Examensarbete *Master Thesis*

Timeliness cost for agricultural sprayers - weed control in cereal crops

Läglighetskostnad för lantbrukssprutor - ogräsbekämpning i spannmålsgrödor

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ABSTRACT

Evaluation of machinery costs is necessary for selecting appropriate farm machinery. Timeliness cost due to untimely operations is an important component of machinery costs. Timeliness costs can be high for crop sprayers, since pesticide application must be carried out within a short time interval.

This Master thesis investigated the timeliness cost and the probability of a suitable workday for spraying. Timeliness factors were estimated for four different crops (oats, spring wheat, winter wheat and barley) using historical weed trial data. Workday probability was estimated using weather data, including temperature, rain, air humidity and wind speed, from four different meteorological stations in Sweden. Ownership and operating costs were also calculated. The optimum sprayer capacity for a specific situation was then calculated for each crop. In addition, the effects of variations in grain price, crop yield and workday probability on optimum sprayer capacity and total costs were studied.

The timeliness factor was estimated to be 0.0150 relative yield loss days^{-1} for oats, 0.0059 relative yield loss days^{-1} for barley, 0.0049 relative yield loss days^{-1} for winter wheat and 0.0035 relative yield loss days^{-1} for spring wheat. The workday probability for spraying was lower than the estimated probabilities for other operations such as tillage, sowing or harvesting. The average workday probability for spraying was estimated to be 0.36 for winter crops and 0.39 for spring crops.

The calculations showed that timeliness costs are an important component of total costs, of similar magnitude to machinery costs. Total costs decreased with increasing sprayer capacity up to a certain limit (optimum capacity) at which total costs were at a minimum. Above this point, total costs for higher capacities began to increase.

Analyses of variations in parameters such as grain price, crop yield and workday probability showed that optimum capacity and total costs varied to a higher degree with varying weather conditions.

SAMMANFATTNING

För att kunna välja lämplig storlek och typ av lantbruksmaskiner är det nödvändigt att uppskatta den totala maskinkostnaden. Läglighetskostnaden kan vara en viktig komponent av den totala maskinkostnaden. Beroende på omständigheterna kan läglighetskostnaden vid användning av lantbruksspruta vara viktig att beakta, eftersom sprutning ofta måste ske inom en relativt kort tidsrymd.

Detta examensarbete undersökte läglighetskostnaden för sprutning av ogräsmedel för olika sprutkapaciteter genom att beräkna läglighetskoefficienter och den sannolika andelen dagar tillgängliga för sprutarbete i fält. Läglighetskoefficienter beräknades för fyra grödor (Havre, Korn, Vårvete och Höstvete) genom att använda historiska försöksdata. Andelen sannolika sprutdagar uppskattades med hjälp av temperatur, nederbörd, luftfuktighet och vindhastighet från fyra väderstationer i Sverige. Även investerings- och arbetskostad beräknades. Optimal maskinkapacitet för specifika maskin- och gårdsdata beräknades för varje gröda. Sedan beräknades inverkan av variationer i avräkningspris, skörd och sannolik andel sprutdagar på den optimala sprutkapaciteten.

De resulterande läglighetskoefficienterna mätt i relativ skördeförlust dag^{-1} för ogräsbekämpning var 0.0150 för havre, 0.0059 för korn, 0.0049 för höstvete och 0.0035 för vårvete. Den beräknade sannolika andelen arbetsdagar för sprutning uppskattades i denna studie till 0.36 för höstsådda grödor och 0.39 för vårsådda grödor. Detta var lägre än tidigare rapporterade värden för andra fältoperationer såsom såbäddsberedning, sådd och skörd.

Beräkningarna visade att läglighetskostnaden för lantbrukssprutan var en viktig del av den totala maskinkostanden. Den totala maskinkostnaden minskade med ökande sprutkapacitet upp till en gräns (vid optimal kapacitet) vid vilken den totala kostnaden hade ett minimum. Över denna gräns ökade den totala kostnaden när sprutkapaciteten ökade.

Analys visade att optimal kapacitet och total maskinkostnad var mer känsliga för variationer i sannolik andel sprutdagar, som resultat av varierande väderlek, i jämförelse med avräkningspris och skörd.

CONTENTS

INTRODUCTION

There is currently a trend for farms to increase their acreage, leading to a need for relatively high capacity farm machinery. The study of machinery selection and machinery costs is an important field, since the goal of farmers is to achieve maximum profits from their work.

In addition to ownership and operating machinery costs, timeliness costs due to untimely operations must be considered in order to obtain a full cost evaluation. Today farmers are using crop sprayers with increasing capacity and applying lower volumes of liquid, despite the increased investment costs for larger machines and the increased risks of insufficient effect due to spray drift. This indicates that farmers have experienced significant timeliness costs when spraying their agricultural crops. Application of pesticides, e.g. herbicide, must be carried out in a short time interval, so timeliness costs for spraying are important.

There are very few objective estimations of timeliness costs for crop sprayers in the literature. There is therefore a high degree of uncertainty when the farmer decides on sprayer capacity, which is a trade-off between the purchase price of the sprayer and the timeliness costs.

The objective of this study was to estimate the timeliness costs for crop sprayers used for weed control, based on historical trial data and weather data. The results of the study are intended to be used as support in decisions on investment in sprayer capacity.

The scope of the study was as follows:

- The spraying operation studied was herbicide spraying.
- The calculations centred on the spraying operation itself, with other operations that could take place at the same time not being taken into account.
- The historical trial data referred to broad-leaved weeds only.
- The crops studied were oats, spring wheat, winter wheat and barley.

Specific objectives were to:

- Estimate timeliness factors for different crop sprayers based on historical trial data on different crops and weed control treatments.
- Calculate a representative probability of suitable weather conditions for spraying (workday probability).
- Calculate ownership, operating and timeliness costs for different sprayer capacities and specific cases.
- Determine the optimum capacity that minimised total costs for the specific case studied.
- Determine the effects of varying grain price, workday probability and yield on optimum sprayer capacity and total costs.

LITERATURE REVIEW

Timeliness

One of the most important indirect machinery costs is crop losses due to untimely establishment, spraying and harvesting. There is a theoretical optimum date when field operations must be carried out to obtain maximum yield. However, field operations cannot usually be completed within one day, and in reality it is necessary to use a course of several days to finish each operation, leading to yield losses and financial penalties.

Numerous individual experiments show that crop yield varies in a predictable way depending on the timing of field operations, although the magnitude of the variation is determined by the unique combination of soil type, weather, crop, geographical location and crop variety at the site (Witney, 1996). This means that there is a timeliness function that links the yield loss (y) with the number of days before or after the optimal date of field operations (k). This can be expressed using the following equation (Castelli & Mazetto, 1989):

$$y = f_a(k) \quad (\text{for } k < 0) \quad (\text{kg/ha})$$
$$y = f_b(k) \quad (\text{for } k \geq 0) \quad (\text{kg/ha})$$

Equation 1

where f_a = function for early operations
f_b = function for late operations
k = number of days from the optimum
y = yield loss.

In principle, this function can have any form, with curve shape differing for early and late operations with respect to the optimal time. By definition, the losses on day 0 will be zero (Castelli & Mazetto, 1989). Figure 1 is a particular example of Equation 1 where the decrease in yield losses is linear for early and late field operations.

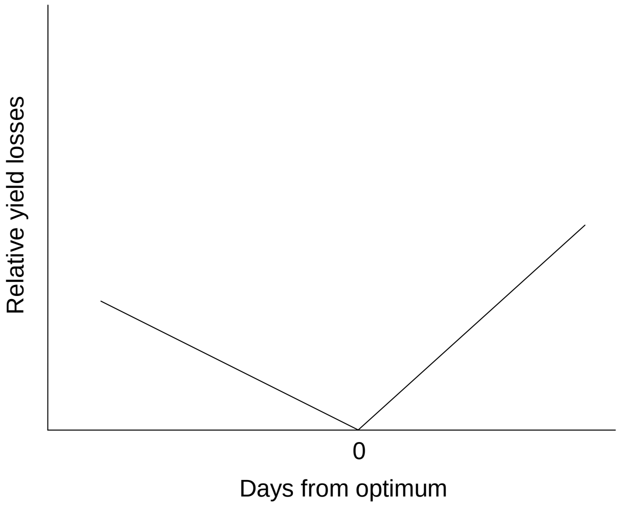

Figure 1. General case of linear yield losses as a function of the number of days before or after the optimum field operations date (after Castelli & Mazetto, 1989).

Direct evaluation of the penalty for untimely operations would require the yield/time response to be determined for each case. This is quite difficult in practical applications, since it depends on multiple factors (Witney, 1996).

Spraying timeliness

The timeliness of herbicide application is very important for the effectiveness and efficiency of this operation. Spraying should be carried out when the weeds are less resistant and the environmental conditions are suitable for effective and safe application. In the case of leaf-acting (foliar) herbicide treatments, this occurs in the following conditions (Motooka *et al.*, 2002):

- **Low energy reserves in the weeds:** This usually happens when the weeds have used stored energy for new growth.
- **Weed leaves have adequate area and the cuticle is thin:** The leaves have adequate area to retain the necessary amount of herbicide and the herbicide seeps easily through the leaf surface.
- **The weeds are young:** Easier to achieve complete coverage on all leaves.
- **The weeds are growing:** Better penetration and translocation of the herbicide.

Weather conditions

The weather is an important factor in crop spraying. The weather conditions determine the available workdays in the critical period for each operation, and therefore have an influence on the timeliness costs. Machinery selection is complicated by the fact that the weather is a very uncertain factor. The principal weather conditions that affect spraying are:

- **Temperature**: According to Jahr (2008), a general reduction in herbicide dose is possible when the air temperature is above 14 ºC, while with a temperature below 10 ºC the full dose is more likely to be required. According to the main manufacturers of herbicides on the Swedish market (DuPont Agro Sweden, Bayer CropScience AB, Dow AgroSciences AB and Monsanto Crop Sciences Sweden AB), the minimum temperature required for spraying ranges between 5 and 10 ºC, depending on the herbicide used.
- **Relative air humidity**: There are generally no formal upper or lower limits for most herbicides. However, when spraying foliar herbicides, a suitable upper limit would be at about 95% (J-Å Svensson, DuPont Agro, pers. comm. 2009). Above this relative humidity limit, there would be high risk of dew on the leaves, allowing the herbicide to wash away from the leaf surface. The herbicide droplets should dry on the leaf, leaving the active ingredient acting directly on the leaf surface.
- **Rain**: The herbicide drops can be washed away by rain. Because of this, there should be a period without rain before and after spraying. According to product information from pesticide manufacturers (see above) and as also stated by Jahr (2008), the time needed depends on the herbicide, but at least two hours without rain are needed.
- **Wind speed**: This is one of the more important conditions, since in situations with sufficient wind the herbicide is spread to places outside the target area. This can cause severe damage to nearby crops or other plants. A review of maximum wind speed studies by Hagenvall (1990) shows that the recommended value varies between 3 km/h and 4.5 km/h.

It is necessary to estimate the days on which it is possible to spray in suitable conditions in order to accurately calculate the timeliness costs.

Machinery costs

Economic pressures are driving farmers to manage their machinery resources more efficiently. A large amount of money is being invested in order to obtain more productive and higher capacity machinery. Both capital investment and annual production are directly related to the machinery used, so farmers must have effective strategies for managing their machinery resources. In practice, the management of machinery includes the following aspects (Dalsted, www):

- The price of each size of machinery
- The quantity of machinery that is needed for a given acreage
- The choice between leasing, renting, custom-hiring or owning machinery
- The purchase of new or second-hand machinery
- The lifetime of the machinery before it is replaced.

Research into machinery costs needs to deal effectively with these aspects. Important basic concepts associated with machinery selection are field capacity and field efficiency. Field capacity is defined as the amount of processing that a machine can accomplish per hour. The theoretical field capacity is decreased by overlapping, the time needed for turning on headlands, the time lost in loading/filling, *etc*. These time losses result in a field efficiency below 100% (Srivastava *et al*., 2006). Machine size directly affects these concepts and is decisive for the time required to perform a field operation.

Machinery costs can be divided in three basic categories: fixed costs, variable costs and timeliness costs (Dalsted, www). Fixed costs include ownership costs such as depreciation of the machine, interest on the investment, and the cost of taxes, insurance and housing of the machine. Variable costs include the costs resulting from use of a machine, *i.e*. the costs of fuel and oil, and repair and maintenance (Srivastava *et al*., 2006). Timeliness costs, which cannot be included in the other categories, are closely related to machinery size. Timeliness is defined by ASAE (1979) as the ability of perform an activity at such a time that both the quality and quantity of the product are optimised. Timely performance of a field operation depends on the size and capacity of the machine and the time constraints resulting from the crop characteristics, weather, soil conditions or management requirements (Hughes & Holtman, 1976).

Timeliness costs associated with the wrong choice of machine size are difficult to calculate precisely, since these costs depend on uncertain factors such as the weather and can vary not only with different crops but also with the operation performed on a given crop (Dalsted, www). However, the timeliness costs can be estimated using the following equation (Srivastava *et al*., 2006):

$$Ct = \frac{K_t\,A\,Y\,V}{\lambda_o\,T\,C_a\,p_{wd}} \qquad \text{Equation 2}$$

where C_t = timeliness costs, SEK/ha

K_t = timeliness coefficient, fraction of annual value lost per day
A = crop area, ha/yr
Y = crop yield, kg/ha
V = crop value, SEK/kg
λ_o = 2 if operation commences or ends at the optimum time
= 4 if operation can be balanced evenly about the optimum time
T = expected work time available for field work, h/day
C_a = effective field capacity of machine, ha/h
P_{wd} = probability of good workday, decimal

Choosing the correct size and capacity of a machine is important for both the machine designer and the farmer. The farmer has the goal of optimising field capacity for maximum profit, while the designer is interested in designing a machine of optimum size for each size of farm (Srivastava *et al*., 2006).

All the costs described above are shown in Figure 2.

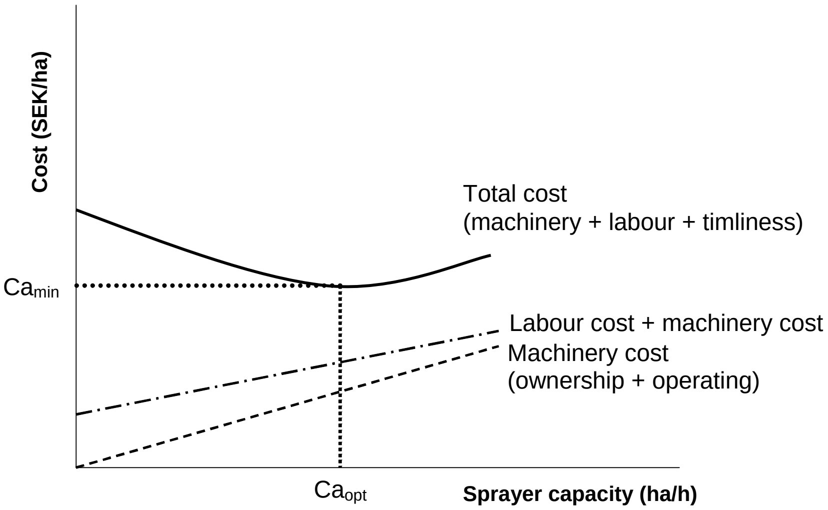

Figure 2. Costs related to crop sprayer capacity for a specific farm (after Burrows & Siemens, 1974).

As shown in Figure 2, the total cost curve has a minimum total cost point (C_{min}). The sprayer capacity at this minimum total cost is the optimum capacity (Ca_{opt})

Studies related to timeliness and machinery selection

A simulation model has been developed to determine available workdays from weather data and compute field operation timeliness (Tulu *et al*., 1974). The weather conditions included in this model are soil moisture and soil temperature. The approach is in accordance with the conceptual framework described by Rutledge & McHardy (1968). The method consists of a tractability criterion for the soil moisture distribution within 15 cm of the surface, computed using a soil moisture budgeting model. In the model, evaporation, runoff and infiltration are used on a daily basis. To compute freezing and thawing dates needed for the soil moisture budgeting, a model presented by Fridley & Holtman (1972) is used. The accuracy of the technique, analysed by comparing the results produced with recorded values (on-farm), has been shown to be good.

Hughes & Holtman (1976) presented an alternative approach for selecting field machinery systems and estimating costs. The study consisted of four steps: system power requirement determination, tractor selection, machine selection and cost analysis. In the model the size of all machine components was determined, a work schedule was set up, and the costs were estimated. The set of field operations was organised into subsets of operations to be completed during specific time periods. It was shown that the machinery should be selected as a system rather than individually.

Danok *et al*. (1980) developed an alternative analytical approach to machinery selection problems using a mathematical programming model. This model was a mixed integer model (MIP) which covered the integer nature of machinery decisions, the joint selection of machinery and crop, and the selection of machinery sets rather than individual machinery. The MIP produced optimal machinery sets for alternative weather probability levels. Instead of choosing a weather probability level in an arbitrary way, stochastic dominance analysis was used. Each of the original machine sets was introduced into the model and it was run for different probability levels to get the net farm income in each machine set and probability. Thus, the machine set that performs well under a wide range of probabilities can be found. The results showed the expected conclusion that a low probability of available field time leads to a need for larger machinery. Those crops that must be planted in the more uncertain periods were ruled out.

Von Bargen (1980) presented a procedure to determine the timeliness factor in a specific situation and the effect that this factor has upon machinery size for barley harvesting. From the model described by ASAE (1979), which assumes linear timeliness costs over a period of calendar days, and typical values for the timeliness factor from Hunt (1973), an alternative procedure was developed for determining a scheduling factor based upon a weighted average loss for each sub-period of the schedule. This average was related to the maximum loss at the end of the total scheduled period for the reference linear loss model.

Edwards & Boehlje (1980) developed a simulation model to estimate net machinery costs for maize-soybean farms. Timeliness costs, income tax savings, other machine operations, labour and ownership costs were considered. The performance of 10 machinery sets was simulated for several years. In this way, the expected mean cost and variance were estimated. The results showed that increased farm size led to an increase in least-cost machinery set sizes. It was also shown that decreasing the proportion of labour and field hours available per land unit increased the least cost machinery size. Furthermore, using a higher proportion of the total crop area for maize and expecting a higher gross revenue from the crop resulted in increased size of the least-cost machinery set.

Shahbazi (1992) examined the impact of energy supply on timeliness costs in a review of the energy requirements for several agricultural operations. It proved possible to minimise the effect of the energy supply by using alternative energy sources such as solar energy and by having good energy management, efficient machinery and energy conservation strategies.

De Toro & Hansson (2004) developed a simulation model for machinery performance comparing two different methods, *Daily Workability Method*, based on daily status of soil workability for a series of years, and *Average Workability Probability Method*, a simpler method based on average probability values of available workdays for operation and season. For calculating the timeliness costs with the Daily Workability Method, maturation days for individual fields were calculated using the model presented by Angus *et al*. (1981). The penalties for delays and other dates were based on a study by Mattson (1990) on daily temperature and photoperiod. With the Average Workability Probability Method, a linear equation described by ASAE (2006a) was used for calculating timeliness costs. The results showed that the Average Workability Probability Method can lead to underestimation of timeliness costs for sowing because it does not take account of chain effects. It was also shown that this method was not appropriate for harvesting operations under the conditions in the study area because the maturation of each field normally does not occur at the same time, so it was difficult to identify single periods without overlap. In contrast, the Daily Workability Method, although more complicated to apply, considered the chain effects of operation sequences.

Gunnarsson & Hansson (2004) examined the effects of changing to organic production on the optimal machinery size. Timeliness factors for organic production were calculated and a model based on mixed integer programming (MIP), developed by Nilsson (1976), was used for calculations of machinery costs and optimisation of sowing. Dates and timeliness penalties used in the study were based on statistical data. The methodology used was based on average data for soil workability, optimal sowing and harvesting dates. The variations between years were not handled. The most important factors in the comparison between organic and conventional farming were the lower yields and the higher product prices in organic farming.

Gunnarsson *et al.* (2005) estimated the timeliness factor for silage production for feeding dairy cows using the value of forage harvested at different times and considering changes in ration formulation, fodder costs and milk yields. Timeliness costs were calculated using the method based of mixed integer programming (MIP) created by Nilsson (1976). Machine costs were calculated by conventional methods using parameters from ASAE (2006b). The results showed that the first cut had higher timeliness factors, and therefore higher timeliness costs, mostly due to higher yield and faster crop development. Total timeliness costs were higher for organic silage production than for conventional. It was demonstrated that the number of workers and transport distance had an important effect upon the timeliness costs.

Gunnarsson (2008) developed a method to value forage for milk production considering higher crop production and lower feed value due to delays in harvesting. Timeliness costs for harvesting were calculated for different machinery systems and capacities, using mixed integer programming. The results showed that timeliness costs were much higher in the first cut than in subsequent cuts, with significant variations between years. Harvesting costs decreased when forage area was increased until a certain threshold area, beyond which the decreasing machine capacity made the timeliness costs increase since harvest took a longer time.

MATERIALS AND METHODS

Timeliness costs for crop sprayers were calculated using Equation 2. Most of the work in this study then focused on estimation of the two important parameters on which timeliness costs depend: the timeliness factor (K_t) and the workday probability (P_{pw}).

Timeliness factors were calculated using data from selected historical weed trials. Timeliness curves could be produced from at least three points where the effect of weed density on crop yield could be determined. Weather data were used to estimate suitable days for spraying. Timeliness costs were calculated for several sprayer capacities, as were the machinery and labour costs. Timeliness costs and optimum sprayer capacities were determined for four different crops for the specific case of a 400 ha farm.

Variations in the optimum capacity and total costs as a result of changes in grain price, yield and probability of suitable weather conditions were also studied.

Calculation of timeliness factors

The estimations of timeliness factors were based on previous work by Larsolle (2008) in which a number of Swedish weed control field trial data (1987-1992) suitable for estimation of timeliness factors were compiled and summarised. From the recorded yield and weed weight, Larsolle (2008) estimated the average weed weight timeliness factor for a number of trial series with broadleaved weed control in spring in winter wheat, spring wheat, oats, barley, oilseed rape and turnip rape.

In the report by Larsolle (2008), data from existing Swedish trials were used to construct timeliness curves with weed weight relative to the time of spraying. Major sources were the SLU field trial database and reports and reviews published in the Swedish Plant Protection

Conference. From the trial plans studied by Larsolle (2008), the trial data finally used are presented in Table 1. These trial plans all had at least three treatment dates.

Table 1. Weed control treatments used for constructing spraying timeliness curves (after Larsolle 2008, with permission)

Year	Plan	Crop	Description
1987 1988 1989	R5-1300	Winter wheat	Oxitril 4: 4.8 l/ha - slightly over recommended dose. Treatment: spring. Spray rate: 200 l/ha. Three dates: 1: When the crop starts growing, as soon as driving possible - beginning of tillering 2: End of tillering - beginning of stem elongation 3: Beginning of shooting stage - 1st-2nd node detectable Treatments: A: Untreated B: 4.8 l/ha - spraying date 1 C: 4.8 l/ha - spraying date 2 D: 4.8 l/ha - spraying date 3
1987 1988	UL5-1406	Barley	Oxitril. Dose: 2.5 l/ha Glean 20 DF 20 g/ha + 0.1% Citowett Five spraying dates. A: Untreated B: Oxitril, crop 2 leaves C: Glean, crop 2 leaves D: Oxitril, crop 4 leaves E: Glean, crop 4 leaves F: Oxitril, tillering main stage G: Glean, tillering main stage H: Oxitril, end of tillering, beginning of stem elongation I: Glean, end of tillering, beginning of stem elongation J: Oxitril, crop 1-2 nodes detectable K: Glean, crop 1-2 nodes detectable
1987 1988	UL5-1306	Winter wheat	Oxitril 4: 5 l/ha. Ally 20 DF: 30 g/ha Three spray dates, treatment: spring A: Untreated B: 5.0 l/ha Oxitril 4, as soon as driving possible in spring C: 30 g/ha Ally 20DF, as soon as driving possible in spring D: 5.0 l/ha Oxitril 4, end of crop tillering E: 30 g/ha Ally 20DF, end of crop tillering F: 5.0 l/ha Oxitril 4, beginning of stem elongation G: 30 g/ha Ally 20DF, beginning of stem elongation H: 5.0 l/ha Oxitril 4, crop 1 node detectable I: 30 g Ally 20DF, crop 1 node detectable J: 5.0 l/ha Oxitril 4, crop 2 nodes detectable K: 30 g/ha Ally 20DF, crop 2 nodes detectable
1991 1992 1994	R5-1927a	Barley	Duplosan DP/MCPA: 2.25 l/ha. A: Untreated B: Weed seed leaf stage C: 1 week later than treatment B D: 1 week later than treatment C

1991 1992 1994	R5-1927b	Barley	Express 75 DF: 6.0 l/ha + wetting agent. A: Untreated B: Weed seed leaf stage C: 0-4 days after treatment B D: 0-4 days after treatment C
1993	R5-1307	Barley	Duplosan MEKO: 0.9 l/ha. + Stomp SC: 1.5 l/ha. A: Untreated B: Weed seed leaf stage C: 1-7 days after treatment B D: 1-7 days after treatment C
1987	R5-4001 R5-4002	Oats, Spring wheat	Oxitril 4: 2.5 l/ha. A Untreated B Crop 1-2 leaves C Crop 3-4 leaves

In this Master thesis, the recorded yield of each treatment shown above was used to calculate the yield loss in relation to the maximum yield in the time series. Thus, the yield loss at the optimal time of herbicide application treatment was zero. The time point for the optimal spraying efficiency was set to day zero. Linear functions with the same shape as Figure 1 could be produced since each treatment had at least three points.

The timeliness function was constructed by calculating the average yield loss for all treatments and for all individual trials (within each trial plan series), for early application (before day zero) and delayed application (after day zero).

As shown in Figure 3, the timeliness factor could be calculated directly as the inclination of the trend line at each side of optimal time point. In other words, the differences in yield loss (segment a) for early or late spraying were divided by the corresponding period of days (segment b). The resulting units of the timeliness factor are relative yield loss day^{-1}. The final timeliness factor for each trial plan was calculated by the average of the two sides of the curve.

Once the timeliness factor for each trial plan had been determined, an average was made in order to calculate the timeliness factor for each crop: oats, barley, winter wheat and spring wheat. In this case, a weighted average was used, taking into account the number of trials existing for each trial plan. Thus, the timeliness factor for a trial plan with a large amount of trials carried more weight in the final average.

Calculations of workday probability

For calculating the probability of suitable weather conditions for spraying, data were taken from four Swedish Meteorological and Hydrological Institute (SMHI) weather stations located in different areas of Sweden: Sala (Västmanland county), Malmö (Västra Götaland county), Örebro (Örebro county) and Hällum (Västra Götaland county). The weather parameters used were precipitation, wind speed, temperature and relative air humidity. The available parameters were recorded at a frequency of one hour for 12 years (1996-2008). There were other weather data available, but the four parameters listed were considered the most influential for spraying.

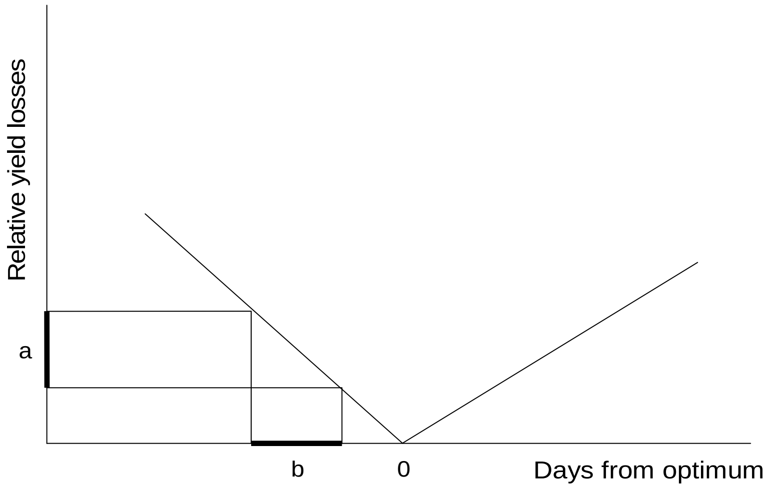

Figure 3. General form of the timeliness function where the timeliness coefficient was calculated with a/b.

The method to estimate workday probability *Pwd* in Equation 2 used a set of low and high limits for each parameter. In the case of wind speed, air humidity and precipitation, values over the high limit (L_h) resulted in the P_{wd} component of the specific parameter being equal to 0, while values under the low limit (L_l) resulted in it being equal to 1. In the case of temperature, the P_{wd} component was set to 1 for temperatures over the high limit and to 0 for temperatures under the low limit. The probability within the range of the low and high limits was interpolated between a high and low probability level. Thus, as shown in Figure 4, the probability component for each weather parameter ranged between 0 and 1.

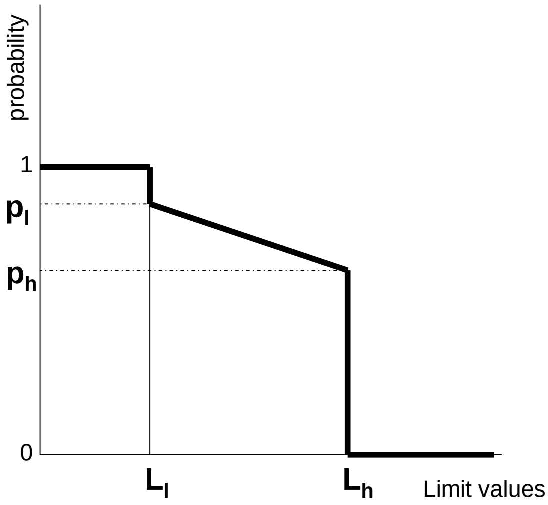

Figure 4. The function for calculating the probability component for the weather parameters, where L_h and L_l are high and low limits for each parameter and P_h and P_l are the probabilities for the high and low limits.

These parameter limits and the corresponding probability levels (Table 2) were chosen according to sources mentioned previously in the literature review section.

Table 2. Parameter limits and probability values (Prob.) used in the calculation of workday probability components for the weather parameters precipitation, wind, relative humidity and temperature

	Wind speed		**Precipitation**		**Temperature**		**Relative air humidity**	
	Value [m/s]	Prob.	Value [mm/h]	Prob.	Value [ºC]	Prob.	Value [%]	Prob.
Under low limit		1		1		0		1
Low limit	0	1	0	1	4	0.5	85	1
High limit	3	0.7	1	0	5	1	95	0.2
Over high limit		0		0		1		0

The workday probability was calculated considering only the spraying period defined as a date range. Specific periods were defined for each region and for autumn-sown and spring-sown crops. The periods for spraying {winter, spring} crops in the region of each weather station were set to: Hällum: {1-5/5, 20/5-1/6}, Örebro: {5-15/5, 25/5-1/6}, Sala: {10-20/5, 25/5-1/6}(K. Jahr, pers. comm. 2009) and Malmö: {10-20/4, 5/5-15/5} (H. Hallqvist, pers. comm. 2009).

A time period per day available for work was also defined. It was assumed that the sprayer operator would consider spraying at time between 7 am and 10 pm.

The probability of suitable weather conditions per hour was set as the lowest workday probability component among the four weather parameters for every station. Thus, considering the spraying periods and daily periods described above, an average workday probability was calculated for both autumn-sown and spring-sown crops. In order to obtain a single probability to be used for the timeliness cost calculations, an average workday probability for the four stations was calculated.

Machinery cost calculations

Sprayer costs were calculated by applying standard methodology (ASAE, 2006a,b). The costs were calculated for an area of 400 ha.

Data on the price of sprayers were provided by J. Andersson, AgroMaskin AB (pers. comm. 2009). These data consisted of prices for several combinations of boom lengths and tank volumes independently. The sprayer sizes studied and the retail price of each are presented in Table 3.

Table 3. Sprayer sizes (combinations of boom length and tank volume) studied and the retail price

Boom length (m)	**Tank volume (m^3)**	**Price (kSEK)**
12	1	193
24	3	447
24	5	581
36	3	594
36	5	727
40	3	648
40	5	782

The sprayer capacity for each combination of boom length and tank volume was calculated using the theoretical capacity and the time losses due to overlapping, the time required for turning, transport, filling or standstills for other reasons. The assumed parameters are shown in Table 4.

Table 4. Parameters used for sprayer capacity calculations

Spraying speed (km/h)	**Spray rate (l/ha)**	**Filling distance (km)**	**Transport speed (km/h)**	**Filling flow (l/min)**	**Time spray off**
10	200	4	20	200	5% of spray time

For calculating the ownership costs, depreciation of the machine, interest on the investment, and the cost of taxes, insurance and housing of the machine were included. Equation 3 was used to determine this cost, with parameter values as shown in Table 5:

$$\mathrm{Cos} = \frac{\left(\frac{\mathrm{P_u - S_v}}{\tau_\mathrm{L}}\right) + \left(\frac{\mathrm{P_u - S_v}}{2}\,\frac{\mathrm{Ir}}{100}\right) + \left(\mathrm{S_C\,A_S}\right) + \mathrm{K}}{\mathrm{A}} \qquad \text{Equation 3}$$

where C_{os}= total annual ownership costs, SEK/ha

P_u = purchase price of the machine, SEK

S_v = selling price, SEK

τ_L = useful life of the machine, years

I_r = real annual interest rate, decimal

S_c = storage cost, SEK/m^2

A_s = storage area, m^2

K = annual cost of taxes and insurance, SEK

A = area, ha.

Table 5. Parameters used for ownership cost calculations

Interest rate (%)	**Storage cost (SEK/m^2)**	**Storage area (m²)**	**Selling price**	**Useful life (years)**	**Insurance tax (SEK/year)**
5	60	8	1% of purchase price	25	50

The operating costs associated with use of the machine were also calculated, using Equations 4-6. They included the cost of repair and maintenance, fuel and oil, and labour. The parameters used for estimating those costs are shown in Table 6:

$$\mathrm{C_{rm}} = \frac{1}{A \cdot \tau_\mathrm{L}}\left(\mathrm{Rf_1\;P_u\;J_f}\left(\frac{\tau_\mathrm{L}\;\mathrm{A\,n}}{\mathrm{C_a}\;1000}\right)^{\mathrm{Rf_2}}\right) \qquad \text{Equation 4}$$

where C_{rm} = repair and maintenance cost, SEK/ha
Rf_1 = repair factor for sprayer, decimal
J_f = adjustment factor for maintenance cost, decimal
n = number of sprays
C_a = sprayer capacity, ha/h
Rf_2 = repair factor for sprayer, decimal.

$$C_{fo} = \frac{Q_i \ A \ P_i (1 + Q_l)}{A} \qquad \text{Equation 5}$$

where C_{fo} = fuel and lubricant cost, SEK/ha
Q_i = fuel consumed, l/ha
P_i = fuel price, SEK/l
Q_l = lubricant consumed as a proportion of fuel consumed, decimal.

$$C_L = \frac{L_c}{C_a} \qquad \text{Equation 6}$$

where C_L = labour costs, SEK/ha
L_c = cost of labour, SEK/h
C_a = sprayer capacity, ha/h

Table 6. Parameters for operating costs calculations

Repair factor 1	Adjustment factor for mainten-ance	Repair factor 2	No. of spray s	Fuel con-sumed (l/ha)	Lubricant consumed	Fuel price (SEK/l)	Cost of labour (SEK/h)
0.4	0.9	1.3	2	2	5% of fuel consumed	7	200

Timeliness costs were calculated using Equation 2. Crop yield was set using data from Statistics Sweden. Data on the production of oats, wheat and barley in the four station counties over the last six years were used to calculate an average yield for each crop. The available hours for field work were set at 8 h/day. For estimating the crop value, the report ‘Guidelines for Fertilizing and Liming’ (*Riktlinjer för gödsling och kalkning*) published by the Swedish Board of Agriculture (Jordbruksverket, SJV) before each growing season was utilised. In the latest guidelines (for 2009) SJV presents recommendations for a range of grain price levels from 1.00 to 2.00 SEK/kg. For estimating the timeliness costs for the specific cases, grain price was set at a medium value of 1.5 SEK/kg.

Optimum sprayer capacity

The total costs C_{total} were calculated as the sum of machinery costs, labour costs and timeliness costs (see Equation 7) for each crop (see Figure 2):

$$C_{total} = C_m + C_L + C_t$$ Equation 7

where C_m = machinery costs [SEK/ha] (see Equation 8)
C_L = labour costs (see Equation 6)
C_t = timeliness costs.

Total machinery costs (depreciation, interest, taxes, insurance, housing, fuel and lubricant) were calculated using Equation 8:

$$C_m = C_{os} + C_{rm} + C_{fo}$$ Equation 8

where C_m = total machinery costs (Equation 3)
C_{os} = ownership costs (Equation 4)
C_{rm} = repair and maintenance costs
C_{fo} = cost of fuel and oil (Equation 5).

A second order polynomial function was fitted to the total machinery costs (C_{total} in Equation 7) using linear regression. From this function the minimum cost was then calculated by finding the capacity where the derivative = 0. The capacity at which total costs are at a minimum is the optimum capacity.

Variations due to grain price, yield and workday probability

The variations due to fluctuations in grain price, yield and the probability of suitable weather conditions were studied using the same procedure as above, but varying the value range of these parameters.

In the case of grain price, the range studied was from 1 SEK/kg to 2 SEK/kg. The yield range depended on the crop, with lower yield and higher yield set according to data from Statistics Sweden for the last six years. The probability of suitable weather conditions (workday probability) ranged between 0.2 and 0.6.

In this way, optimum sprayer capacity for each parameter value was calculated.

Finally, the resulting optimum capacity was used to calculate total costs for the different parameter values. Thus, variations in total costs due to fluctuations in grain price, yield and workday probability were also calculated.

RESULTS

Timeliness factors

The estimations of timeliness factors (K_t) for each trial plan are summarised in Table 7, where the number of available trials is specified. As explained in the Materials and Methods section, K_t was calculated from experimental data (shown in Figures A.1-A.10 in Appendix A), where relative yield loss was calculated in relation to the application time (no. of days from optimal day of spraying) for each treatment.

Table 7. Timeliness factors for each trial plan, estimated using field experimental data and crop, herbicide, dose and number of trials for each trial plan

Trial plan	Crop	Herbicide	Dose	K_t (relative yield loss day^{-1})	No. trials
R5-4001	Oats	Oxitril 4	2.5 l/ha	0.015	6
R5-4002	Spring wheat	Oxitril 4	2.5 l/ha	0.003	6
R5-1300	Winter wheat	Oxitril 4	4.8 l/ha	0.007	9
R5-1406a	Barley	Oxitril 4	2.5 l/ha	0.012	3
R5-1406b	Barley	Glean	20.0 g/ha	0.005	3
R5-1306	Winter wheat	Oxitril 4	5.0 l/ha	0.002	3
R5-1306	Winter wheat	Ally	30.0 g/ha	0.002	3
R5-1927a	Barley	Duplosan	2.25 l/ha	0.006	18
R5-1927b	Barley	Express 75	6.0 l/ha	0.005	18
R5-1307	Barley	Duplosan+Stomp	0.5+1.5 l/ha	0.006	2

Workday probability

Figure 5 shows the workday probability (P_{wd}) estimated using weather data and the procedure illustrated in Figure 4 for each station and for both autumn-sown and spring-sown crops. The average probability for autumn-sown crops was 0.36 and for spring-sown crops 0.39.

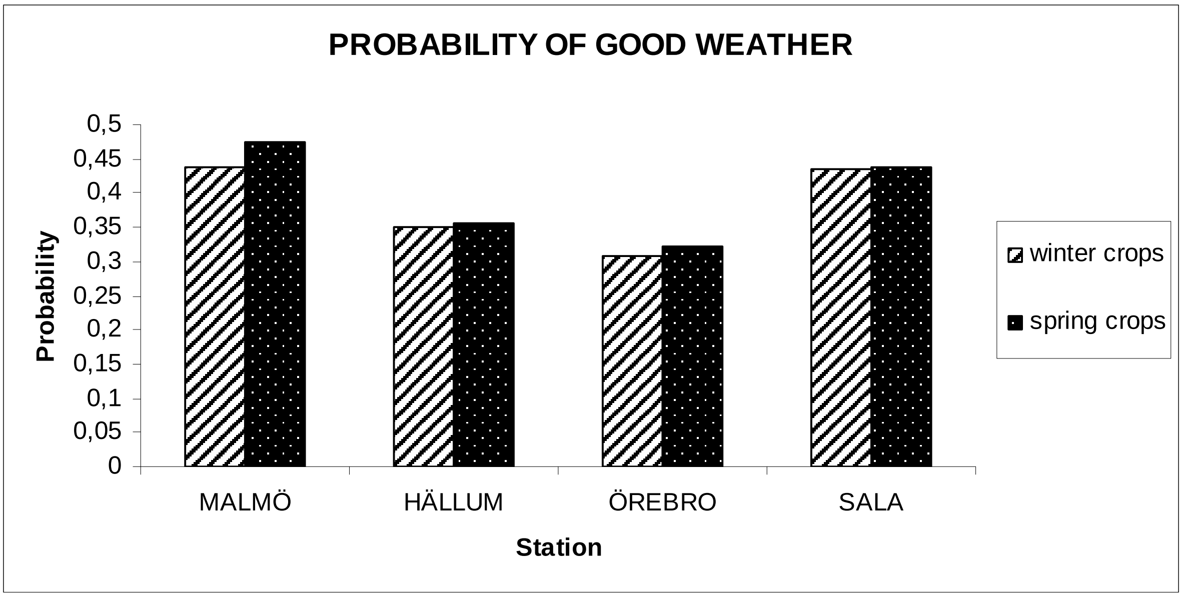

Figure 5. Workday probability (Pwd) for the four weather station regions Malmö, Hällum, Örebro, and Sala.

The standard deviations between years for workday probabilities are presented in Table 8.

Table 8. Standard deviations between years for the probability of good weather (P_{wd})

	Malmö	Hällum	Örebro	Sala	Average
Winter crops	0.12	0.13	0.08	0.09	0.10
Spring crops	0.10	0.17	0.16	0.15	0.15

Machinery and labour costs

The machinery and labour costs were calculated for different boom widths and tank volumes. The combinations of sizes studied (see Table 2) together with the capacities for the sprayer boom length and tank volume combinations, calculated as described in the Materials and Methods section, are presented in Table 9.

Table 9. Sprayer sizes and capacities studied

Boom width (m)	Tank volume (m^3)	Spraying capacity (ha/h)
12	1	5.6
24	3	11.8
24	5	13.5
36	3	14.0
36	5	16.5
40	3	14.6
40	5	17.3

Machinery and labour costs with respect to sprayer capacity, calculated using Equations 8 and 6 respectively, are shown in Figures 6 and 7. The line is a second-degree linear function fitted to the seven sprayer boom/tank combinations studied.

Timeliness costs

The weighted timeliness factor (K_t) average, calculated from the timeliness factors for each trial plan, and the average yield are shown in Table 10. The timeliness costs could then be calculated with Equation 2 using the timeliness factors for each crop (Table 10), the average yield for each crop, an area of 400 ha, a crop value of 1.5 SEK/kg, the expected hours for field work of 8 h/day and the workday probability presented in Figure 5. The resulting timeliness costs (C_t) with respect to sprayer capacity are shown in Figures 8-11 for oats, sprig wheat, winter wheat and barley, respectively, all with a fitted second degree linear trendline.

Table 10. Timeliness factor and yield for each crop

Crop	Average timeliness factor (relative yield loss day^{-1})	Yield (kg/ha)
Oats	0.0150	3498
Winter wheat	0.0049	6407
Spring wheat	0.0035	5270
Barley	0.0059	4696

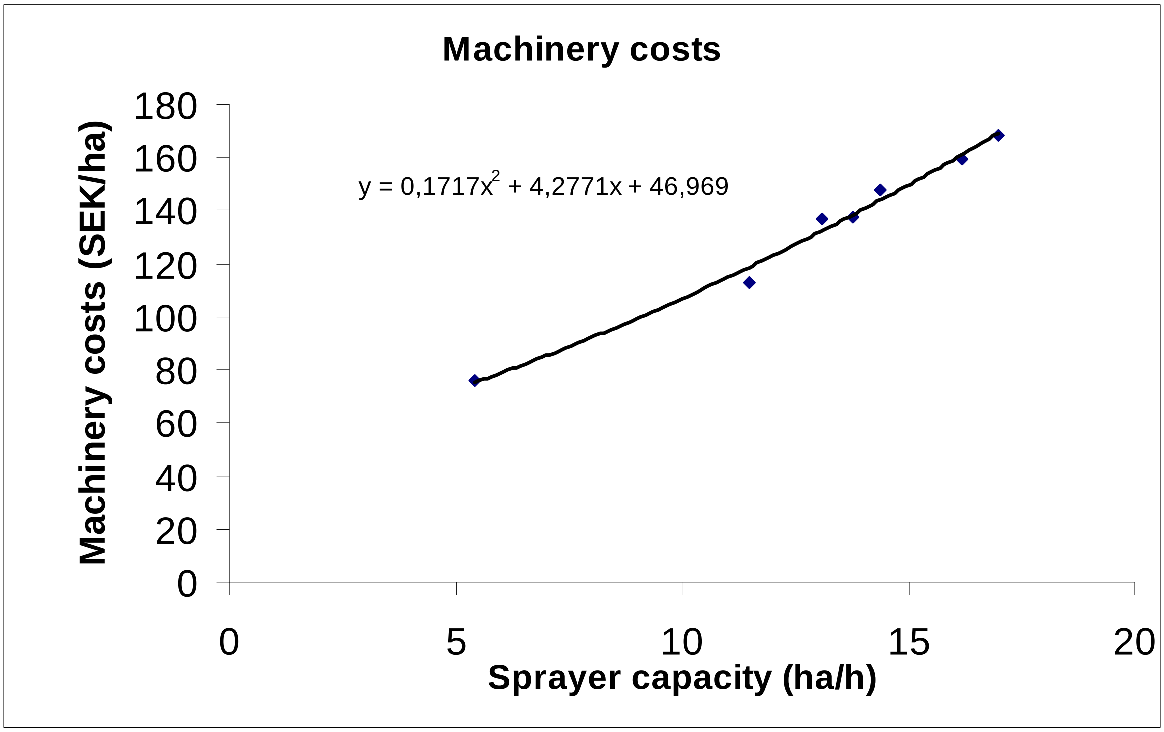

Figure 6. Machinery costs in relation to sprayer capacity.

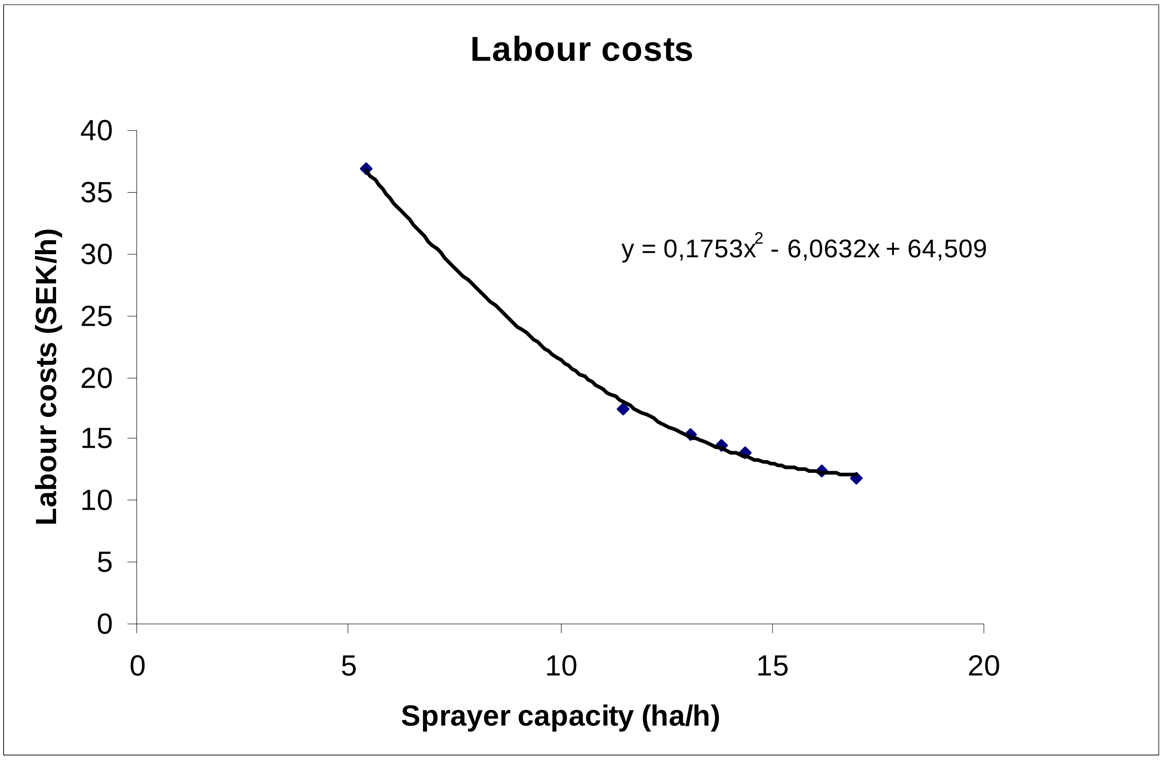

Figure 7. Labour costs in relation to sprayer capacity.

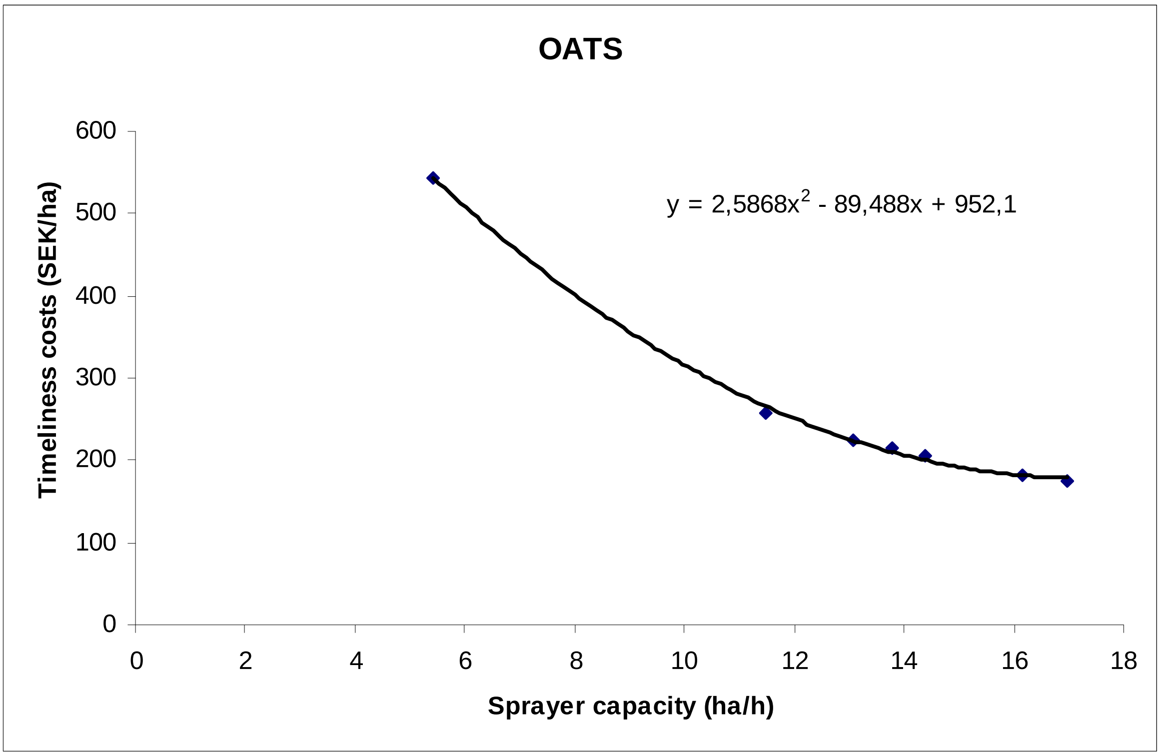

Figure 8. Timeliness costs in relation to sprayer capacity for oats, calculated using the timeliness factor and the yield presented in Table 10, an area of 400 ha, a crop value of 1.5 SEK/kg, the expected hours for field work of 8 h/day and the workday probability 0.39 .

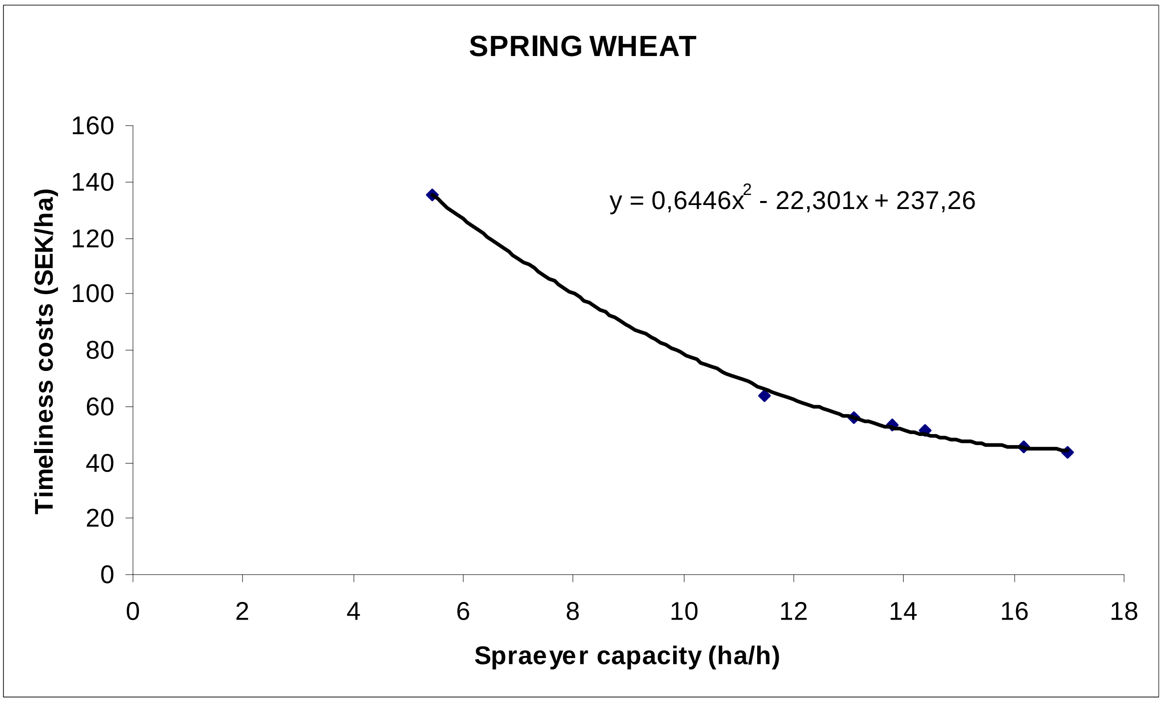

Figure 9. Timeliness costs in relation to sprayer capacity for spring wheat, calculated using the timeliness factor and the average yield presented in Table 10, an area of 400 ha, a crop value of 1.5 SEK/kg, the expected hours for field work of 8 h/day and the workday probability 0.39.

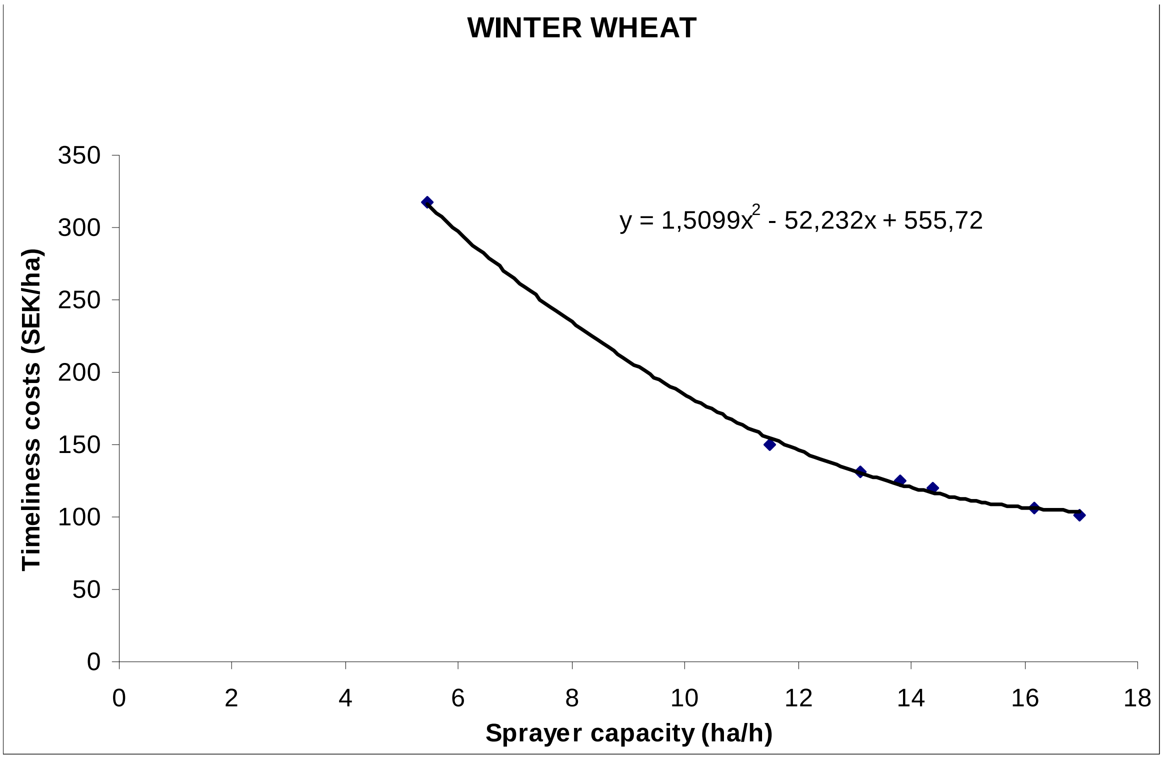

Figure 10. Timeliness costs in relation to sprayer capacity for winter wheat, calculated using the timeliness factor and the average yield presented in Table 10, an area of 400 ha, a crop value of 1.5 SEK/kg, the expected hours for field work of 8 h/day and the workday probability 0.36.

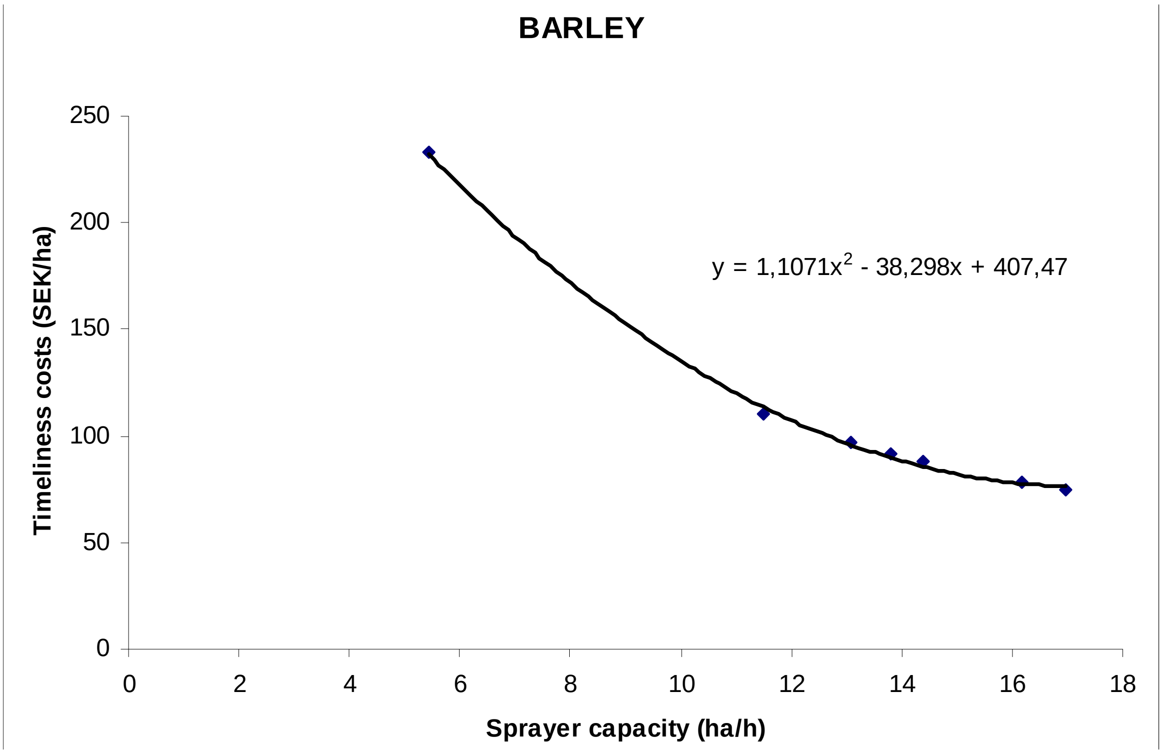

Figure 11. Timeliness costs in relation to sprayer capacity for barley, calculated using the timeliness factor and the average yield presented in Table 10, an area of 400 ha, a crop value of 1.5 SEK/kg, the expected hours for field work of 8 h/day and the workday probability 0.39.

Optimum sprayer capacity

Figures 12-15 show the total costs from Equation 7, accumulated from the three components machinery costs, labour costs and timeliness costs for all four crops. A second degree linear function was fitted using regression to the total costs calculated for the seven sprayer boom length and tank volume combinations studied (see Table 9).

Optimum sprayer capacities were calculated from the zero derivative of the fitted polynomial function (as described previously). The resulting optimal capacities are summarised in Table 11.

Table 11. Optimum sprayer capacity and minimum total cost

Crop	Optimum sprayer capacity (ha/h)	Minimum total cost (SEK/ha)
Oats	16	354
Spring wheat	12	202
Winter wheat	15	274
Barley	14	243

Variations due to grain price, yield and workday probability

Figures B.1-B.24 in Appendix B show how optimum capacity and total costs varied with grain price, yield and workday probability.

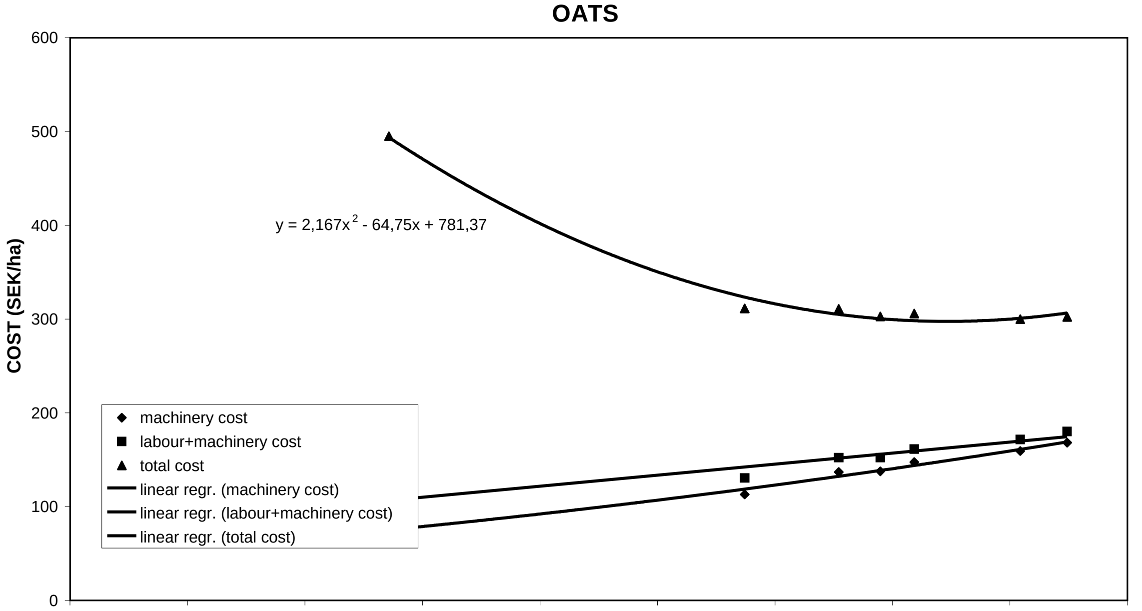

Figure 12. Total costs, displayed as the sum of the three components machinery, labour and timeliness costs, in relation to sprayer capacity for oats, calculated using the timeliness factor and the average yield presented in Table 10, an area of 400 ha, a crop value of 1.5 SEK/kg, the expected hours for field work of 8 h/day and the workday probability presented in Figure 5.

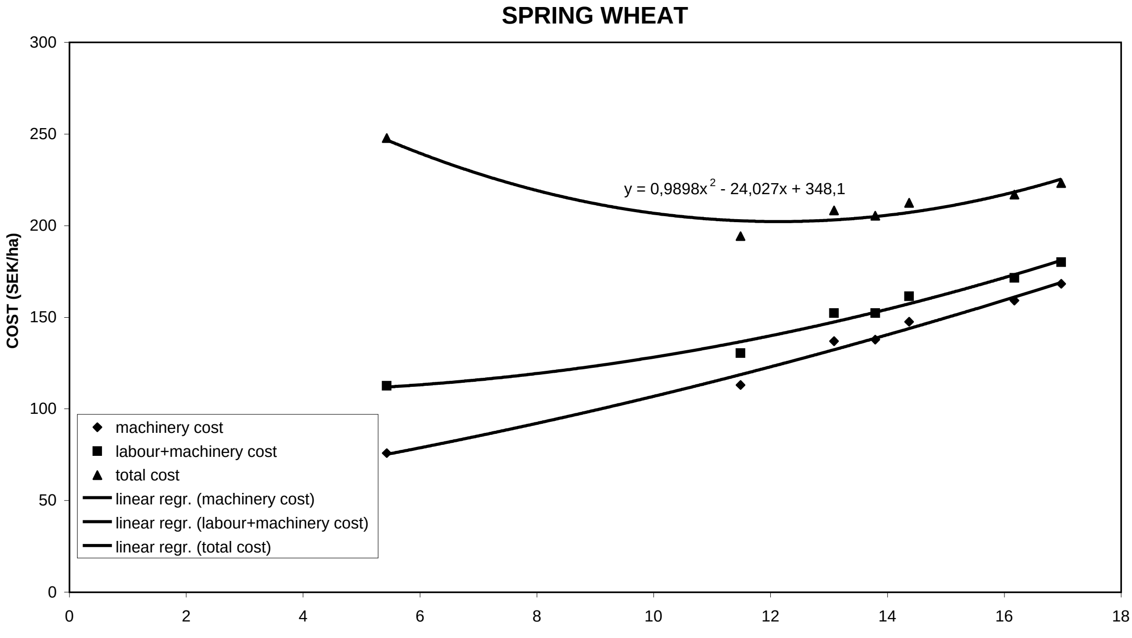

Figure 13. Total costs, displayed as the sum of the three components machinery, labour and timeliness costs, in relation to sprayer capacity for spring wheat, calculated using the timeliness factor and the average yield presented in Table 10, an area of 400 ha, a crop value of 1.5 SEK/kg, the expected hours for field work of 8 h/day and the workday probability presented in Figure 5.

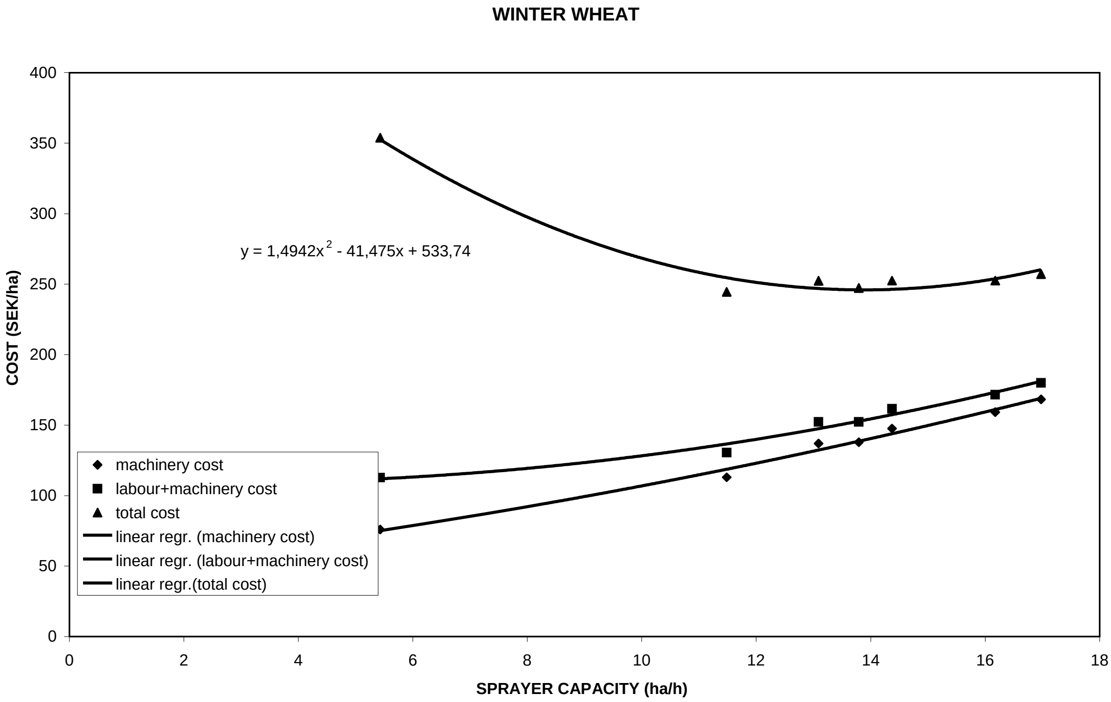

Figure 14. Total costs, displayed as the sum of the three components machinery, labour and timeliness costs, in relation to sprayer capacity for winter wheat, calculated using the timeliness factor and the average yield presented in Table 10, an area of 400 ha, a crop value of 1.5 SEK/kg, the expected hours for field work of 8 h/day and the workday probability presented in Figure 5.

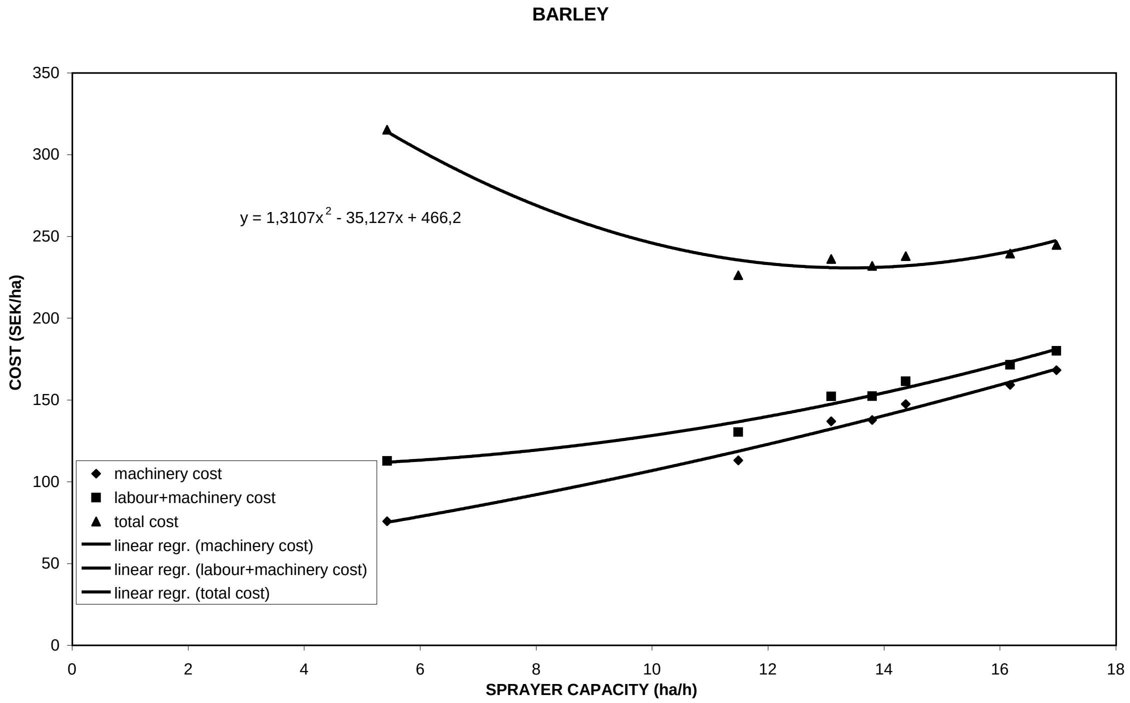

Figure 15. Total costs, displayed as the sum of the three components machinery, labour and timeliness costs, in relation to sprayer capacity for barley, calculated using the timeliness factor and the average yield presented in Table 10, an area of 400 ha, a crop value of 1.5 SEK/kg, the expected hours for field work of 8 h/day and the workday probability presented in Figure 5.

DISCUSSION

Timeliness factors

No estimations of the timeliness factor for spraying were found in the literature. In studies where timeliness costs were calculated, estimations of timeliness factors were usually available, for instance in Von Bargen (1980) or De Toro & Hansson (2004). This was the case for operations such as sowing and harvesting. In frequently used machine data (for example ASAE (2006) Standard D497), there are estimated timeliness factor values for tillage, sowing and harvesting, but not for crop spraying. The lack of timeliness factor estimations for spraying was one of the main motivations behind this study.

The procedure to estimate the timeliness factors for weed control developed here has the advantage of using experimental data recorded in the actual areas for which calculations were produced. The field experiments are quite unique, as the recorded crop yield is the result of conditions in the specific area and season, but they can be considered representative for other parts of Sweden since these conditions do not vary greatly in other areas of Sweden. The available trial data used in this thesis included several trials for each trial plan and several treatment dates for each trial, i.e. large amounts of data, so the timeliness factors calculated should be realistic. Thus, the use of these factors for timeliness cost calculations should be more accurate than the use of general factors calculated for a different area.

However, the timeliness factors also resulted in a high degree of uncertainty, since the variations between individual trials were high (see Figure A.9). Final timeliness factors were calculated based on averages, which could lead to errors when estimating the timeliness costs for a specific situation. For example, it was assumed that untimely spraying gave the same yield losses in all years. In reality, however, yield losses are higher in some years and lower in others because of higher or lower values of the timeliness coefficient. Furthermore, variations in yield can depend on other factors in addition to untimely spraying, but such factors are very difficult to control since the prevailing conditions are never exactly the same on each application occasion.

The same number of trials was not used for each trial plan, which made some estimations of timeliness factor slightly unreliable in some cases. In other words, in the trial plans where only two or three trials were available, resulting yield could have varied not only because of application date, but also because of the natural variations between individual trials. This would lead to a relatively high error in the estimation of timeliness factors. For that reason, a weighted average was used to calculate the final timeliness factor for each crop.

In this regard, the end-use of the calculated timeliness costs must be borne in mind. One important case is deciding on investment. In this case, the cost of the investment (for example a new sprayer) would be depreciated over several years. Thus, although there could be some error in estimation of the timeliness factor, the timeliness costs will not vary to a large extent since they are studied over a several-year period.

The timeliness factors produced showed a much higher loss per day for oats and barley in some cases (Trial plans R5-4001 and R5-1406a) than for winter wheat (R5-1306), as shown in Table 7. The rest of the factors differed less in quantity. As mentioned previously, the difference between these two crops and the other crops may be the result of natural variations rather than a statistically significant result. It must be taken into account that trial plans R5-4001 and R5-4002 had only six and three trials, respectively, while two of the other barley trial plans (R5-1927a and R5-1927b) had eighteen trials and a 50% lower timeliness factor.

Workday probability

The four weather stations chosen were selected in order to give representative weather data for different zones of Sweden. The weather parameters used were considered to be the more important ones for crop spraying. There are other factors such as radiation that can affect the effectiveness of spraying, but to a lesser degree. In the case of wind, a high limit of 3 m/s was considered an appropriate limit over which there will be a risk of drift, even though some studies state a limit of about 4.5 m/s. In this instance, the probability of suitable weather assigned for the limit of 3 m/s was higher than the probability that would have been assigned for 4.5 m/s. Thus, this criterion difference has been taken into account. The chosen limit for rain was 1 mm/h, that means that for every hour it is not raining the probability of good weather would be 1. In practice, this would not always be the case, since if it had been raining before spraying operations, the effectiveness of the herbicide could be insufficient. The method used for calculating the probability depending on rain does not take this aspect into account. The temperature limit was set at 5 ºC and it was considered that higher temperatures would result in a probability of suitable weather equal to 1, but much higher temperatures could reduce the effect of the herbicide. However, in the time period for spraying in the spring, temperatures are not usually very high. The humidity limit was set at 95%, as higher humidity makes it more difficult for the drops to stay and dry on the leaves. A low relative humidity limit was not considered, although very low humidity could result in drift caused by high spray liquid evaporation.

The probability of suitable weather conditions for each hour was set to the lowest probability among the specific probabilities for the four parameters rain, relative air humidity, temperature and wind speed. Another way to calculate the total probability would be to use the product of the four parameters, but the lowest probability among the four parameters was considered a suitable method for estimating the final workday probability. The choice between the two methods only had minor effects on the results.

The resulting probabilities for each weather station showed that there was a difference between Örebro and Hällum, and between Malmö and Sala, with the latter two having a higher probability. The average probability was estimated at 0.36 and 0.39 for winter and spring crops, respectively. This is lower than the estimated probabilities for other operations such as tillage (ASAE, 2006), sowing or harvesting (De Toro & Hansson, 2004). Although in this study an average was made in order to give a single probability for the timeliness cost estimations, in reality the workday probability would depend on the region studied. However, it must be borne in mind that different weather conditions are associated with different spraying periods, so the workday probability should not vary too much between regions.

Cost calculations and optimum capacity

The machinery cost curve (Figure 6), which included the ownership costs and operating costs (labour costs excluded), showed a variation of 100 SEK/ha from the lower capacity to the higher in an almost linear trend. The labour cost curve (Figure 7) showed a variation of 25 SEK/ha, which was more noticeable from a capacity of 5 to 10 ha/h.

The diagrams of total costs for the different crops (Figures 12-15) show the effect of timeliness costs on the total costs. For oats, there were much higher total costs in absolute terms and a higher variation in these total costs for the lower capacities than for the rest of the crops. There was a variation of 300 SEK/ha for oats between the choice of a capacity from 5 to 13 ha/h because oats had a much higher timeliness factor. This increased the timeliness costs for low capacities since the yield loss per day of delay was higher. The crop with the second highest costs was winter wheat, since although it did not have a higher timeliness factor than spring wheat and barley, it had a higher yield, making the timeliness costs higher. The variation in this case was less pronounced, 150 SEK/ha for the capacity range 5 to 11 ha/h. The barley showed a variation of 100 SEK/ha from 5 to 12 ha/h, while the spring wheat showed a much lower variation because of its lower timeliness factor. On the other hand, all the curves showed a similar tendency at high sprayer capacities, with a relatively low variation in the total costs for capacities over 10 ha/h.

Optimum capacity for each crop in the specific case studied (Table 11) ranged between 12 and 16 ha/h. These capacities fitted the minimum cost for each case. The minimum total costs for the specific case studied were 354 SEK/ha for oats, 274 SEK/ha for winter wheat, 243 SEK/ha for barley and 202 SEK/ha for spring wheat. The timeliness cost component in this total minimum cost was as important as the machinery costs or even higher in the case of oats. This differs from total costs for other operations such as harvesting or sowing, where the machinery costs are much higher than the timeliness costs (De Toro & Hansson, 2004; Gunnarsson, 2008).

Choosing these capacities would be the optimal selection for a farmer in economic terms. However, higher capacities could still be chosen since, as discussed, the total costs did not vary greatly at higher capacities. Thus, a farmer could consider it worthwhile to choose a higher capacity in order to finish spraying earlier and have time for other activities. In other words, other factors can be taken in account when choosing sprayer capacity, not only the minimum cost. This aspect was not considered in this study.

Variation in optimum capacity and total costs with grain price, yield and workday probability

Grain price, yield and the probability of suitable weather conditions are important factors to take into account, since they are uncertain parameters and it is only possible to make estimations. Thus, it could be of value to know how variations in these factors affect sprayer capacity selection and the total costs.

The grain price varies each year due to market conditions, leading to variations in optimum capacity and total costs (Figures B.1-B.8). In oats, there was a variation of more than 1 ha/h in the optimum capacity when the grain price ranged between 1 and 2 SEK/kg. Wheat and barley underwent higher variations in optimum capacity of more than 2 ha/h. Thus, it can transpire that the chosen capacity is insufficient if the actual price is greater than the assumed price, or excessive if the actual price is lower. For that reason, a sprayer capacity selected for an estimated grain price could lead to greater than estimated costs if the grain price increases. The total costs can vary by more than 120 SEK/ha when grain price ranges between 1 and 2 SEK/kg for oats, 40 SEK/ha for spring wheat, 80 SEK/ha for winter wheat and 60 SEK/ha for barley (Figures B.1-B.8). This means that when an optimum capacity has been calculated for a estimated price between 1 and 2 SEK/ha, the real total costs will be greater when the grain price exceeds the assumed price used for the optimum capacity calculation.

Crop yield is another uncertain factor. Although it is possible to find yield data for past years, it is impossible to know the yield of the following season. As Figures B.9-B.16 show, there was a variation of around 2 ha/h in the optimum capacity for oats and barley and a variation of 1 ha/h for wheat when the yield ranged between extreme values. In total cost terms, the difference could be more 130 SEK/ha for oats, and between 40 and 60 SEK/ha for the other crops. Thus, an optimum capacity calculated for a medium yield could turn out to be insufficient if the yield is higher, which would lead to higher total costs.

As regards variations in workday probability, an estimation of the workday probability was made in this study. The reality is that different areas could have different weather conditions and these conditions will affect the timeliness costs. As shown in Figures B.17- B.24, this parameter made the most noticeable change in optimum capacity. Thus, if the workday probability increases from 0.2 to 0.6, the optimum capacity will decrease by 1 ha/h for oats, more than 2 ha/h for winter wheat, 4 ha/h for spring wheat and 3 ha/h for barley. This highlights the importance of accurate estimation of the workday probability for the region studied, since the use of inaccurate probability values will lead to suboptimal choice of sprayer capacity and ultimately economic losses. For instance, if a medium workday probability of 0.4 had been used in the calculations, the losses would have been around 125 SEK/ha for oats if the real probability was 0.2. For the other crops the losses would be lower, between 60 and 40 SEK/ha.

CONCLUSIONS

- The timeliness factor for spraying herbicides against broad-leaved weeds in the spring was estimated to be 0.0150 relative yield loss days^{-1} for oats, 0.0059 relative yield loss days^{-1} for barley, 0.0049 relative yield loss days^{-1} for winter wheat and 0.0035 relative yield loss days^{-1} for spring wheat.
- The average timeliness factor for oats was much higher than the factors for other crops. The reliability of these values is questionable, however, since they were calculated for a small amount of data.
- Malmö and Sala had better weather conditions for spraying, since the workday probability was higher (about 0.45) than the probability for Hällum and Örebro (0.35 and 0.30 respectively).
- The average workday probability for spraying was estimated to be 0.36 for winter crops and 0.39 for spring crops. This probability is lower than the workday probability for other operations.
- The timeliness cost component in the total costs for the studied case of a farm of 400 ha, was as important as the machinery costs for the crop sprayer, in contrast with other operations where the machinery costs are much higher than the timeliness costs.
- Timeliness costs decreased as sprayer capacity increased for the studied case of a farm of 400 ha, particularly at low capacities, while for high capacities the variation was much less. Thus, it should be possible to choose excess capacity over the minimum total cost capacity without greatly increasing the total costs.
- Grain price, yield and weather conditions are variable factors that have an influence on optimum sprayer capacity and total costs. This influence is particularly significant in the case of weather conditions. Thus, a variation of 0.2 in the workday probability could lead to a increase of 125 SEK/ha in the total costs for oats.

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Me gustaría dedicar este trabajo fin de carrera a la persona más sabia que he conocido, en agricultura y en lo que no es agricultura, mi tío José.

APPENDIX (A)

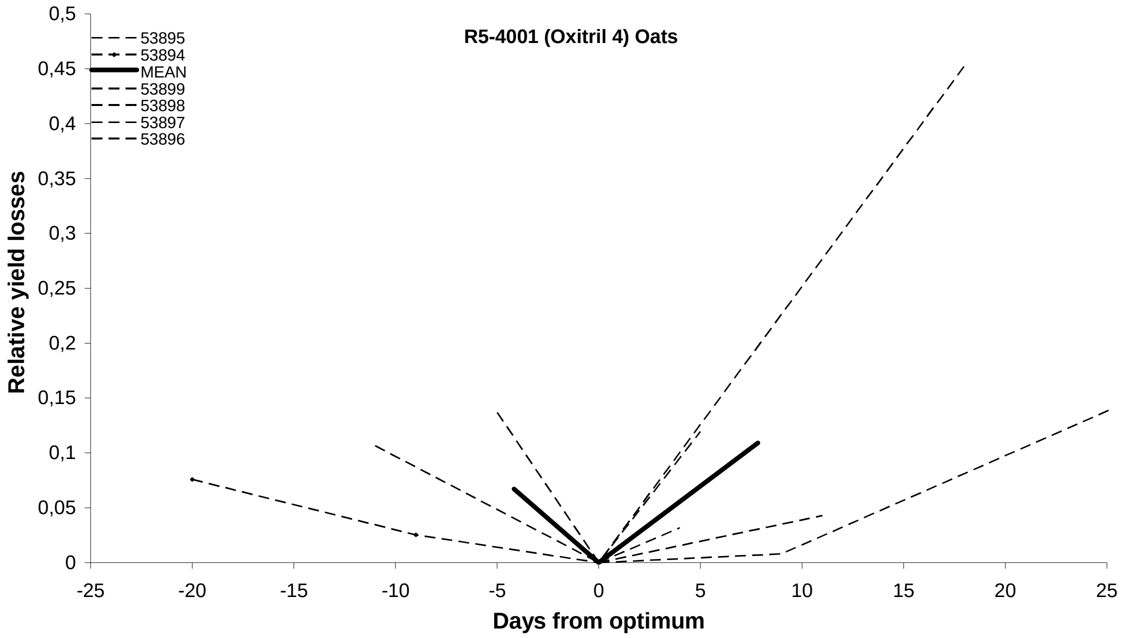

Figure A.1. Yield losses related to days from optimum for a Oxitril 4 (2.5 l/ha) treatment for oats.

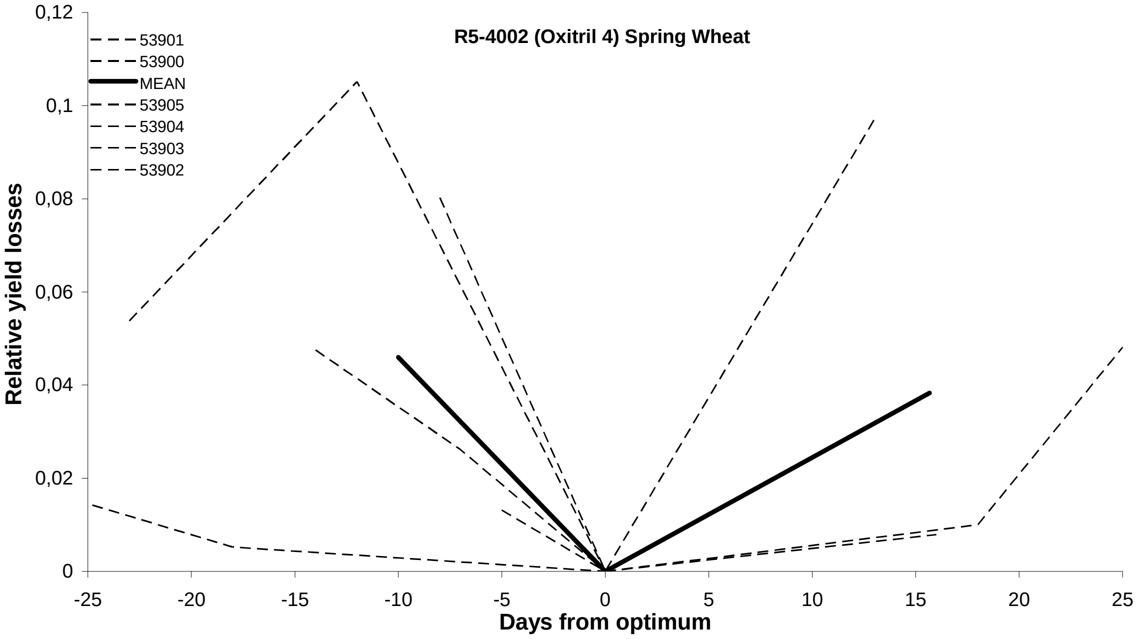

Figure A.2. Yield losses related to days from optimum for a Oxitril 4 (2.5 l/ha) treatment for spring wheat.

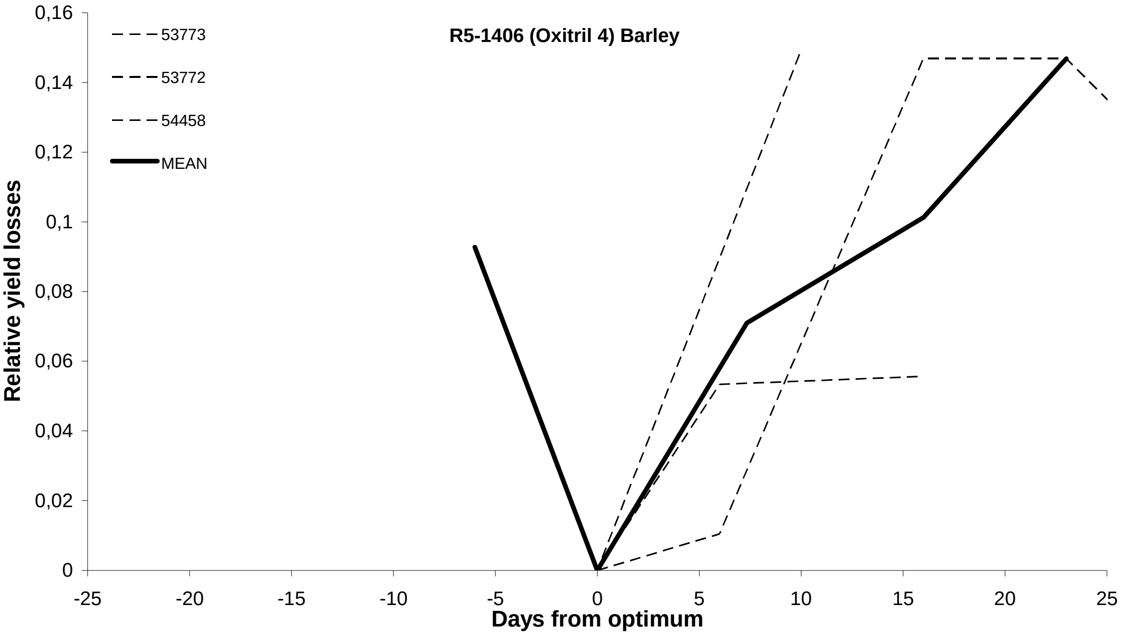

Figure A.3. Yield losses related to days from optimum for a Oxitril 4 (2.5 l/ha) treatment for barley.

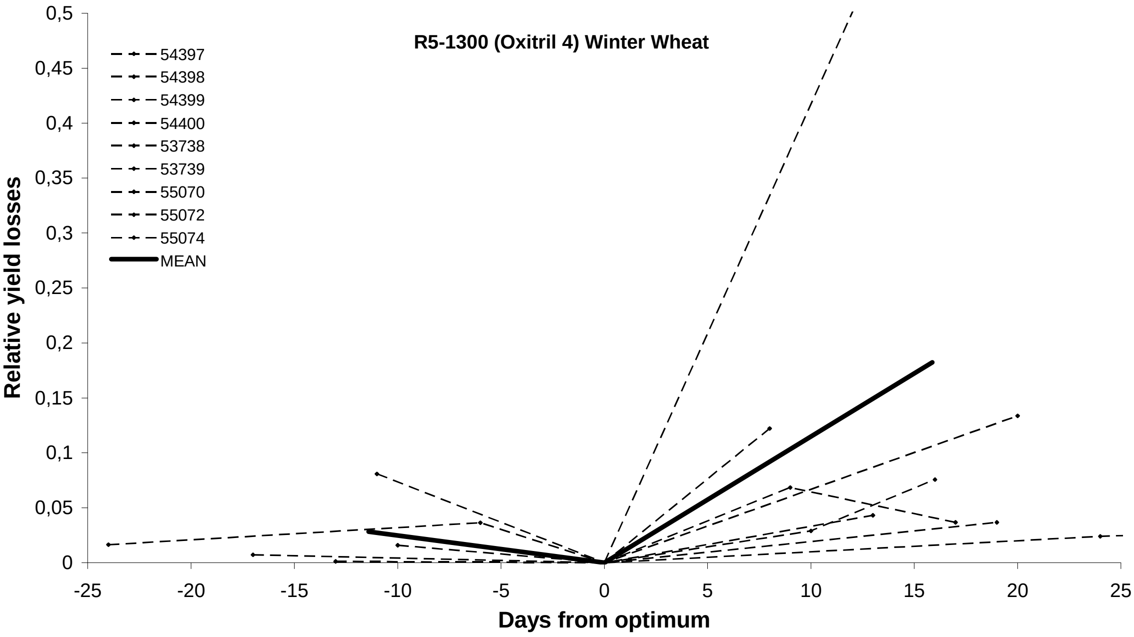

Figure A.4. Yield losses related to days from optimum for a Oxitril 4 (4.8 l/ha) treatment for winter wheat.

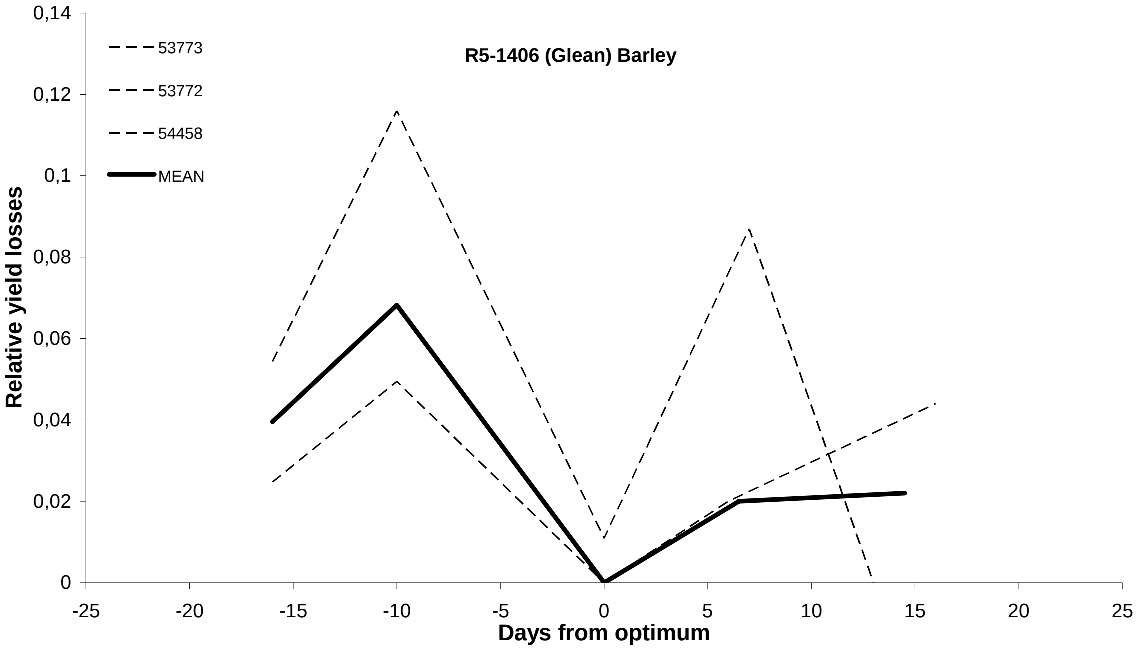

Figure A.5. Yield losses related to days from optimum for a Glean (20 g/ha) treatment for barley.

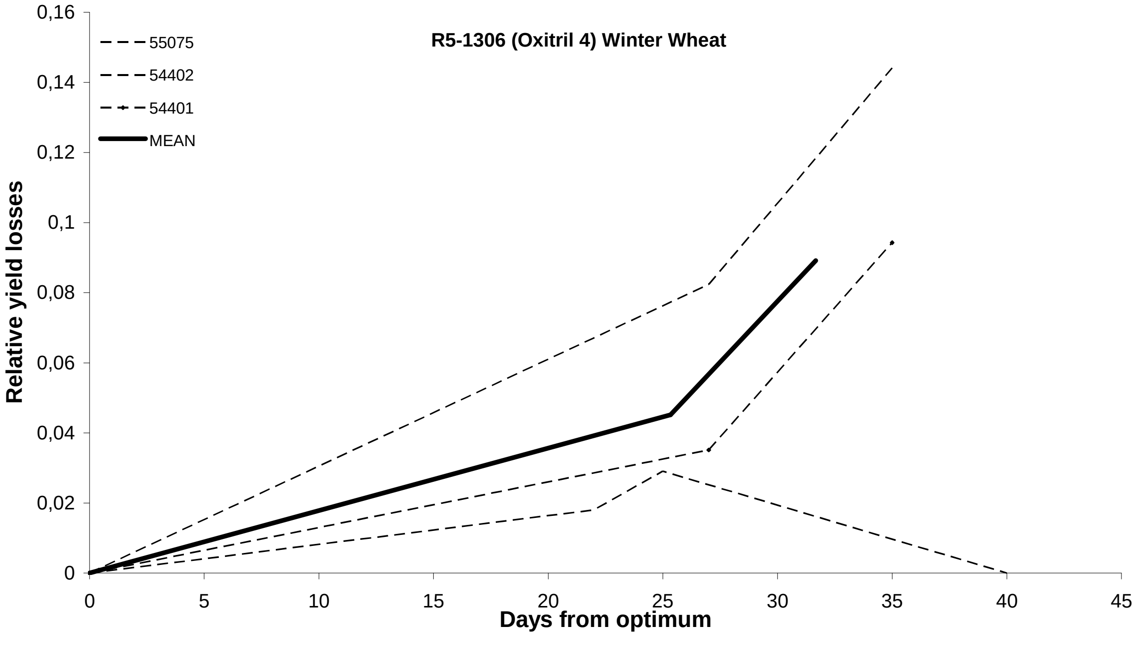

Figure A.6. Yield losses related to days from optimum for a Oxitril 4 (5 l/ha) treatment for winter wheat.

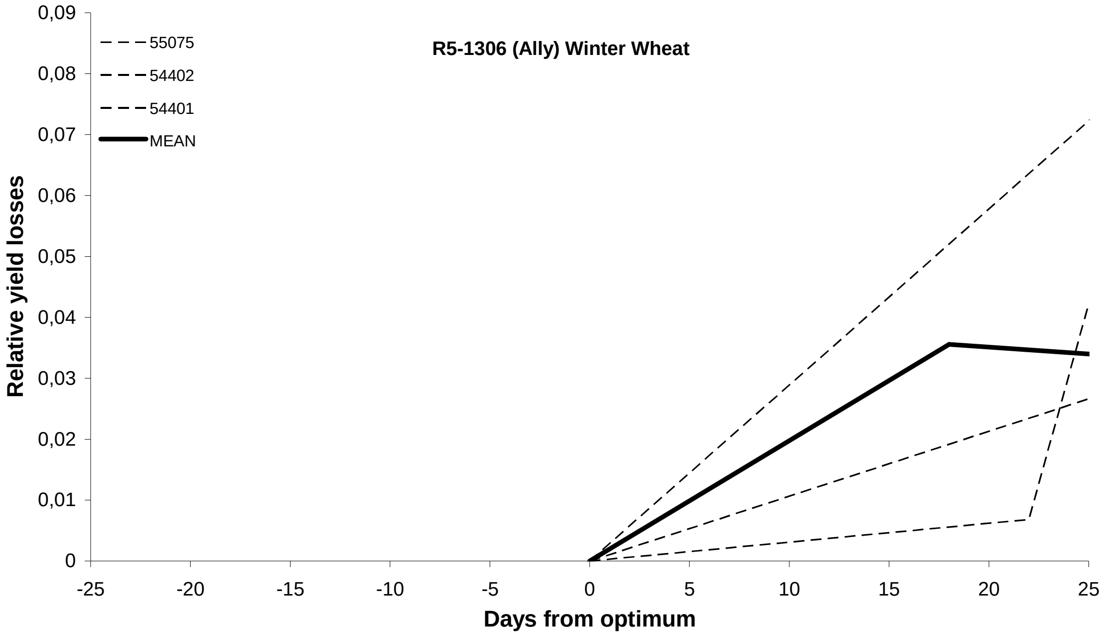

Figure A.7. Yield losses related to days from optimum for a Ally (30 g/ha) treatment for winter wheat.

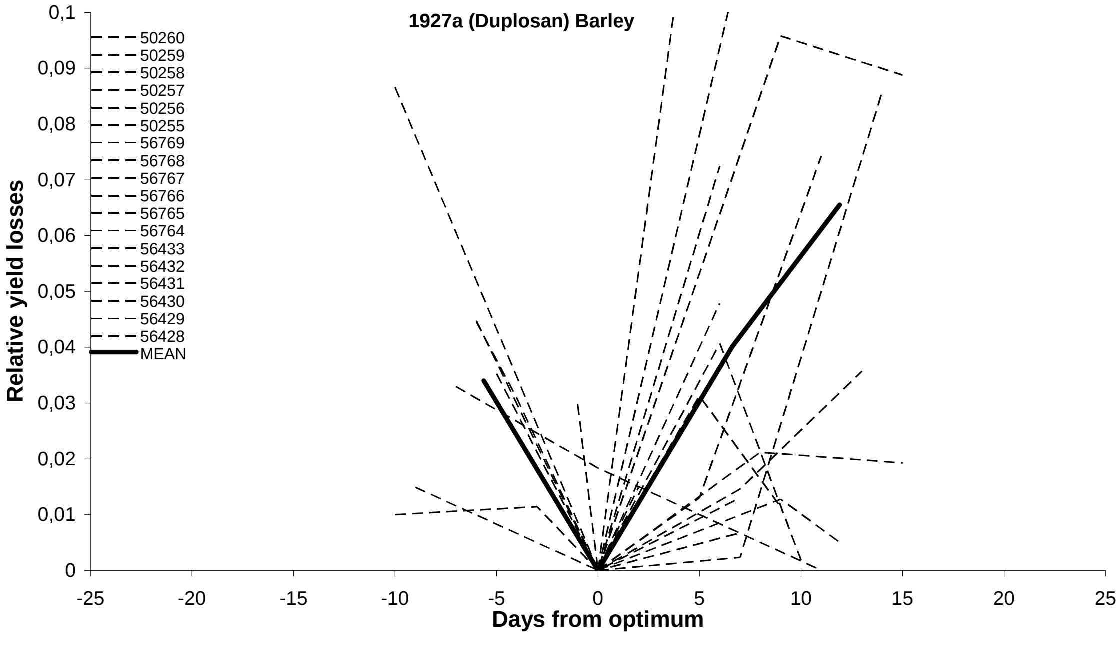

Figure A.8. Yield losses related to days from optimum for a Duplosan (2.25 l/ha) treatment for barley.

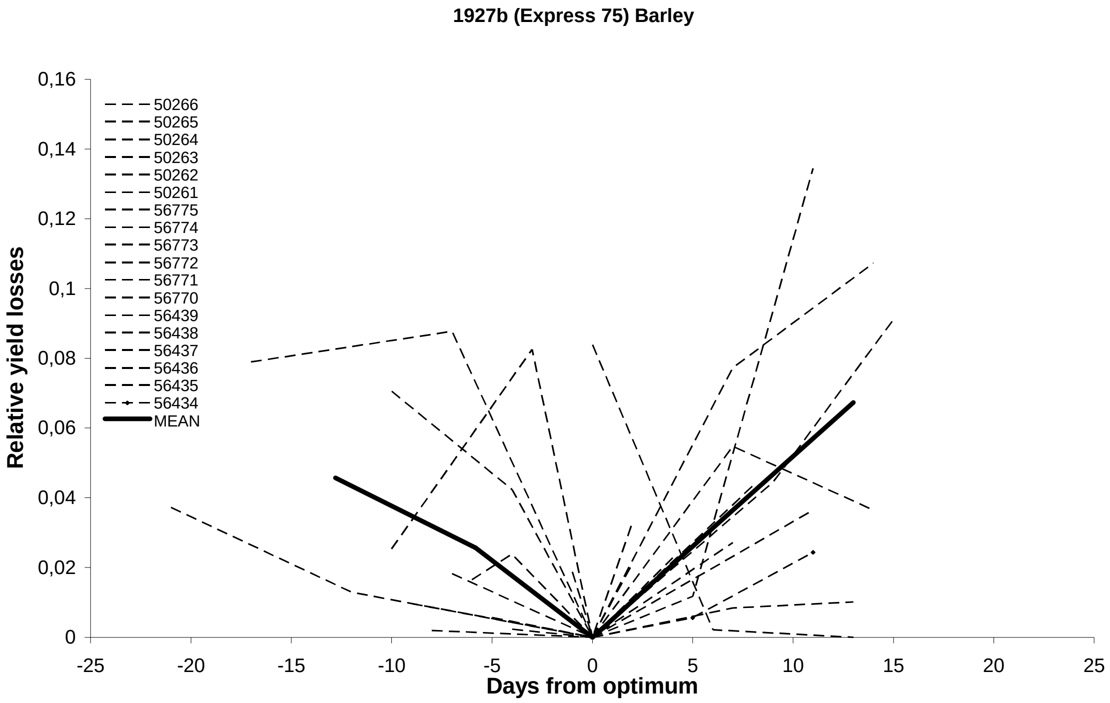

Figure A.9. Yield losses related to days from optimum for a Express 75 (6 l/ha) treatment for barley.

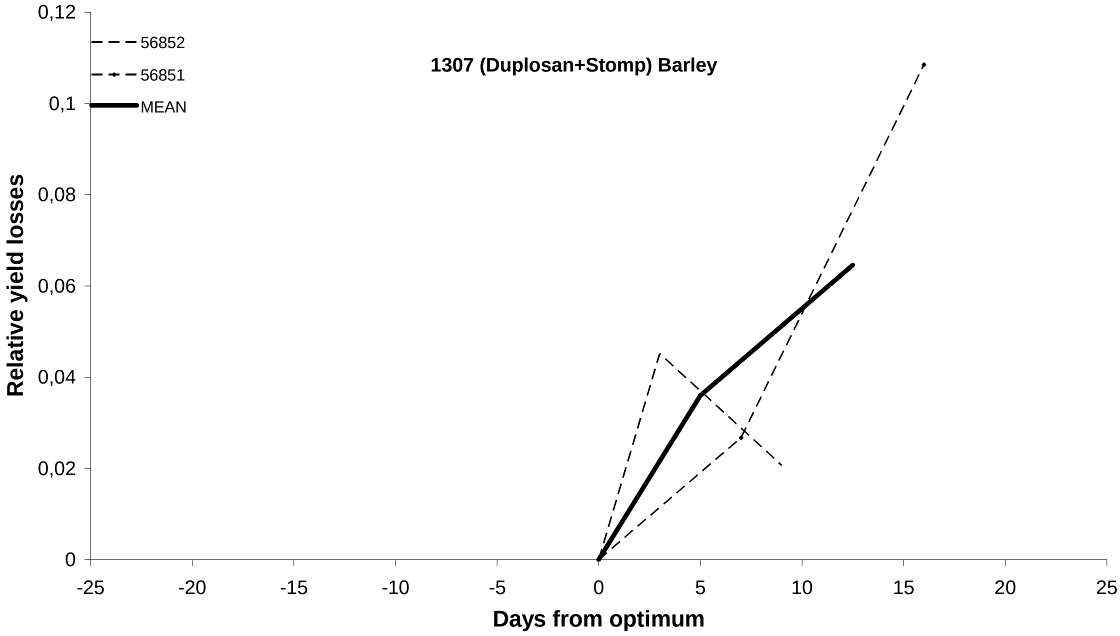

Figure A.10. Yield losses related to days from optimum for a Duplosan+Stomp (0.5 l/ha + 1.5 l/ha) treatment for barley.

APPENDIX (B)

Variations in optimum capacity and total cost due to grain price, yield and workday probability calculated using the timeliness factors for each crop (Table 10), an area of 400 and the expected hours for field work of 8 h/day.

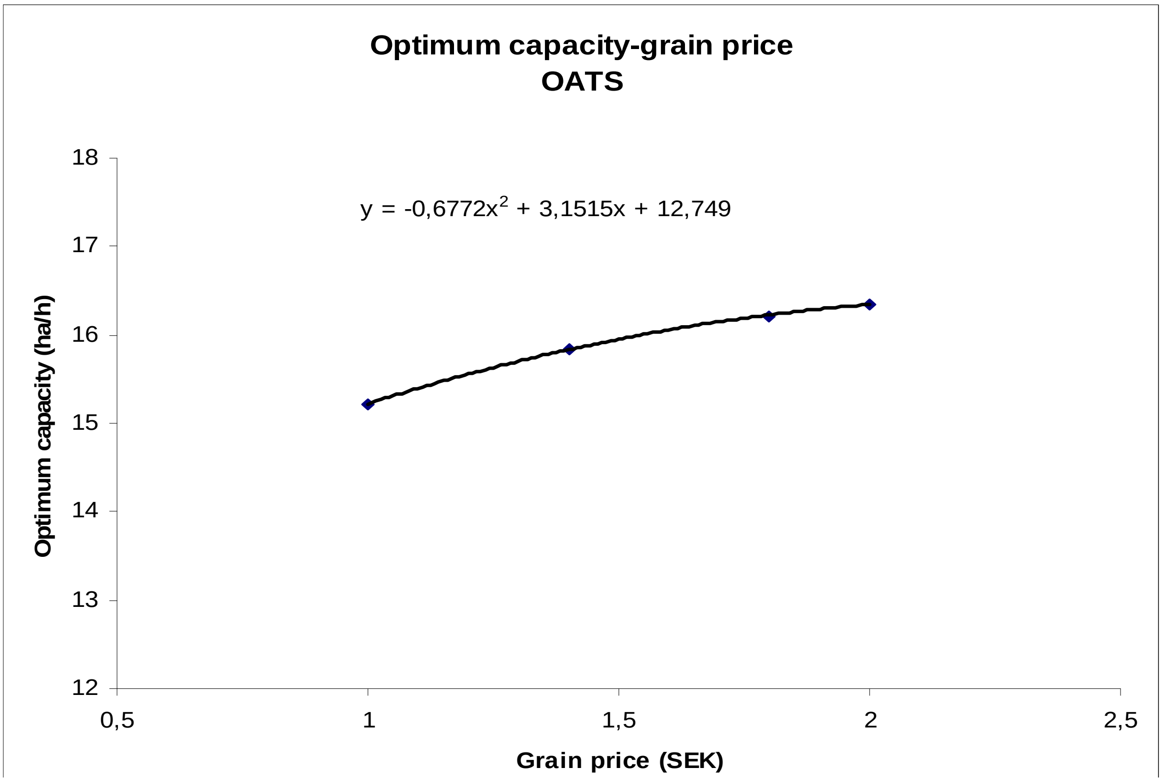

Figure B.1. Optimum capacity in relation to grain price for oats. See farm conditions above.

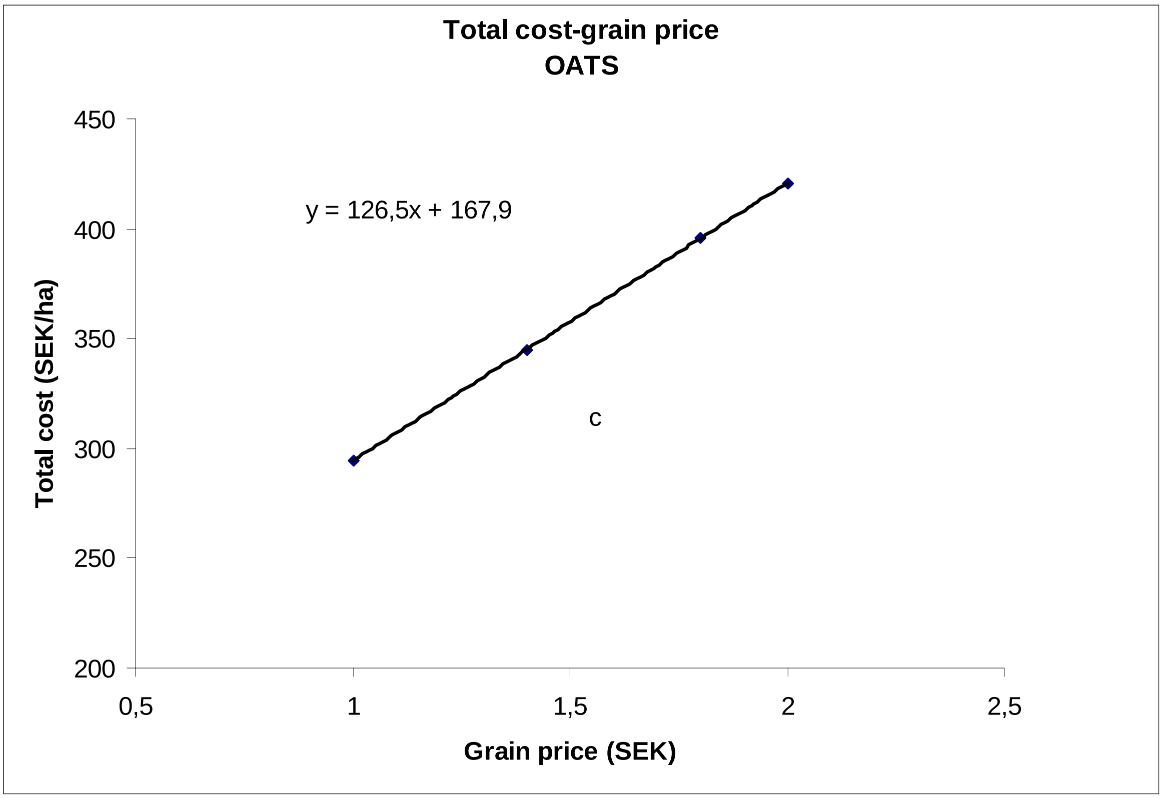

Figure B.2. Total costs in relation to grain price for oats. See farm conditions above.

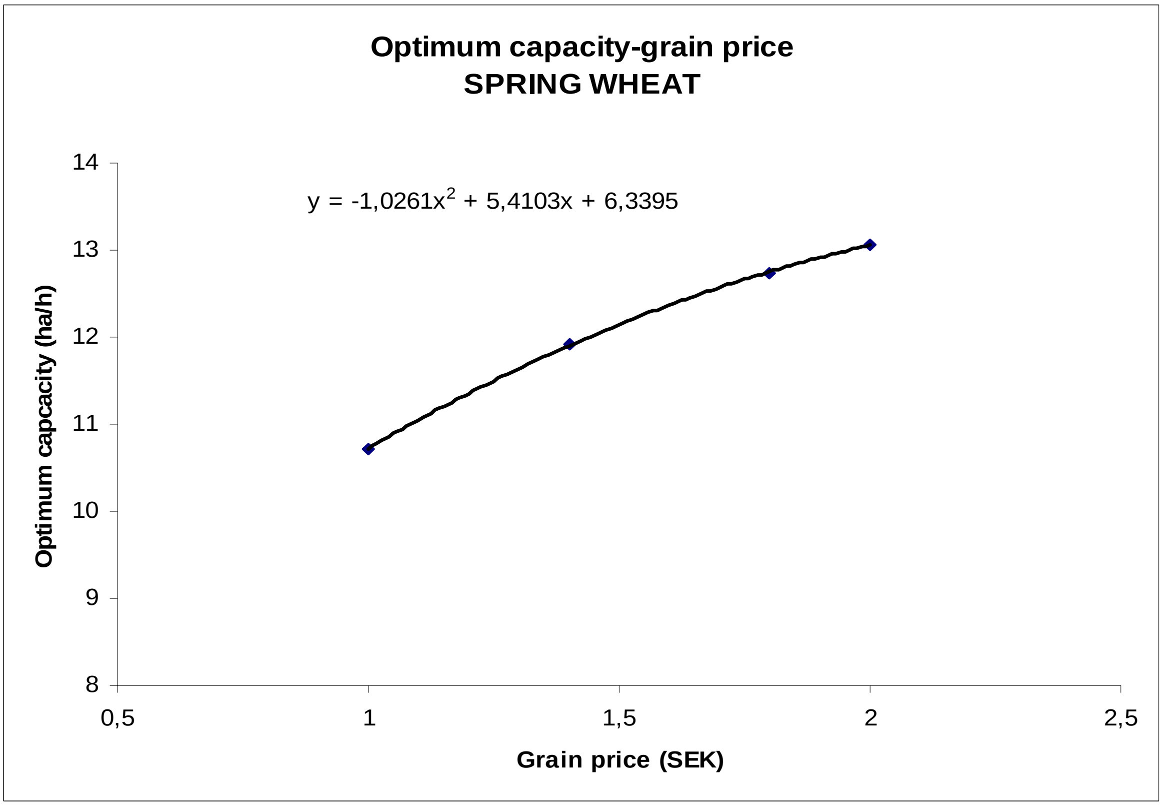

Figure B.3. Optimum capacity in relation to grain price for spring wheat. See farm conditions above.

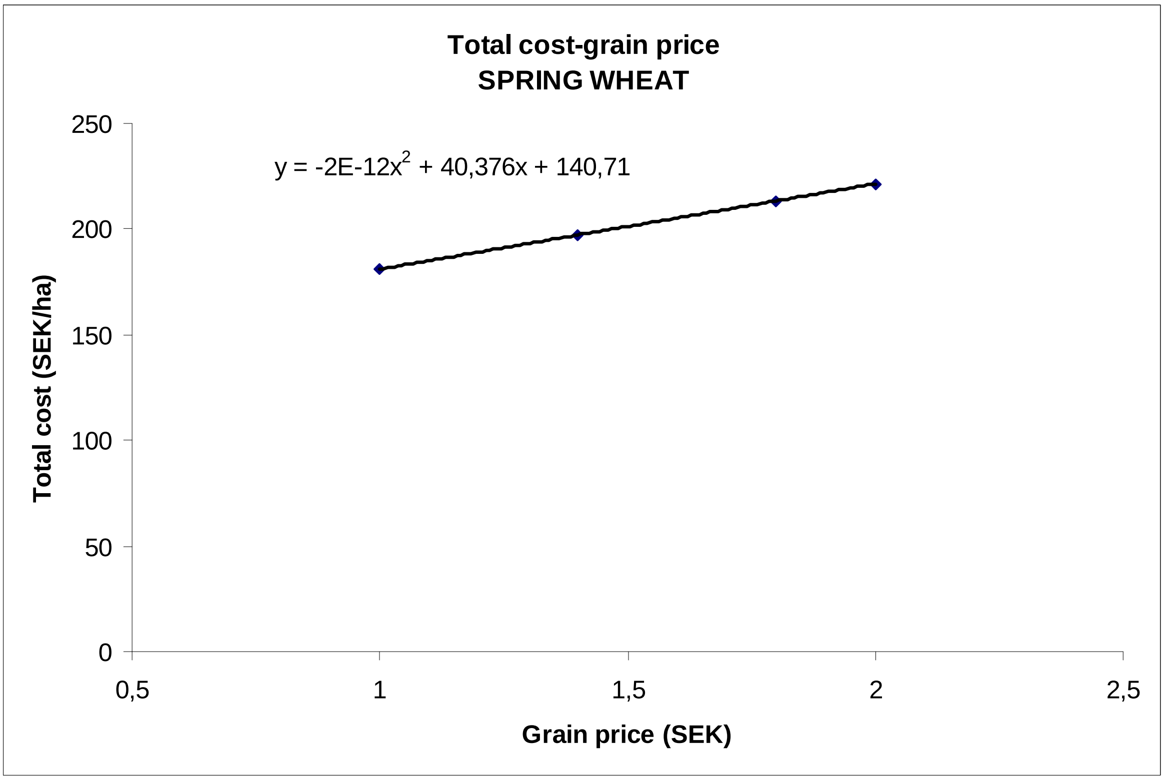

Figure B.4. Total costs in relation to grain price for spring wheat. See farm conditions above.

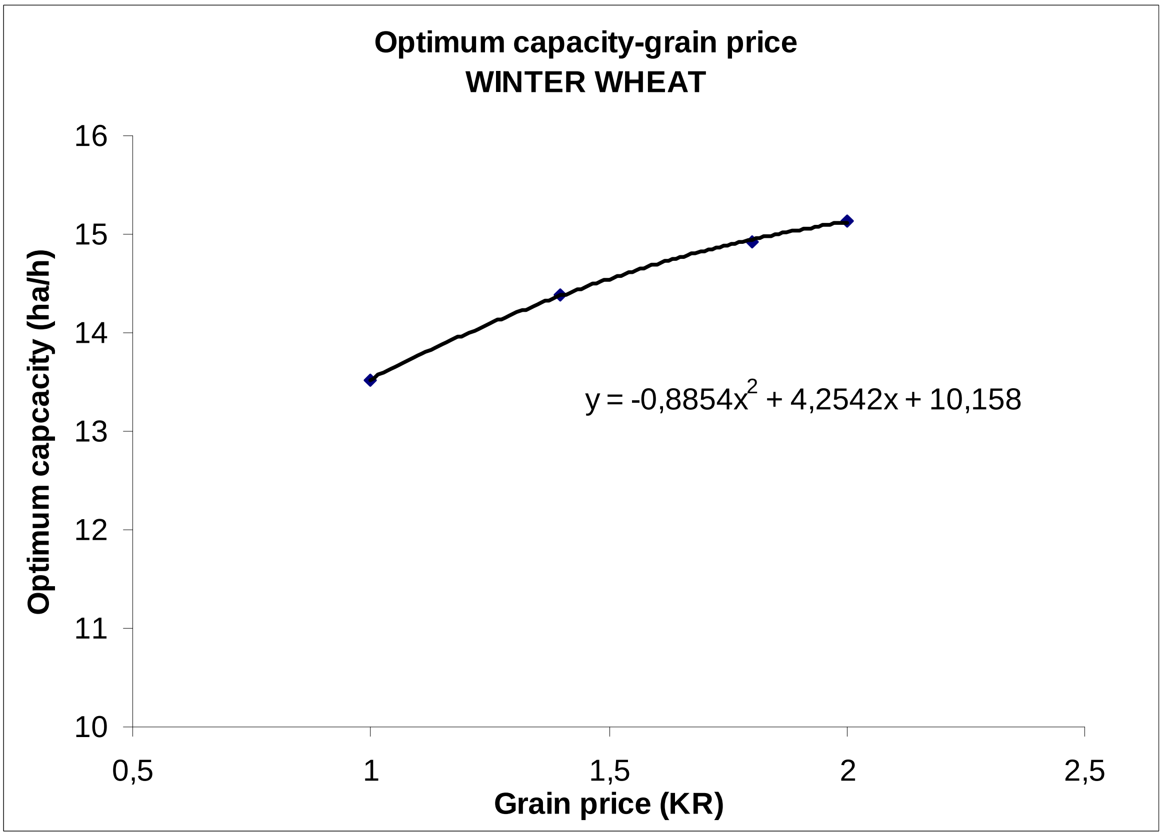

Figure B.5. Optimum capacity in relation to grain price for winter wheat. See farm conditions above.

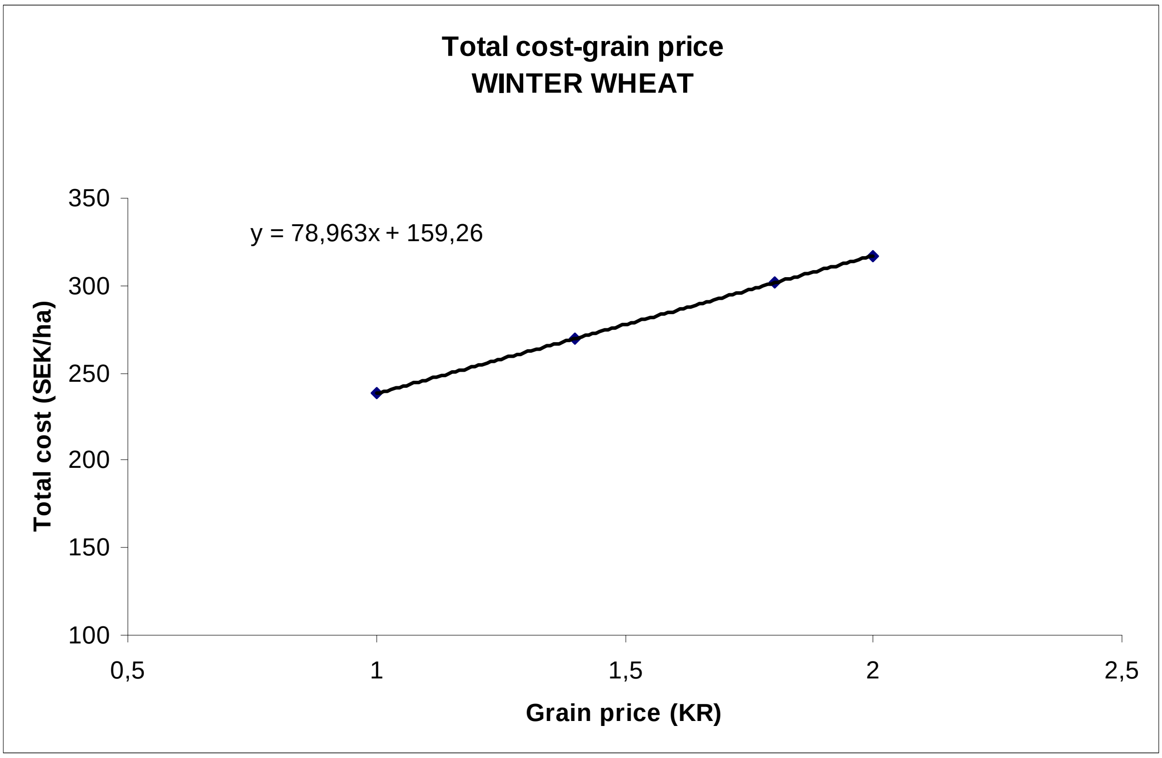

Figure B.6. Total costs in relation to grain price for winter wheat. See farm conditions above.

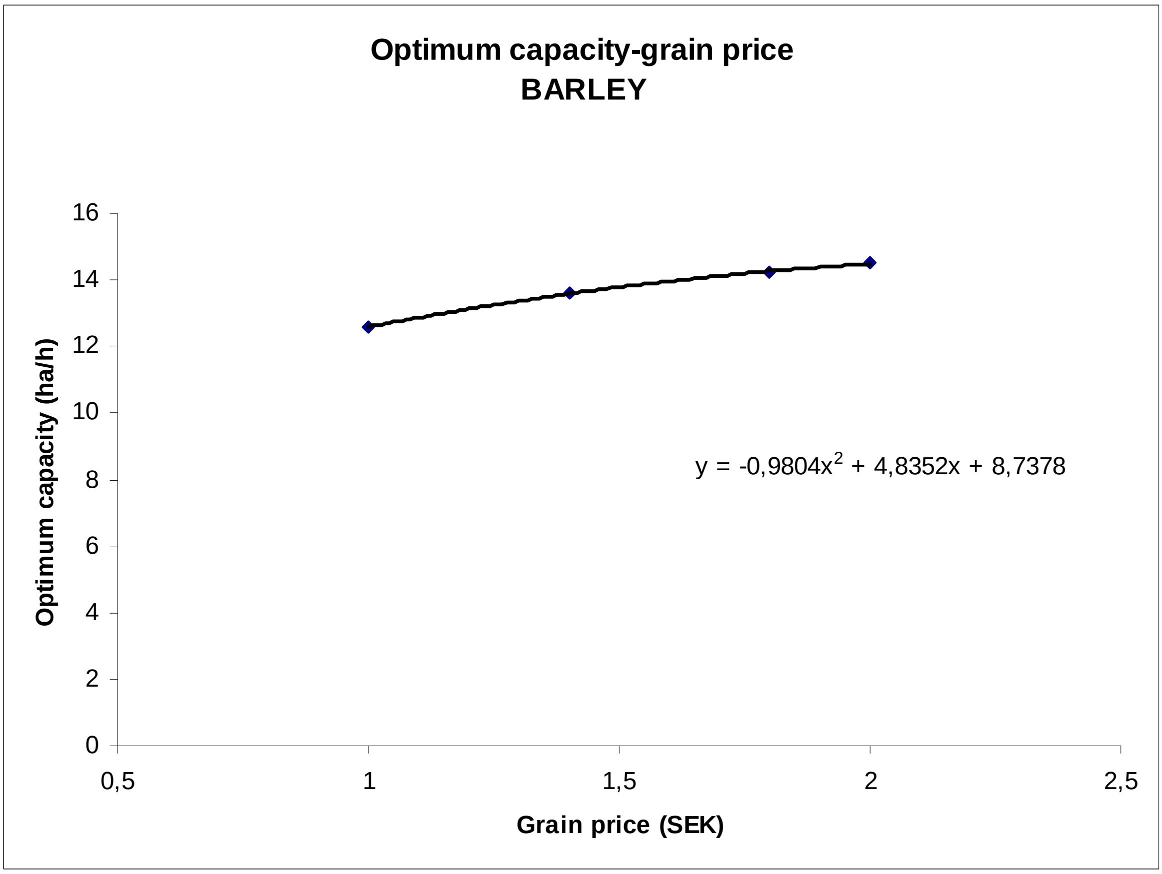

Figure B.7. Optimum capacity in relation to grain price for barley. See farm conditions above.

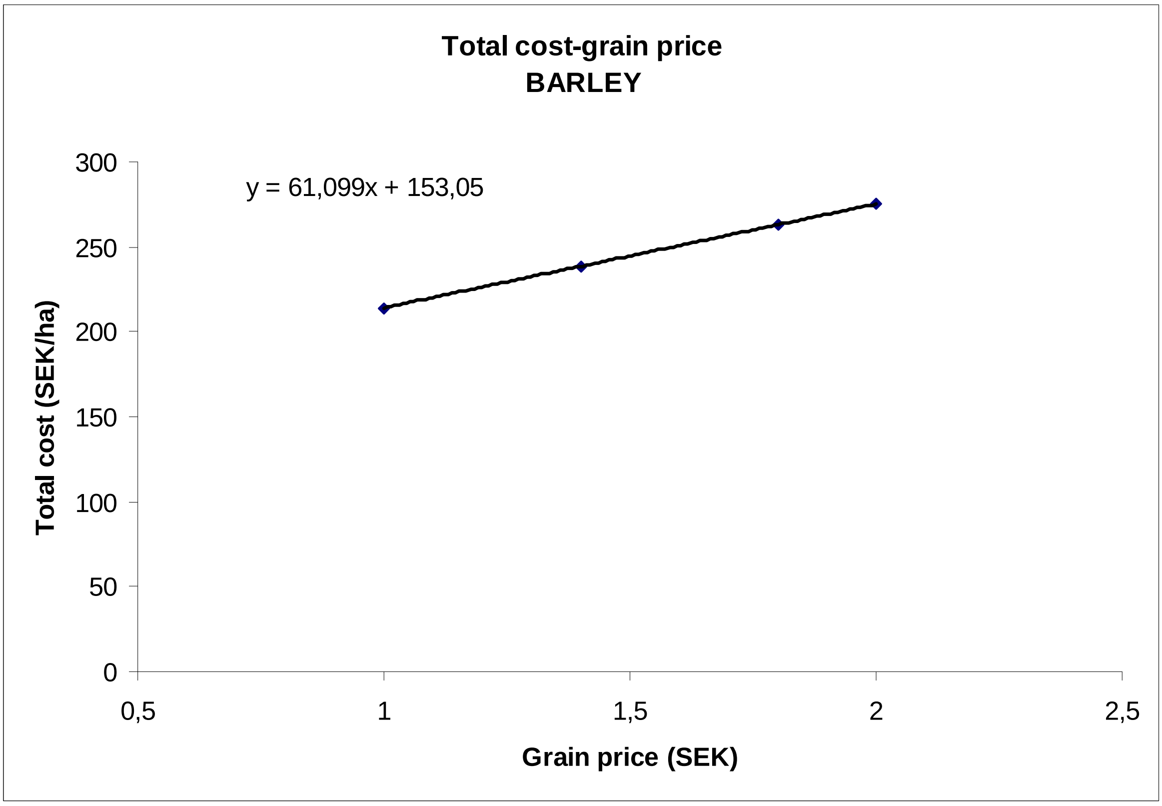

Figure B.8. Total costs in relation to grain price for barley. See farm conditions above.

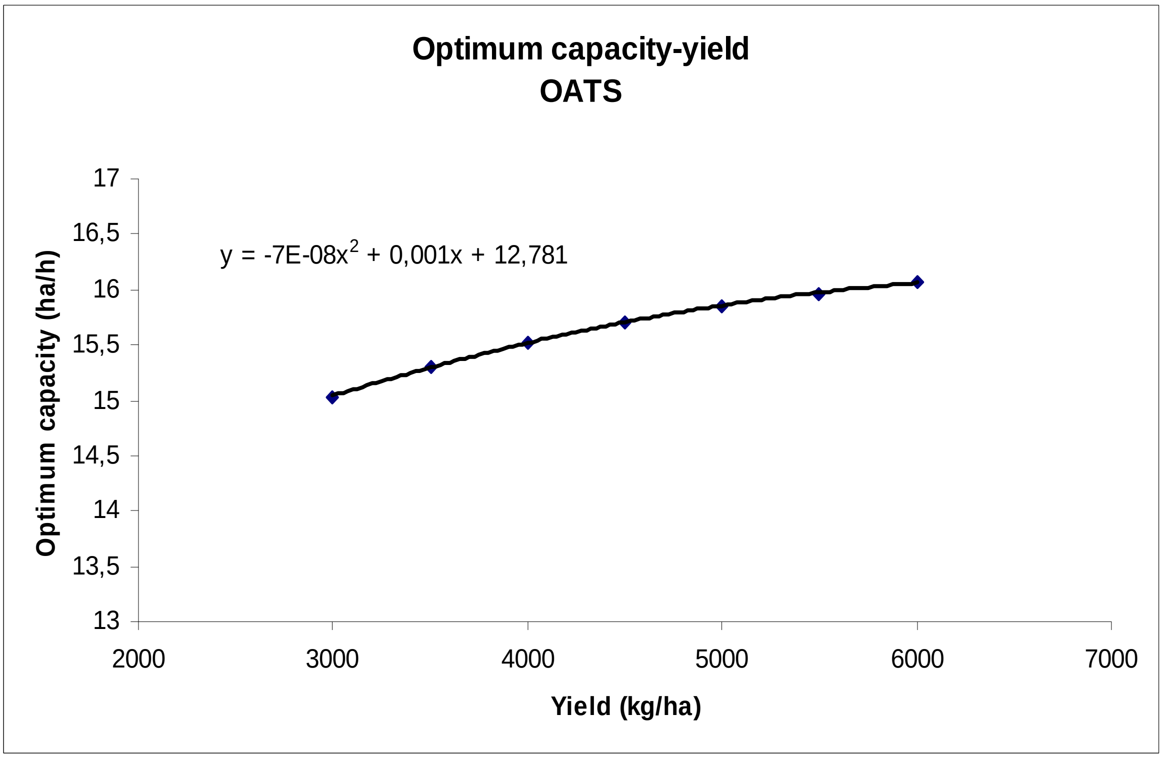

Figure B.9. Optimum capacity in relation to yield for oats. See farm conditions above.

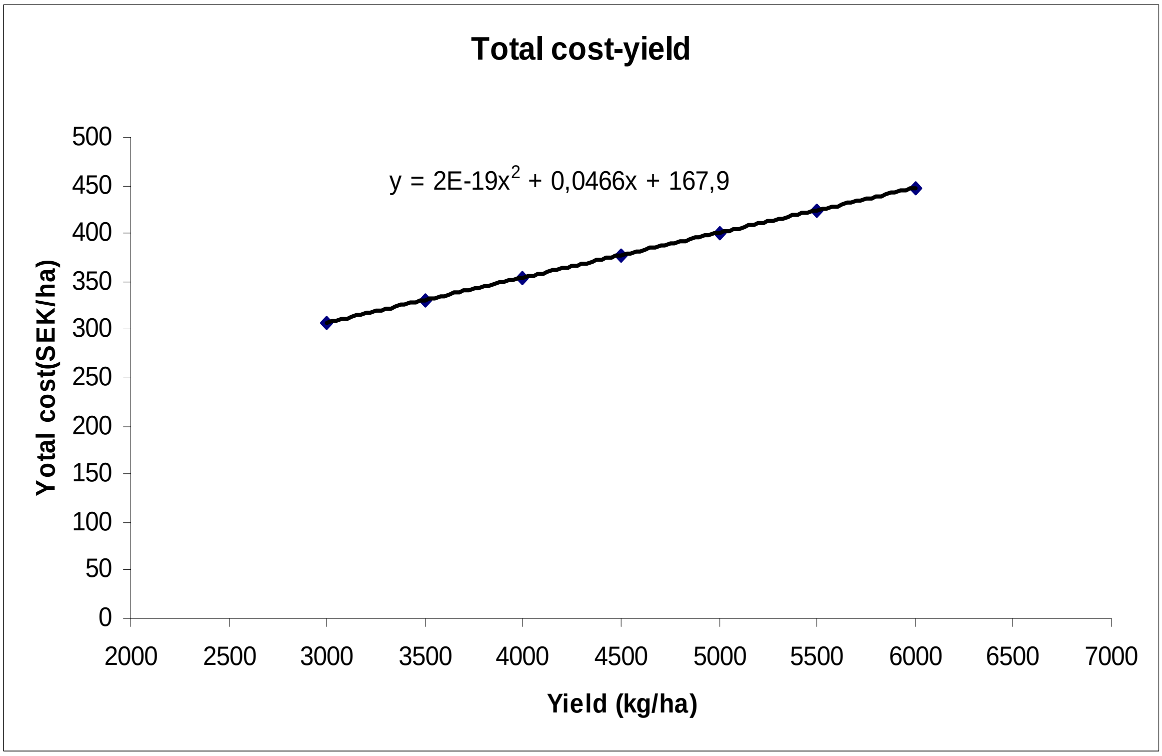

Figure B.10. Total costs in relation to yield for oats. See farm conditions above.

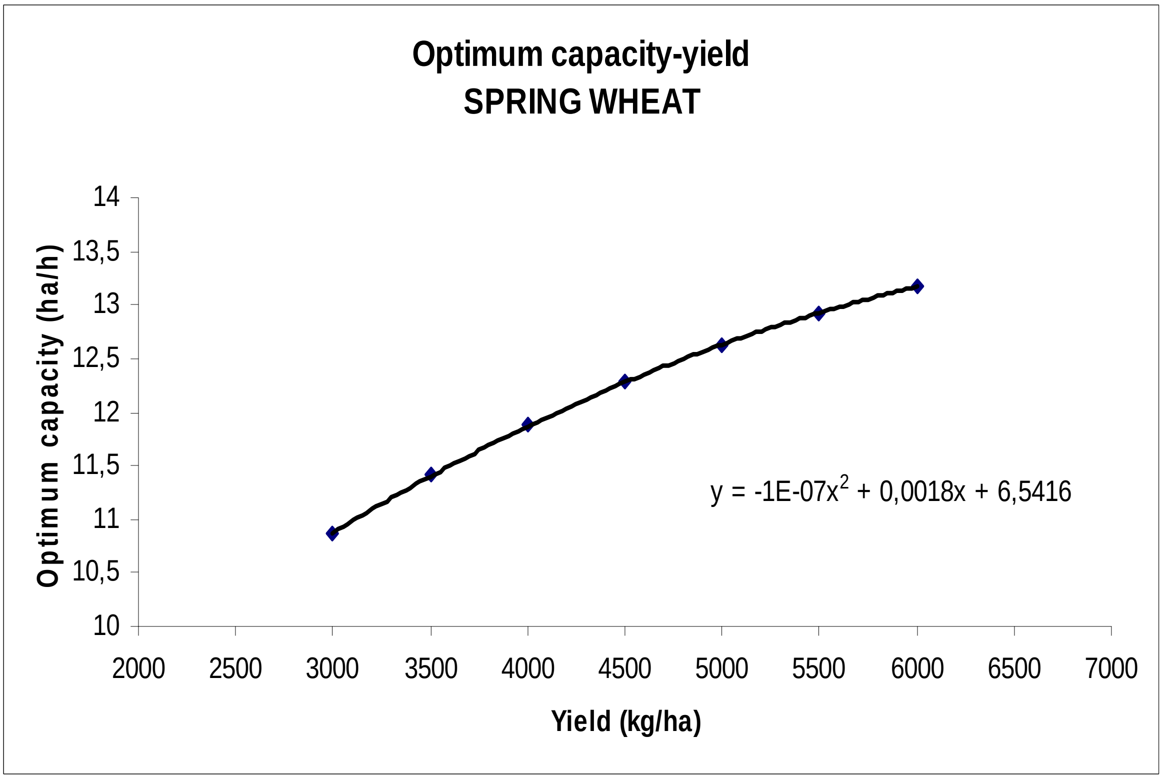

Figure B.11. Optimum capacity in relation to yield for spring wheat. See farm conditions above.

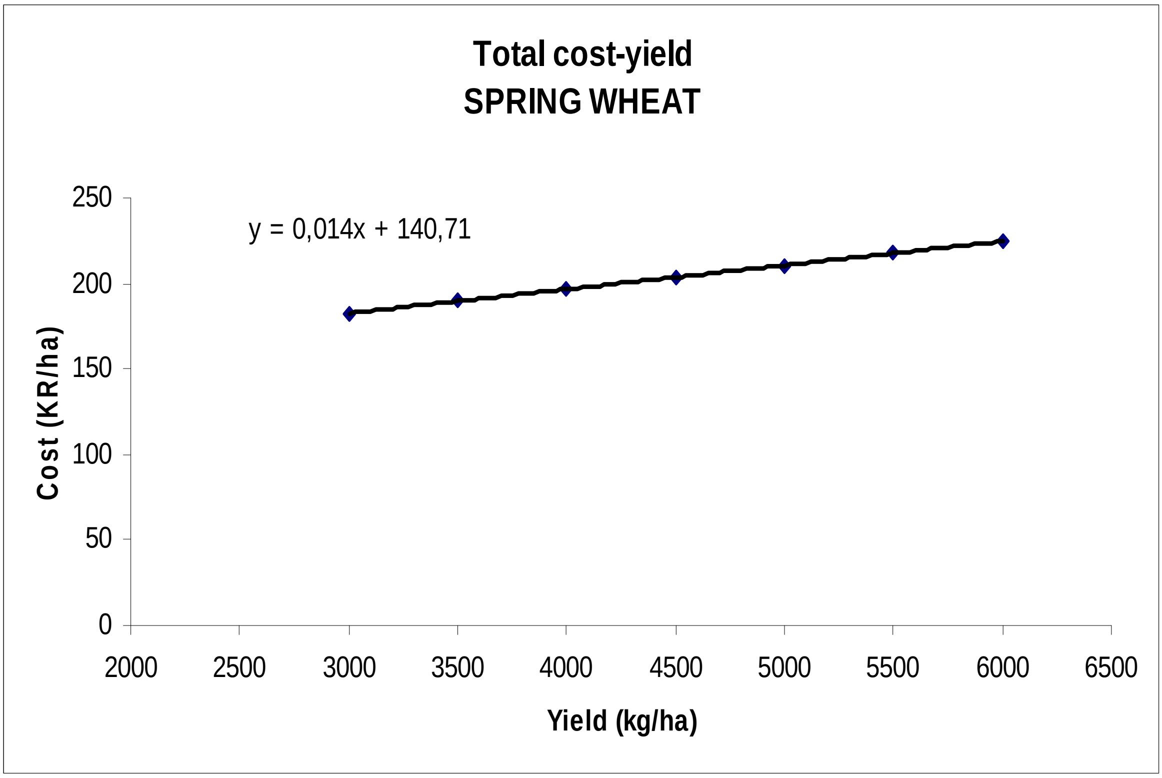

Figure B.12. Total costs in relation to yield for spring wheat. See farm conditions above.

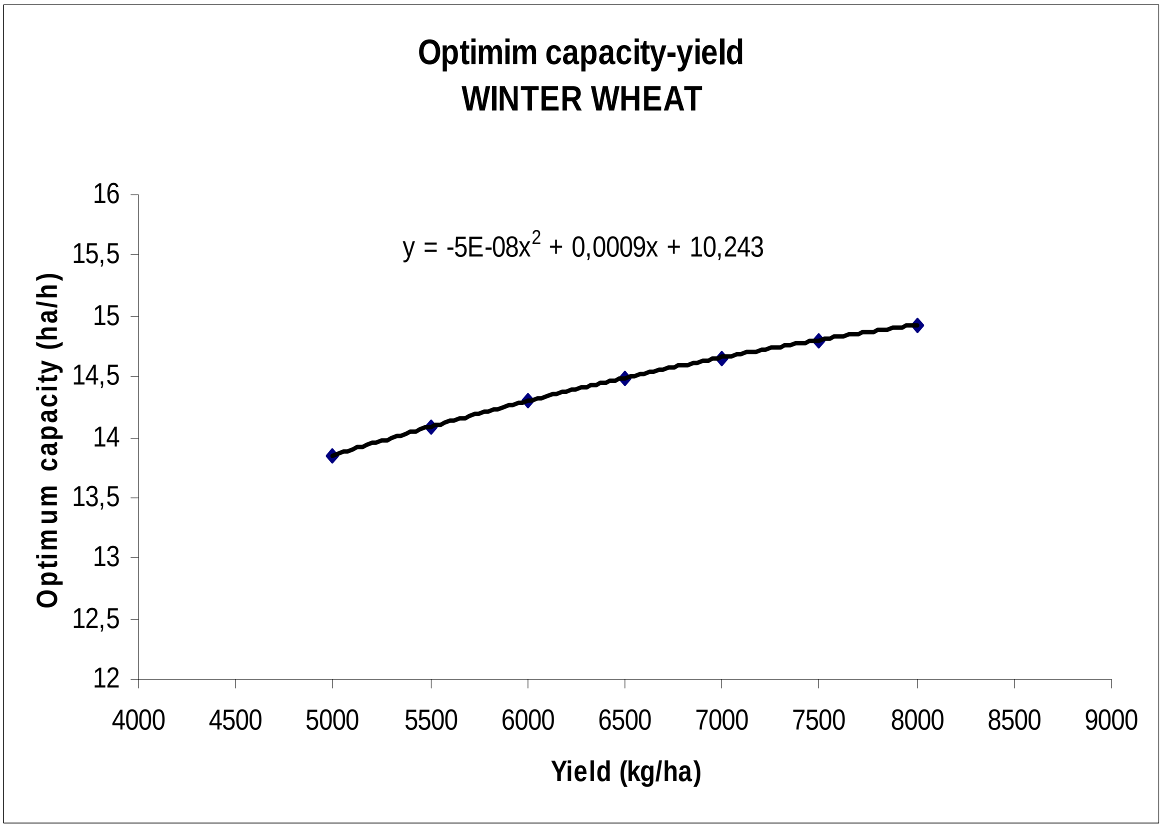

Figure B.13. Optimum capacity in relation to yield for winter wheat. See farm conditions above.

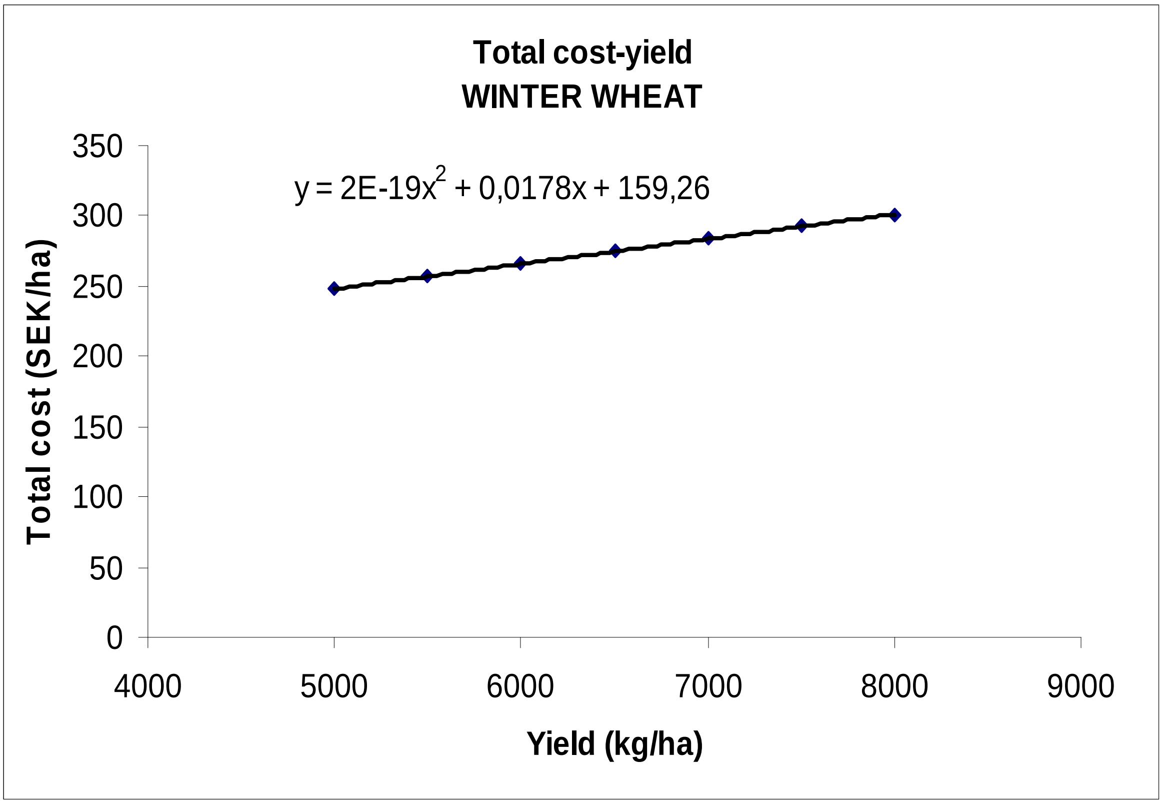

Figure B.14. Total costs in relation to yield for winter wheat. See farm conditions above.

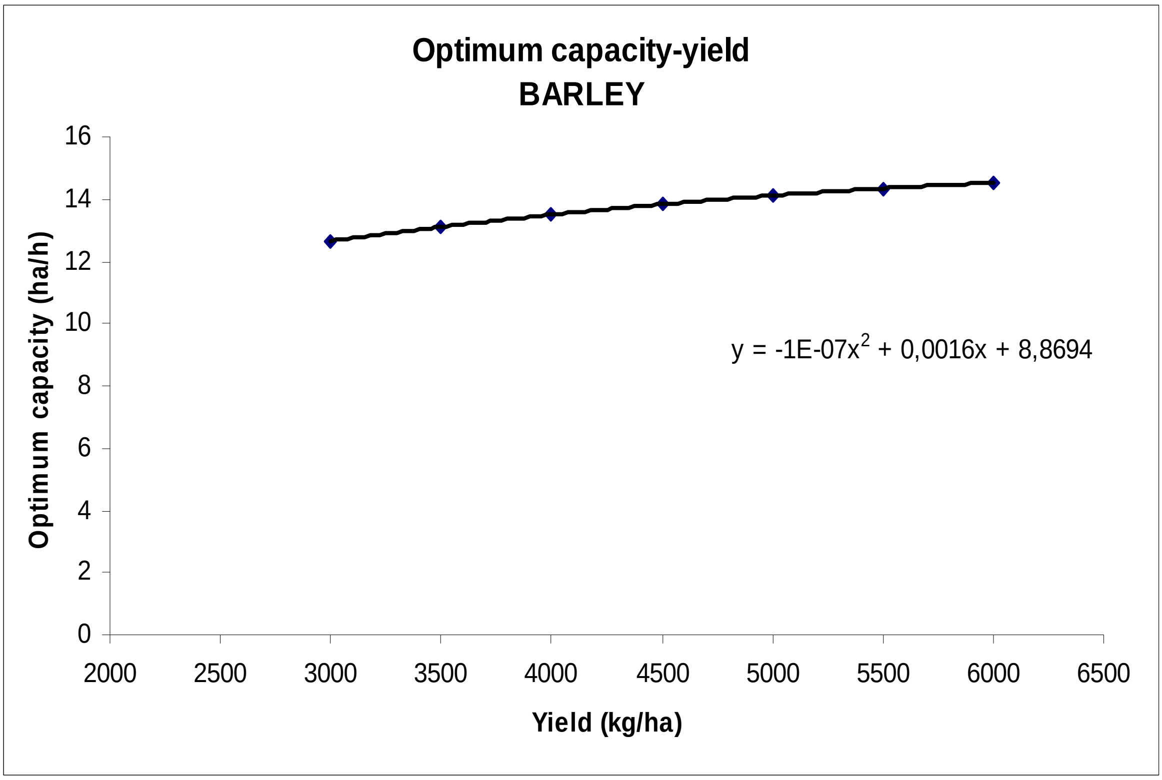

Figure B.15. Optimum capacity in relation to yield for barley. See farm conditions above.

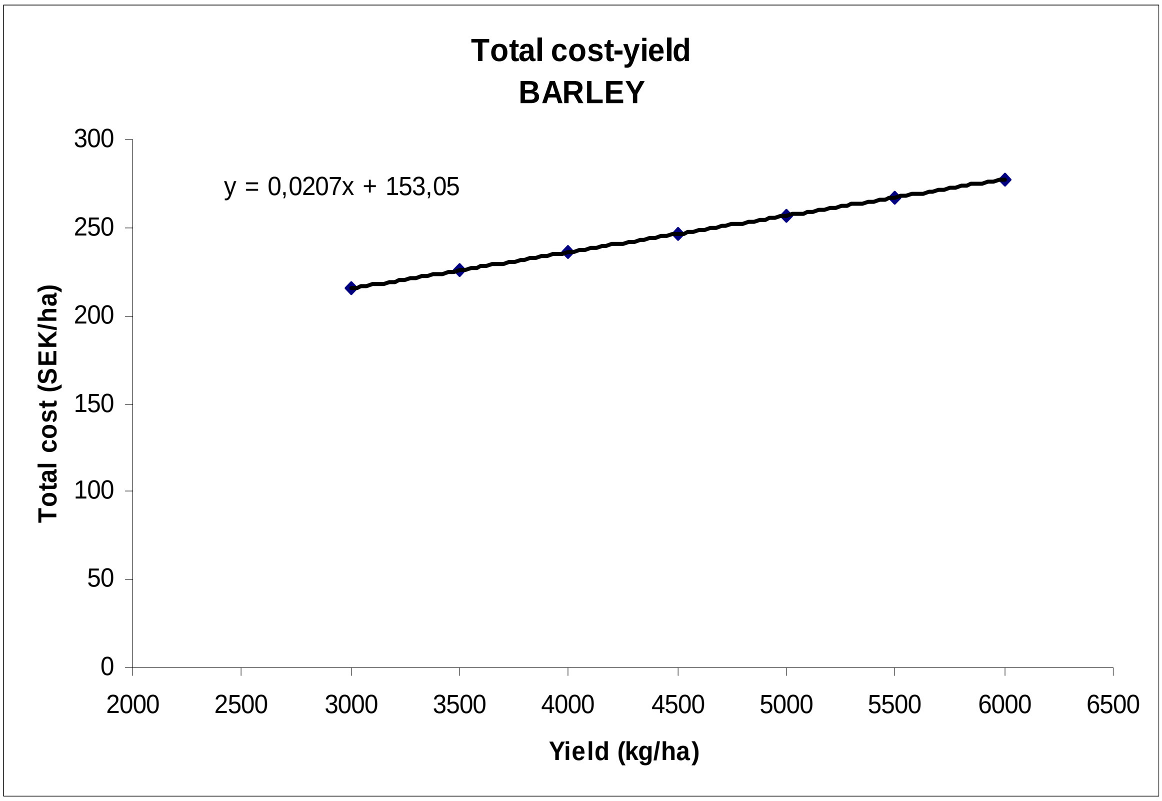

Figure B.16. Total costs in relation to yield for barley. See farm conditions above.

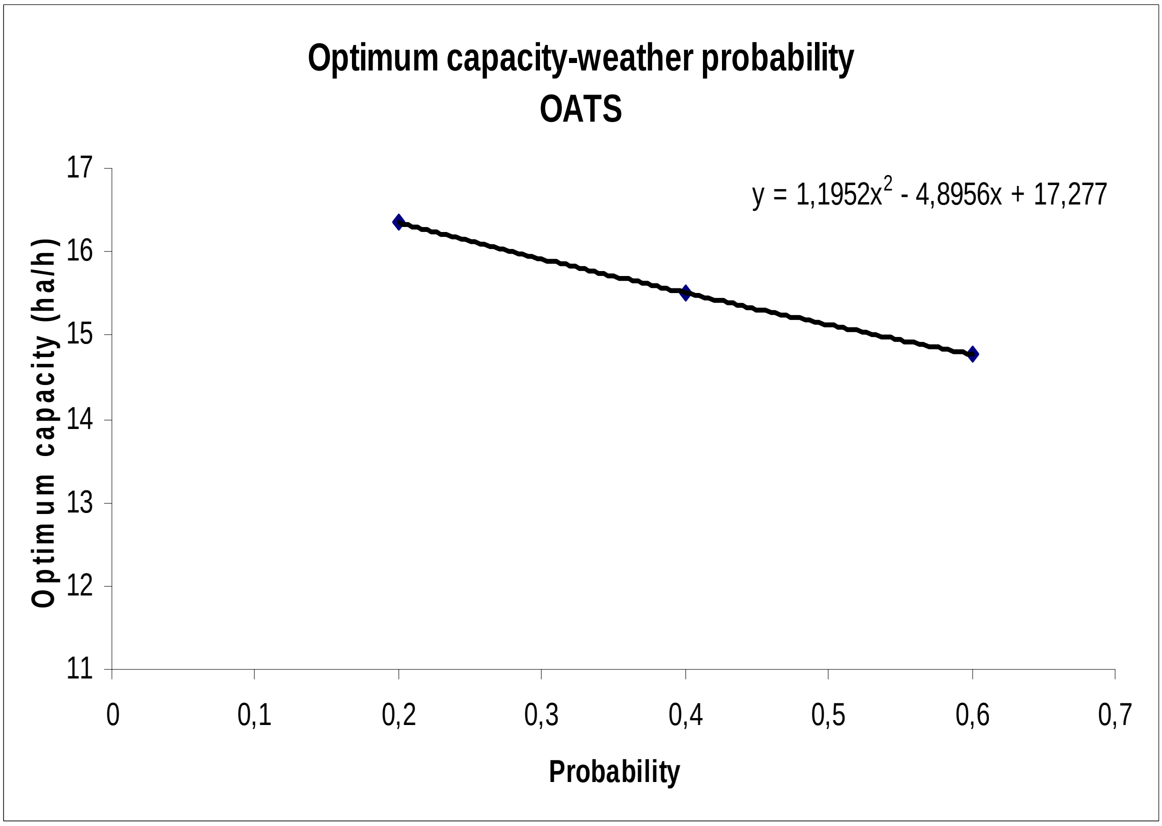

Figure B.17. Optimum capacity in relation to workday probability for oats. See farm conditions above.

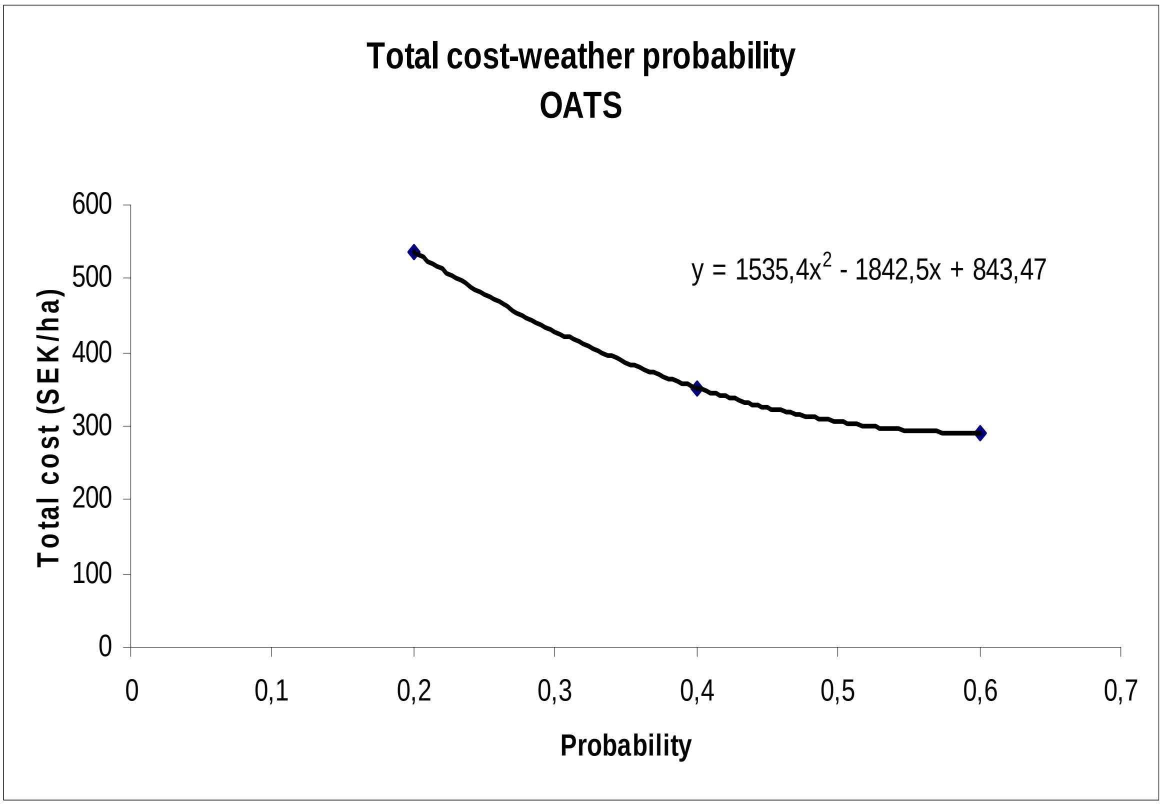

Figure B.18. Total costs in relation to workday probability for oats. See farm conditions above.

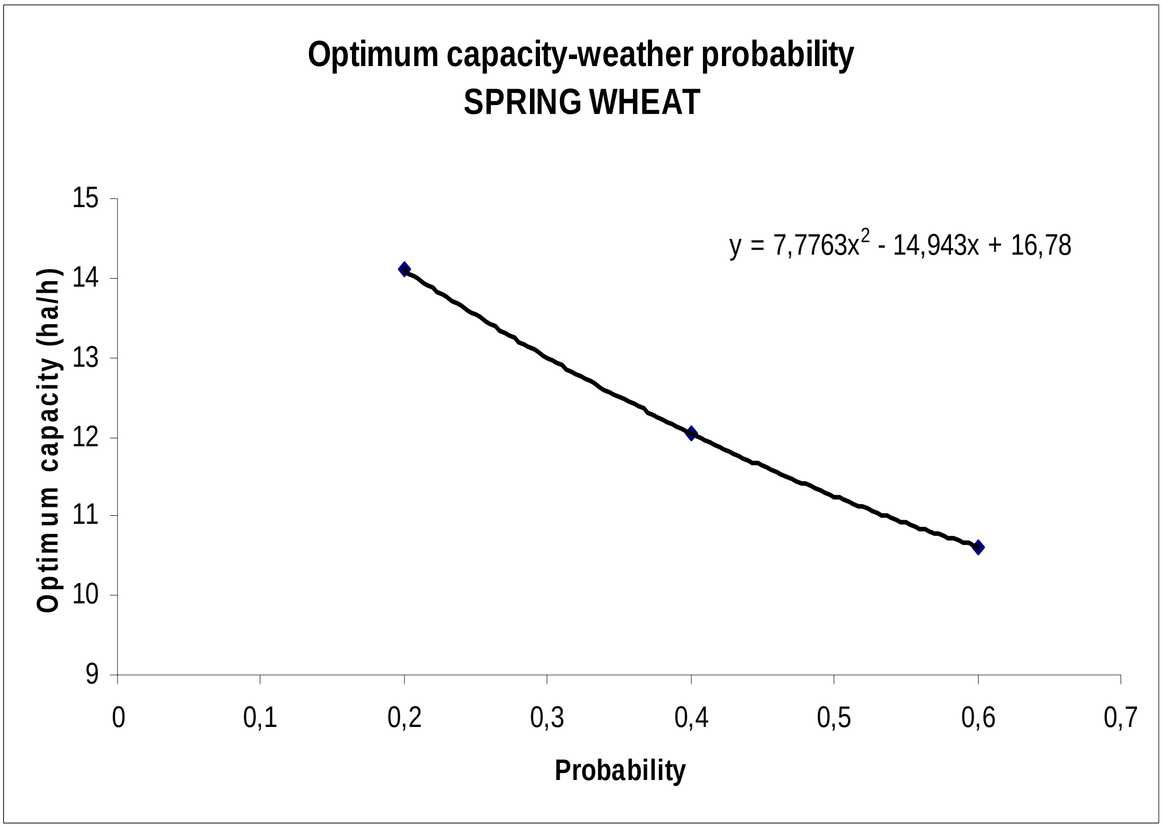

Figure B.19. Optimum capacity in relation to workday probability for spring wheat. See farm conditions above.

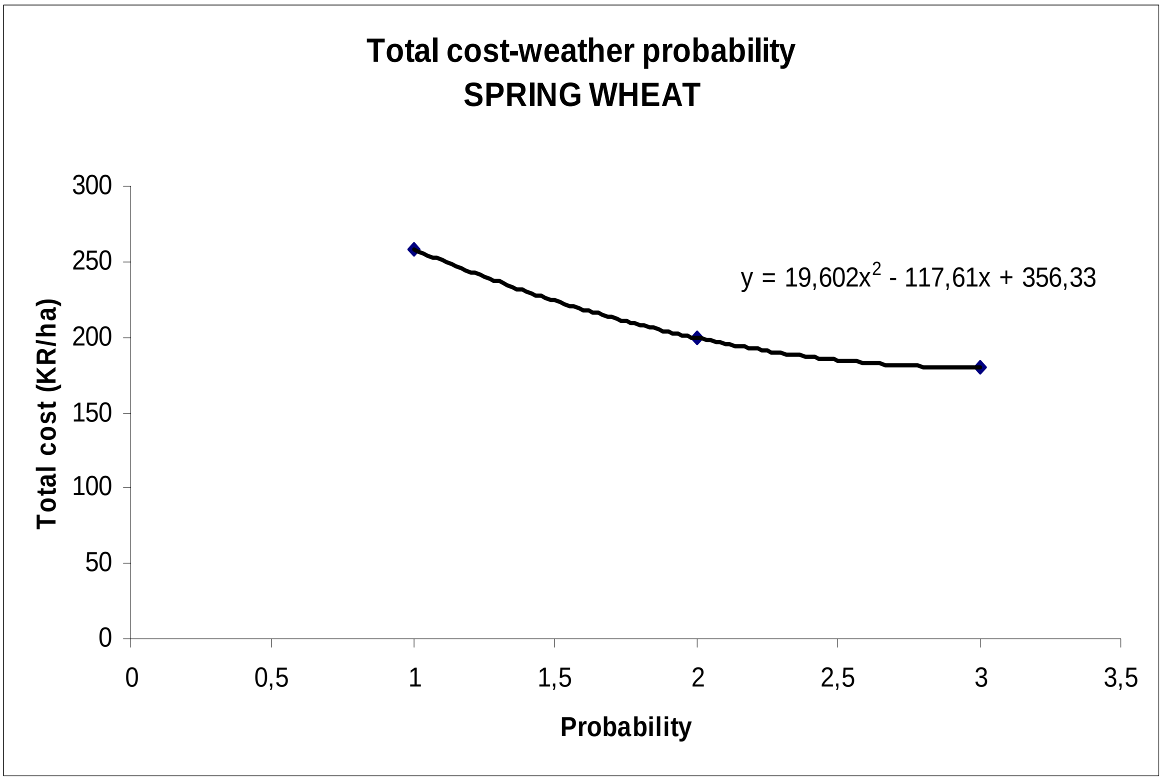

Figure B.20. Total costs in relation to workday probability for spring wheat. See farm conditions above.

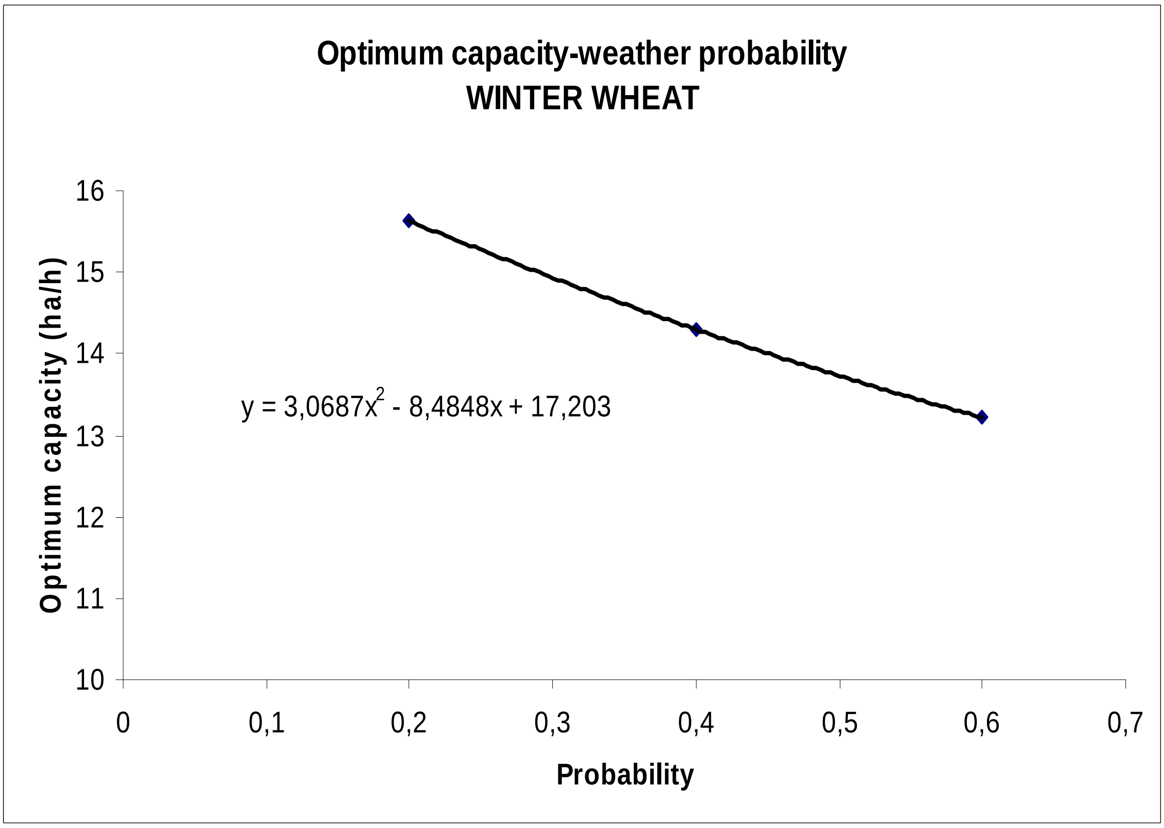

Figure B.21. Optimum capacity in relation to workday probability for winter wheat. See farm conditions above.

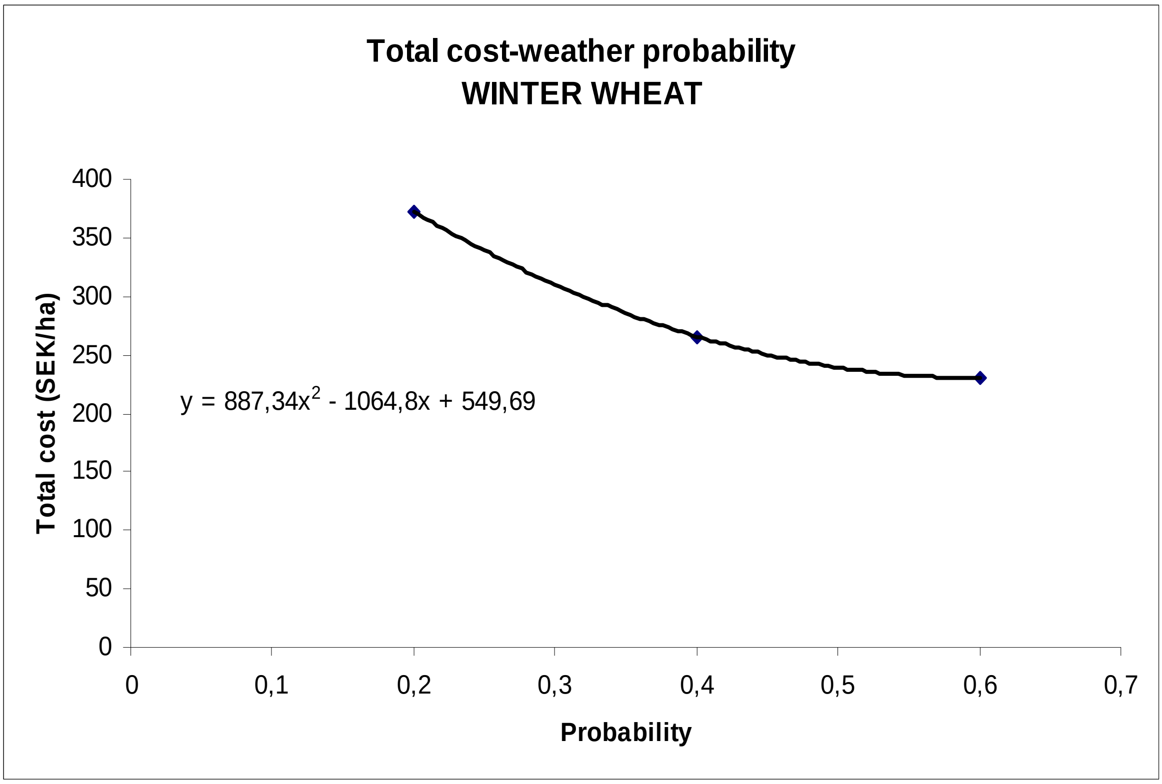

Figure B.22. Total costs in relation to workday probability for winter wheat. See farm conditions above.

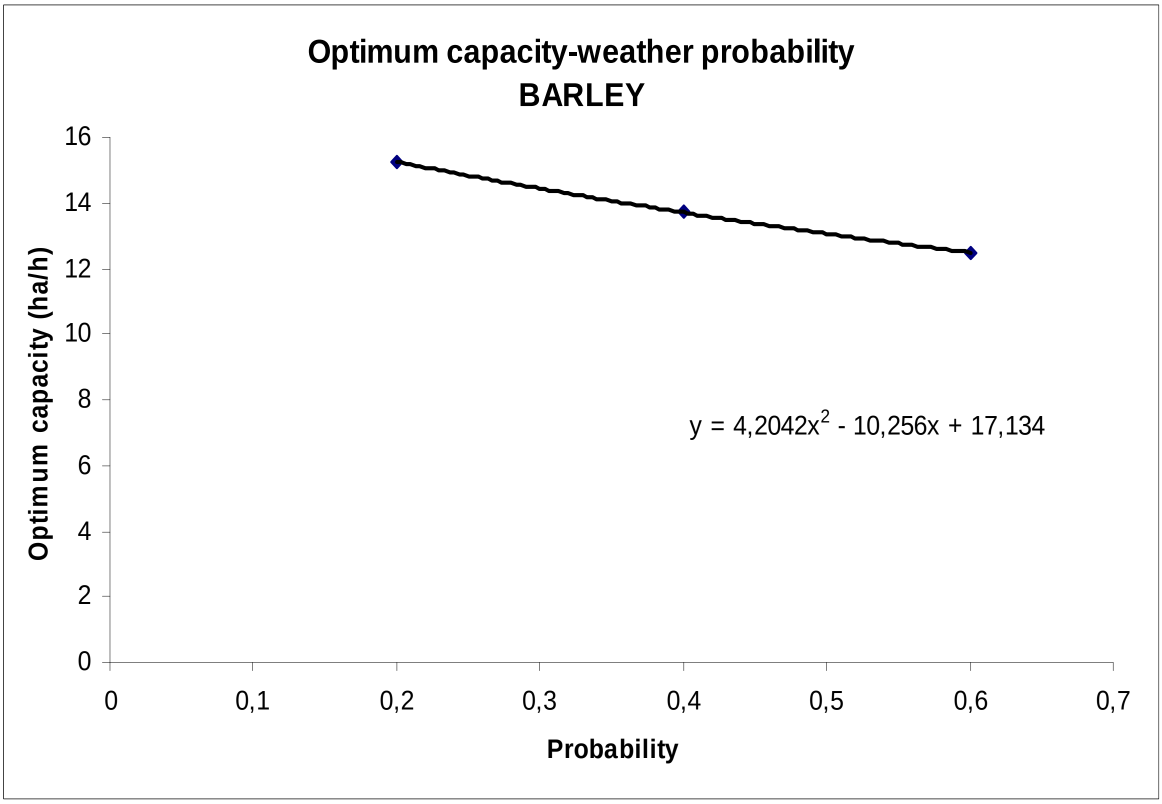

Figure B.23. Optimum capacity in relation to workday probability for barley. See farm conditions above.

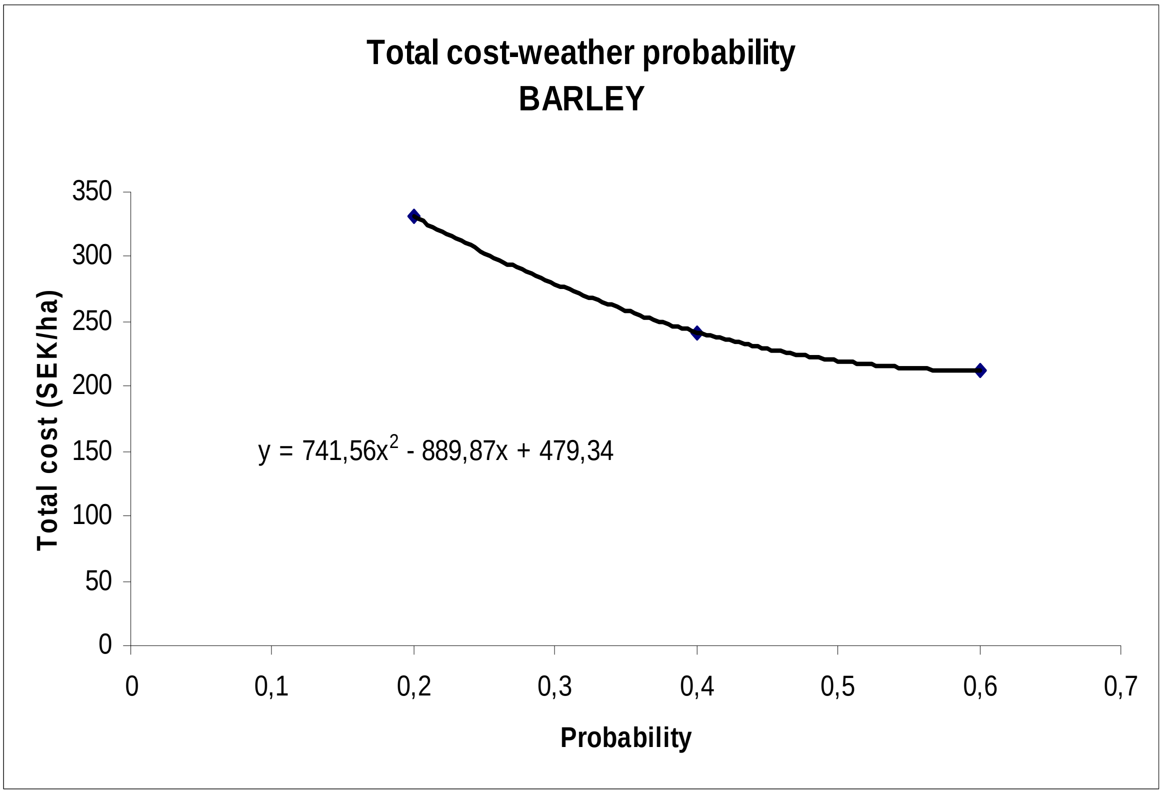

Figure B.24. Total costs in relation to workday probability for barley. See farm conditions above.

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