. Ökande internationell konkurrens sätter press på lantbruket att höja produktiviteten och minska produktionskostnaderna. Kostnaderna för de maskiner som används för växtodling utgör omkring en fjärdedel av produktionskostnaderna på en svensk gård. Rätt maskinval och effektivare användning av maskinerna har därför potential att sänka produktionskostnaderna.

För grödor finns en tidpunkt när dess värde med avseende på kvalitet och/eller kvantitet är maximalt. Värdet av de förluster som uppstår när exempelvis sådd eller skörd inte utförs vid denna optimala tidpunkt kallas läglighetskostnader. Läglighetskostnaderna för en specifik fältoperation är beroende av eventuella förseningar av starten och därefter av hur lång tid operationen tar att genomföra och därmed av kapaciteten på de maskiner som används. Dessutom påverkas operationens längd av eventuella avbrott och fördröjningar när vädret inte tillåter att operationen kan genomföras. Hög maskinkapacitet minskar den tid fältoperationen tar och därmed även läglighetskostnaderna. Om läglighetskostnaderna inte beaktas finns risk att kostnader och erforderlig maskinkapacitet underskattas.

Avhandlingens övergripande mål var att förbättra underlaget för maskinval vid odling av jordbruksgrödor. Huvudsyfte var därför att utveckla och tillämpa metoder för att beräkna läglighetskostnader som tar hänsyn både till kvalitets- och kvantitetsförluster när en fältoperation inte utförs vid den optimala tidpunkten. Läglighetsfaktorer vilka anger kostnaden för var dags försening av sådd och/eller skörd av spannmål och vall beräknades genom att undersöka förändringen i grödans värde med tidpunkten för operationen. Effekten på maskinkostnader och val av maskinkapacitet med hänsyn till läglighetskostnaderna undersöktes därefter för olika typgårdar och maskinsystem.

Läglighetskostnaderna för spannmål vid försenad sådd och skörd var högre i ekologisk jämfört med konventionell produktion. Spannmål värderades med hänsyn till både kvalitets- och kvantitetsförluster och läglighetskostnaderna var högre såväl per kg som per ha producerad spannmål. Skillnaderna var framför allt beroende på lägre skördar och högre produktpriser i ekologisk produktion. Högre läglighetskostnader resulterade i att det var ekonomiskt optimalt med en större tröska med högre kapacitet vid övergång till ekologisk produktion. Dock var minskningen i totala kostnader liten jämfört med om den mindre tröskan behölls. Större delen av läglighetskostnaderna uppkom pga. förseningar i start av sådd eller skörd. Läglighetskostnaderna i spannmålsodling kan därför reduceras genom att välja grödor och sorter med olika optimala tidpunkter för sådd och skörd.

För skörd av vall utvecklades en metod för att värdera vall till mjölkproduktion och beräkna läglighetskostnader med avseende på att skörden ökar och vallens fodervärde minskar med skördetidpunkten. Värderingen resulterade i läglighetsfaktorer som var signifikant högre i första skörd jämfört med i andra och tredje skörd. De varierade dessutom mycket i storlek mellan år.

Läglighetsfaktorerna användes tillsammans med mer gårdsspecifika faktorer som påverkar skördens kapacitet såsom tillgång på arbetskraft, transportavstånd etc. för att beräkna skördekostnader för olika maskinsystem med varierande maskinkapacitet och vallareal. Vid ökande vallareal minskade skördekostnaderna upp till en viss areal eftersom ökad årlig maskinanvändning sänkte maskinkostnaderna per ha. Därefter vägdes de sänkta maskinkostnaderna upp av ökade läglighetskostnader när skörden tog längre tid att slutföra.

Genom att låta skörden utföras genom maskinsamverkan eller med inlejda maskiner kunde skördekostnaderna sänkas, speciellt vid små vallarealer. För att undvika höga läglighetskostnader är det dock viktigt att undvika förseningar i skörden.

Vallen värderades även när den användes för att producera biogas genom att ta hänsyn till förändringar i vallens skörd och metanproduktion vid olika skördedatum. För de studerade systemen var läglighetskostnaderna små så länge skördens inleddes vid optimal tidpunkt. När skörden utförs med flera samverkande maskiner är det viktigt att matcha de olika maskinernas kapacitet för att undvika outnyttjad kapacitet och minimera kostnader.

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Acknowledgements

Finally, I would like to thank,

Firstly and especially Per-Anders Hansson, my main supervisor for guiding me through this project in the best way possible. For giving me freedom to develop the project but also for keeping me on track. I really have appreciated that you always took the time to help me sort things out when I came knocking on your door!

Secondly, Rolf Spörndly, my assistant supervisor, for engaging in my project, for feeding me with rations and for encouraging comments on my achievements.

Alfredo, for acting as my pre-opponent and going through my papers and for guidance in field machinery. And for providing me with the function which made yield calculations easier.

My co-authors for inspiring cooperation.

The farmers across Uppland who shared their experiences in practical agriculture with me.

Colleagues at the department; I have enjoyed working with you, and luckily I will not go far away! Special thanks to fellow PhD students, those off you still there and those of you finishing before me. And to Majsan, Berit and Sven for practical support and Tomas for statistical help.

Mary McAfee for quick and very valuable improvements of my English and Eva-Lotta and Serina for improving my Swedish.

My friends for caring, in particular Anneli, Annelie, Caroline, Elisabeth, Marina and Monica for party arrangements and joyous muskvällar, and Ingrid, Serina, CC and Maj for happenings after work.

Last but not least, my warmest thoughts to my family; Mamma and Dick, Lola and Jenny with families– just for always being there. Brita and Hartmuth- for all help and care. Stephan, Felix and Fredrik- together with you everything else seems less important.

The financial support for this thesis project, provided by the Swedish University of Agricultural Sciences and the Swedish Farmers' Foundation for Agricultural Research (SLF) are gratefully acknowledged.