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Research Paper

Cereal harvesting – strategies and costs under variable weather conditions

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This study simulated 30 years of harvesting operations on an hourly basis with a harvesting model linked to a grain moisture model capable of predicting the moisture content of standing ripe wheat using historical weather data from Stockholm, Sweden, as input, in order to assess the effects of weather on cereal harvesting costs. Several combinations of harvester size and grain moisture ceiling were assessed on three cereal areas in terms of overall costs (machine + labour + timeliness + drying) and their annual variations.

The main findings obtained by simulation and valid for regions with similar climate and agricultural conditions to the studied region were that: (a) available combining time was highly dependent on grain moisture ceiling, which showed large annual variation, e.g. a moisture ceiling of 21% (w.b.) was related to a potential harvesting time of 65% and a standard deviation of 24% ($n = 30$ years); (b) in order to complete harvesting operations in most years, it was necessary to operate at a moisture ceiling of 22–24% (w.b.), however, the average moisture content of the harvested grain was much lower, about 17–18%; (c) overall harvesting costs were estimated at approx. €140 ha^{-1} for those systems performing relatively well, i.e. with a daily harvesting capacity of 4–5% of the cereal area and operating at a moisture ceiling of 22–24% (w.b.); and (d) the main sources of annual cost variation were firstly the timeliness costs and secondly the drying costs.

1. Introduction

Harvesting is the most expensive operation in cereal production and at the point of harvest considerable expense has already been incurred in crop growing, so it is crucial to be as ‘successful’ as possible (Agriwise, 2011). Around Stockholm, Sweden, as in many other regions, harvesting is performed during a period with uncertain weather conditions where the average rate of available workdays is about 60%, but the annual variation is large (de Toro, 2005). In extended periods of inclement weather, reductions in harvested yield and quality cause losses in the order of €50–100 ha^{-1} year^{-1} normally (de Toro, 2005), in addition to higher drying costs.

The overall costs of harvesting operations can be regarded as the sum of the machine, labour and drying costs, in addition to the timeliness costs (the value of yield and/or quality losses if the operation is not carried out during its ‘optimal’ time). Naturally, farmers are interested in operating with the least cost system for their conditions.

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However, to design (and optimise) such a system is difficult as several factors are interrelated, i.e. crop area, daily machine capacity, machine costs, available combining time, timeliness costs, grain moisture content, drying capacity and drying costs. The most difficult item to determine of all the above is the available harvesting time, as it is closely related to the grain moisture content of the standing crop, which in turn is highly dependent on weather, an uncertain and variable factor.

In order to estimate the available harvesting time, researchers have developed models to predict the moisture content of pre-harvested ripe cereals. Some of these are based on regression equations from experimental data, and can be called descriptive models (e.g. Crampin & Dalton, 1971; Donaldson, 1968; van Kampen, 1969; Philips & O'Callaghan, 1974; Smith, Bailey, & Ingram, 1981). Others are based on the physical drying process, and can be called explanatory models (e.g. Atzema, 1993; Brück & van Elderen, 1969; van Elderen & van Hoven, 1973; Sørensen, 2003; Stewart & Lievers, 1978), which often distinguish four main processes affecting the moisture content of pre-harvested grain depending on weather (e.g. Atzema, 1993; Sørensen, 2003). These are (1) drying due to the relative humidity of the air being lower than the grain equilibrium moisture content; or wetting due to (2) precipitation, (3) dew or (4) the relative humidity of the air being higher than the grain equilibrium moisture content.

van Elderen and van Hoven (1973) compared some descriptive models (Brück, 1967; Crampin & Dalton, 1971; van Kampen, 1969; Voight, 1955) with their explanatory model based on weather data using an approach similar to that for calculating potential evapotranspiration and concluded that 'some descriptive models can achieve the same as the explanatory models'.

Similarly two main approaches can be distinguished to assess or optimise harvesting operations. Optimisation models (e.g. Boyce & Rutherford, 1972; Sørensen, 2003), generally use a single probability value of available working days, leading to an 'optimal' harvester size and/or drying capacity for a given farm under average or more severe weather conditions. Simulation models, where the operation is replicated over a series of years, either on a daily or hourly basis, usually linked to a model for predicting the moisture content of pre-harvested ripe cereals (e.g. Abawi, 1993; Donaldson, 1968; van Elderen, 1980; van Kampen, 1969; Nawi, Chen, & Zare, 2010; Philips & O'Callaghan, 1974; Sokhansanj, Mani, & Bi, 2004). This approach should allow a more detailed assessment of the operation, particularly as it is possible to capture the effects of weather variability and its interactions with the system variables.

As no in-depth assessment of cereal harvesting operations was found in the literature for Swedish conditions, this study sought to evaluate such operations over a series of years in order to determine the least cost systems under variable weather. The aim was to use the results to draw up guidelines for practical farming. In order to determine the least cost systems, the daily harvesting capacity and related machinery and labour costs for given cereal areas were balanced with the respective timeliness and drying costs using real weather data.

2. Materials and methods

2.1. *Outline*

The following steps were taken to achieve the objectives of the study:

- Field experiments were carried out at two sites in Sweden, Linköping (58°28′N, 15°36′E) and Uppsala (59°53′N, 17°38′E), during the 2009 harvesting season in order to collect data on the moisture content of ripe standing wheat and to relate this to climate data.
- The data collected in Uppsala were used to infer the main parameters for a grain moisture model based on hourly climate data. This model was validated with the data from the experiment in Linköping.
- The grain moisture model, using as input 30 years of historical climate data from Stockholm (59°20′N, 18°03′E), was then applied to predict the hourly grain moisture content of standing ripe wheat.
- Next, the predicted moisture content data were used as input in a simulation model for harvesting operations, working on an hourly basis. The operation was repeated for 30 years, allowing drying and timeliness costs to be estimated in detail.
- Several harvesting options in terms of varying moisture ceiling and harvester size on three cereal areas were tested to determine the least cost systems.

2.2. *Collection of grain moisture data from two field experiments*

The grain moisture content of ripe standing wheat was measured during August and September in Linköping and Uppsala, while hourly weather data (i.e. temperature, global and net radiation, air relative humidity, wind speed and precipitation) were collected using weather stations located in the fields. Most of the grain moisture measurements were carried out three times per day (approx. 7.00, 14.00 and 19.00 h) but on some days five determinations were made. For each measurement, three samples of approximately 30 g grain were collected with an electric-powered manual harvester in different parts of the field and kept in sealed vessels until the moisture content was determined using ASAE standard methods (ASAE S352.1, 1983), when a portion of about 15 g grain was dried at 130 °C for 19 h.

2.3. *Simulation model of harvesting operations*

The simulation model used for harvesting operations was a modified version of the model developed by de Toro and Hansson (2004a, 2004b) using a discrete event simulation technique (Kelton, Sadowski, & Sturrok, 2007). Harvesting operations were replicated hour by hour applying the procedure outlined in Fig. 1. The model took as its functional unit 1 ha and included a procedure described by Angus, Mackenzie, Morton, and Schafer (1981) for estimating annual maturity date for each field based on daily temperature and

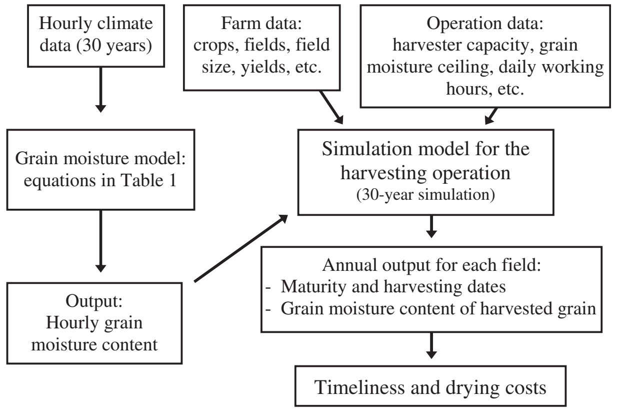

Fig. 1 – Flowchart of the procedure used to estimate the timeliness and drying costs.

photoperiod. Thus, diverse annual maturity dates and/or overlapping 'optimal' harvesting times for individual fields were taken into account in estimating the annual timeliness costs. The former factors are difficult to capture with the ASABE formula (ASABE, 2006a) for timeliness costs when applied to a whole farm.

2.4. *Specific machine and labour costs*

The specific machine costs (i.e. for the combine harvester) were estimated using the ASABE Standard method (ASABE, 2006a, 2006b) with the following parameters: depreciation was calculated with the straight line method based on list price, with residual value adjusted to age and annual use. The maximum economic life was 20 years and the real interest rate was set to 5%. The ASABE parameter for repair cost was reduced by about 40% for the most expensive harvesters and adjusted to annual use (reduced in the case of low annual use, assuming that a 'new' harvester has fewer breakdowns). Field efficiency was fixed at 75%, working speed 6 km h^{-1} and fuel consumption 18 L ha^{-1} diesel at a cost of €0.84 L^{-1} (€1 = SEK 8.9, January 2011). Labour costs were set at €23 h^{-1}, available on an hourly basis.

2.5. *Timeliness and drying cost estimations*

The timeliness costs were calculated from the maturity and harvesting dates for each individual field and year (outputs from the simulation model, Fig. 1) using Eqn. (1). A delayed operation schedule was assumed and the main parameters are presented in Table 2. The equation is a modified version of an existing equation for estimating timeliness costs (ASABE, 2006a); for further details see de Toro and Hansson (2004a, 2004b) and de Toro (2005).

$$Y_l = P_d A_f (D_s - D_o) + 0.5\, P_d A_f (D_f - D_s) \qquad (1)$$

where: Y_l = annual yield losses for each field for the harvesting operation, kg; P_d = penalty per day (Table 2), kg day^{-1} ha^{-1}; A_f = field area, ha; D_s = start day for harvesting, day number; D_o = optimum day for harvesting (Table 2), day number; D_f = finishing day for harvesting, day number.

As mentioned, the 'optimum day for harvesting' for individual fields and years was calculated by the model applying a procedure based on temperature and photoperiod (Angus et al., 1981). Similarly, the drying cost estimate was based on the individual field moisture content outputs from the simulation model for harvesting operations and the drying fee charged by Lantmännen (2010) (Table 3). It was assumed that all harvested grain was dried to 14% moisture content.

Afterwards, mean annual timeliness, drying costs and their variance were calculated for the harvesting systems simulated.

2.6. *Farm conditions*

The virtual farms had a combinable crop area of 100, 300 and 600 ha, of which 35% was winter wheat, 55% barley and oats and 10% oilseeds. The yield (at 14% m.c.) was 5770, 4330, 4210 and 1900 kg ha^{-1}, respectively. The farms comprised 20 to 40 fields depending on their size. Cereal transport and drying capacities were assumed to be large enough to match the harvesting capacity. The daily schedule for harvesting was from 11.00 to 19.00 h, including weekends.

Table 1 – Grain moisture model equations for ripe standing wheat.[a]

Process	Conditions	Differential equation	Value of the parameter 'c'
Drying	$Prec^{b} = 0$; $Dew = 0$; $Rh \le M_{EMC}$	$\frac{dM(t)}{dt} = cEvt(M_{(t-1)} - M_{EMC})$	$c = 0.20$ if $M_{(t-1)} > 0.4$ $c = 0.15$ if $M_{(t-1)} \le 0.4$
Wetting due to high air rel. humidity	$Prec = 0$; $Dew = 0$; $Rh > M_{EMC}$	$\frac{dM(t)}{dt} = cRh(M_{max} - M_{(t-1)})$	$c = 0.02$
Wetting due to dew	$Prec = 0$; $Dew > 0$	$\frac{dM(t)}{dt} = cEvt$	$c = 0.15$
Wetting due to precipitation	$Prec > 0$	$\frac{dM(t)}{dt} = c\sqrt{Prec}(M_{max} - M_{(t-1)})$	$c = 0.10$

a Modified versions of the equations proposed by Sørensen, 2003. For further details see Section 3.1.

b $Prec$ = precipitation mm h^{-1}; dew in mm h^{-1}; Rh = air relative humidity, decimal; $M_{(t-1)}$ = moisture content at previous time step, decimal; M_{EMC} = moisture at equilibrium moisture content, decimal; Evt = potential evapotranspiration in mm h^{-1}; t = time unit (d = 1 h); dM_t/dt = variation in grain moisture content per unit time, M_{max} = maximum grain moisture content, decimal (set to 0.54). All moisture contents expressed on dry matter basis.

Table 2 – Some parameters and penalties used in estimating timeliness costs for the harvesting operation.

Parameter	Source	
Cereal and oilseeds prices, € kg^{-1}	Assumed	0.13 (Wheat) 0.10 (Barleys) 0.10 (Oats) 0.29 (Oilseeds)
Optimum day for harvesting	Calculated by the model + random number[a]	
Random number added to harvesting date		
Spring crops	Agric. Statistics	0–6
Winter wheat		0–5
Penalty, kg day^{-1} ha^{-1}	Nilsson (1976)	40
Penalty for unharvested fields, kg ha^{-1}	Agric. Statistics	Yields for the respective crop (see Section 2.6)

[a] Random number added to the estimated maturity day in order to take account of the cultivar differences in maturation time. It was based on the average maturity day ranges for 5 years for the current winter wheat cultivars (Fältforskningsenheten, 2002), and for spring crops based on the range of median harvesting dates (Jordbruksstatistisk årsbok, 1989–1993).

3. Simulation results

3.1. *Weather and validation of the grain moisture model*

Cereal harvesting operations in the Stockholm region are mainly carried out in August, a month with mean monthly precipitation of about 60 mm and 33% rainy days on average, but the annual variation is considerable (Fig. 2). This involves a degree of uncertainty and economic consequences, which must be analysed in any long-term assessment. In order to carry out such analysis some kind of evaluation of the expected grain moistures and their variation is required.

In order to predict the grain moisture content of standing wheat from weather parameters over a series of years, the data collected in the experiment at Uppsala were used as input to the grain moisture model developed by Sørensen (2003). However, the results were not immediately transferable due to differences in input data – especially in terms of the calibrated maximum and minimum moisture contents, and also due to the limitations that 'explanatory models' still present. The model was therefore modified using potential evapotranspiration as the main term to represent the drying/wetting power of the atmosphere, excluding precipitation. The well-known Penman–Monteith formula was used to determine hourly evapotranspiration, applying the procedure and parameters described by Atzema (1993). The equilibrium moisture content of grain was estimated by applying the Chung equation (Brooker, Bakker-Arkema, & Hall, 1992).

The equations used to predict changes in grain moisture content (Table 1) are modified versions of those presented by Sørensen (2003). Several values for the parameter 'c' were tested in order to calibrate the model using the moisture contents determined in the field experiment in Uppsala with the collection of weather data. The results of the calibration are shown in Fig. 3, where the simulated moisture contents applying the equations from Table 1 and the measured values are presented. Fig. 4 presents the same variables for the field experiment in Linköping, whose values were used to validate the model. The coefficient of variation of the root mean square deviations for the measured and simulated moisture contents was 13 and 17% (w.b.) for Uppsala and Linköping, respectively (grain moisture content is expressed on a wet basis hereafter unless otherwise stated).

In general, there was good agreement between measured and simulated moisture contents at both locations, particularly during the last two weeks. The better agreement at Uppsala can be attributed to the model being built using data from this location. However, the limited agreement in the first 10 days at the validation location (Linköping) indicates that there are other factors influencing the drying process which the model was unable to capture. As the model was only validated in one location its general validity is restricted, so its application should be limited to locations with similar climate conditions to Uppsala. If applied in other zones, calibration or further development would be required.

Taking account that the model:

- was intended to estimate grain moisture content in the Stockholm region;
- to be used for managerial purposes, which does not require a very high degree of accuracy for short periods of time, e.g. for individual hours, but rather good estimations on a weekly basis;
- there was sufficiently good agreement between predicted moisture content and measured data (Figs. 3 and 4)

the model was considered to be an useful tool for predicting the moisture content of pre-harvest ripe wheat from weather data on an hourly basis under the conditions specified.

3.2. *Moisture content for a series of years*

The hourly moisture content of ripe pre-harvested wheat was predicted from July 15 to September 30 (harvesting season in the Stockholm region) for the period 1980–2009 using historical climate data from Stockholm and the grain moisture model in a spreadsheet computer application. Weather data (temperature, wind speed, relative humidity of air, rainfall and global radiation) were obtained from SMHI (2010a, internet source), most of it including measurements every 3 h

Table 3 – Drying fees for barley, oats and wheat with various moisture contents charged by the Swedish Farmers Association in 2010 (Lantmännen, 2010).

Water content (w.b.), %	0–14	14.2	14.5	15.0	15.5	16.0	17.0	17.5	Per %-unit above 17.5%
€ t^{-1}	0	2.53	6.63	8.12	8.88	9.63	10.67	11.24	+1.07

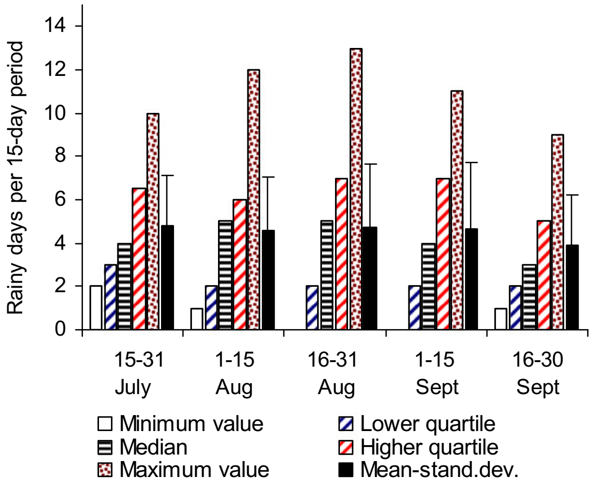

Fig. 2 – Quartile distributions, mean and one standard deviation (error bar) of rainy days (≥ 1 mm) by 15-day periods during the cereal harvesting season in the Stockholm region, based on weather data for 1980–2009 from SMHI, 2010a (internet source, own compilation).

except for precipitation, which was measured every 6 or 12 h. Hourly data and missing values were obtained by linear interpolation. Hourly global radiation, a variable needed to calculate potential evapotranspiration, was obtained with the simulation model Strång, which is used by the Swedish Meteorological and Hydrological Institute (SMHI, 2010b, 2010c, internet source).

3.3. *Grain moisture distribution*

Fig. 5(a) presents the average time proportions of grain moisture content between 11.00 and 19.00 h in August (i.e. the month when cereal harvesting is concentrated) estimated with the grain moisture model. The mean moisture content was 19.2% ($n = 8370$ h) and the standard deviation was 5.0%, which denotes a considerable moisture variation during this month.

Now, considering the same month but only when the moisture content of the cereal did not exceed 24%, the moisture mean was 17.4% ($n = 6892$ h, s.d. = 3.1). Hence, in the region of Stockholm the average moisture content of the harvested grain for a series of years could be expected to be close to this mean when operating at a moisture ceiling of 24%. However, a large hourly variation can be expected, which is well depicted by the quartile distributions [Fig. 5(b)].

3.4. *Available combining times*

Fig. 6 depicts the estimates for the operational time probabilities at various moisture content ceilings in the Stockholm region. Available combining time increased with higher ceilings and decreased as the harvesting season advanced, reflecting the lower drying power of weather during September, particularly for the lower ceilings. Annual variation was large, as shown by the standard deviations (error bars). According to these estimates, the expected available combining time at a moisture ceiling of 21% or below was relatively low (less than 50% on average).

3.5. *Overall harvesting costs*

The best performing systems in monetary terms had overall costs of about €140 ha^{-1}. The major cost components were the machine (i.e. harvester) and drying costs, which on several occasions exceeded the labour and timeliness costs for those systems with lower costs (Fig. 7). The alternatives operating at a moisture ceiling below 22% showed very high timeliness costs, mainly due to some fields being left unharvested, and their annual cost variation was also high, as denoted by the standard deviations, particularly for the larger farms.

Several combinations of moisture ceiling and harvester size gave equally low cost estimates. Within certain limits, the higher machinery costs of the systems with larger harvesters were offset by their lower labour and timeliness costs. The least cost systems were the combined effect of a moisture ceiling between 20 and 22% and a daily harvesting capacity of about 8% of the cereal area for the 100 ha farm. For the larger farms (300 and 600 ha cereal area), the least cost systems were

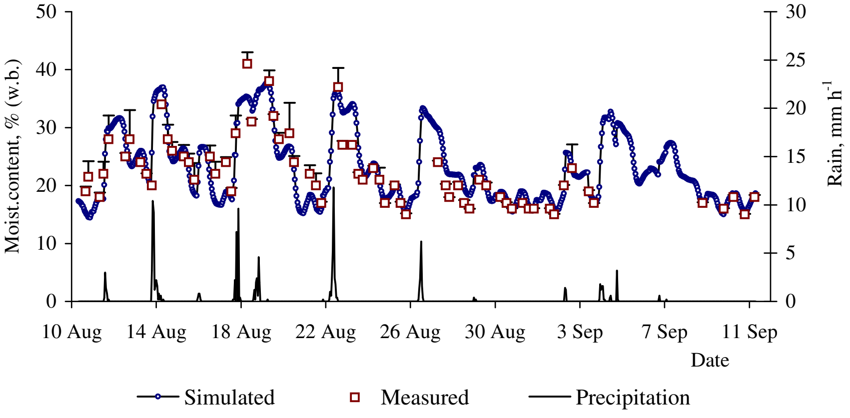

Fig. 3 – Comparison of grain moisture contents (%, wet basis) of wheat obtained by simulation from August 11 to September 11, 2009, and values measured in the field experiment in Uppsala and used to calibrate the grain moisture model. The error bars denote one standard deviation for the measurements ($n = 3$). Precipitation is also given.

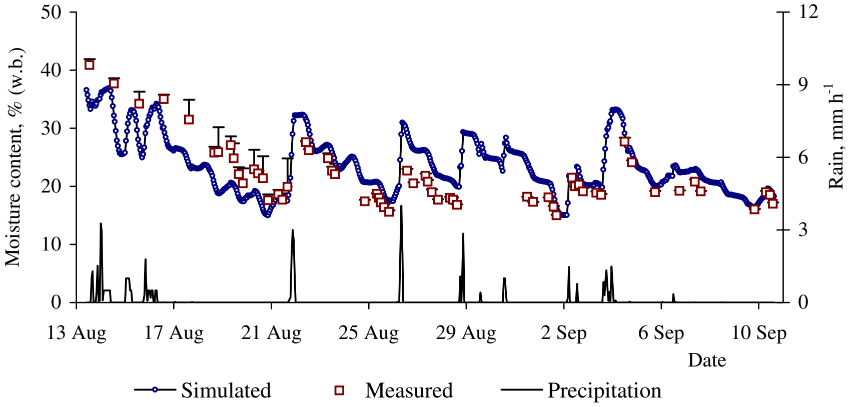

Fig. 4 – Comparison of grain moisture contents (%, wet basis) for wheat obtained by simulation from August 14 to September 11, 2009, and values measured in the field experiment in Linköping and used to validate the grain moisture model. The error bars denote one standard deviation for the measurements (n = 3). Precipitation is also given.

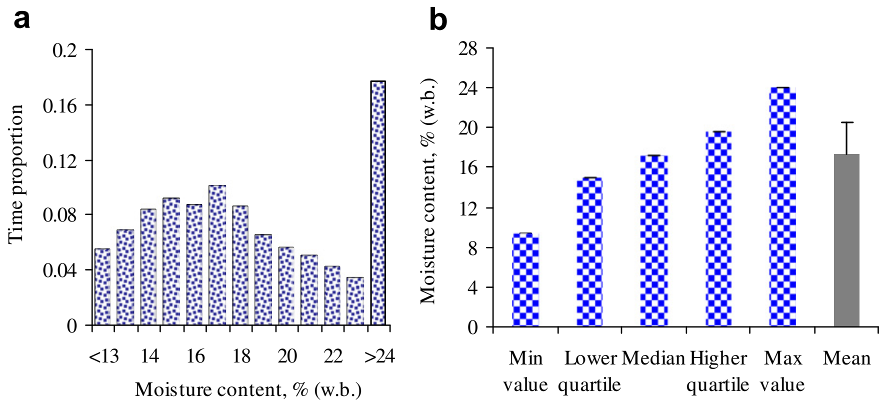

Fig. 5 – (a) Grain moisture time proportions and (b) quartile distributions, mean and standard deviation (error bar, n = 6892 h) of the moisture content time when it did not exceed 24% (w.b.) during harvesting hours (11.00 to 19.00 h) in August. Estimates based on hourly simulations using weather data from Stockholm for the period 1980–2009.

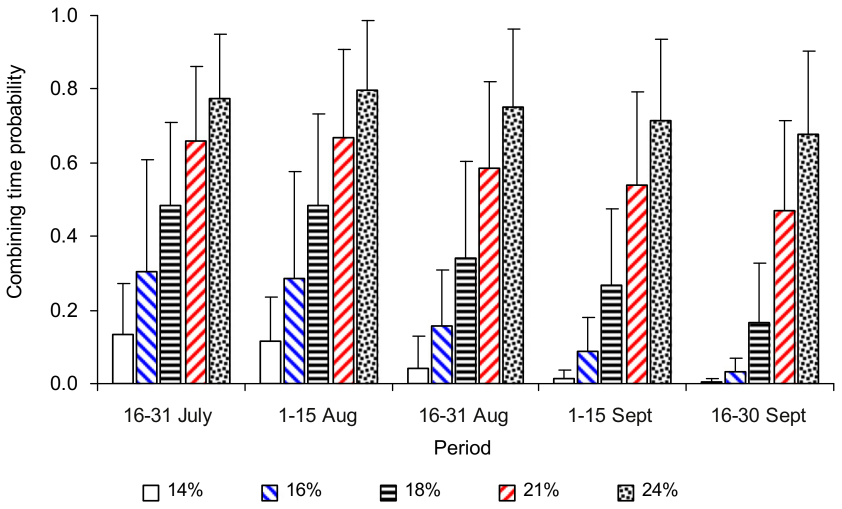

Fig. 6 – Probability estimates of available combining time for wheat at various harvesting moisture ceilings (w.b.) by 15-day period. Grain moisture content was set 2% higher than the estimated ceiling at the beginning of each period in the grain moisture model. The error bars indicate one standard deviation (n = 30 years). Estimation based on weather data from Stockholm for the period 1980–2009.

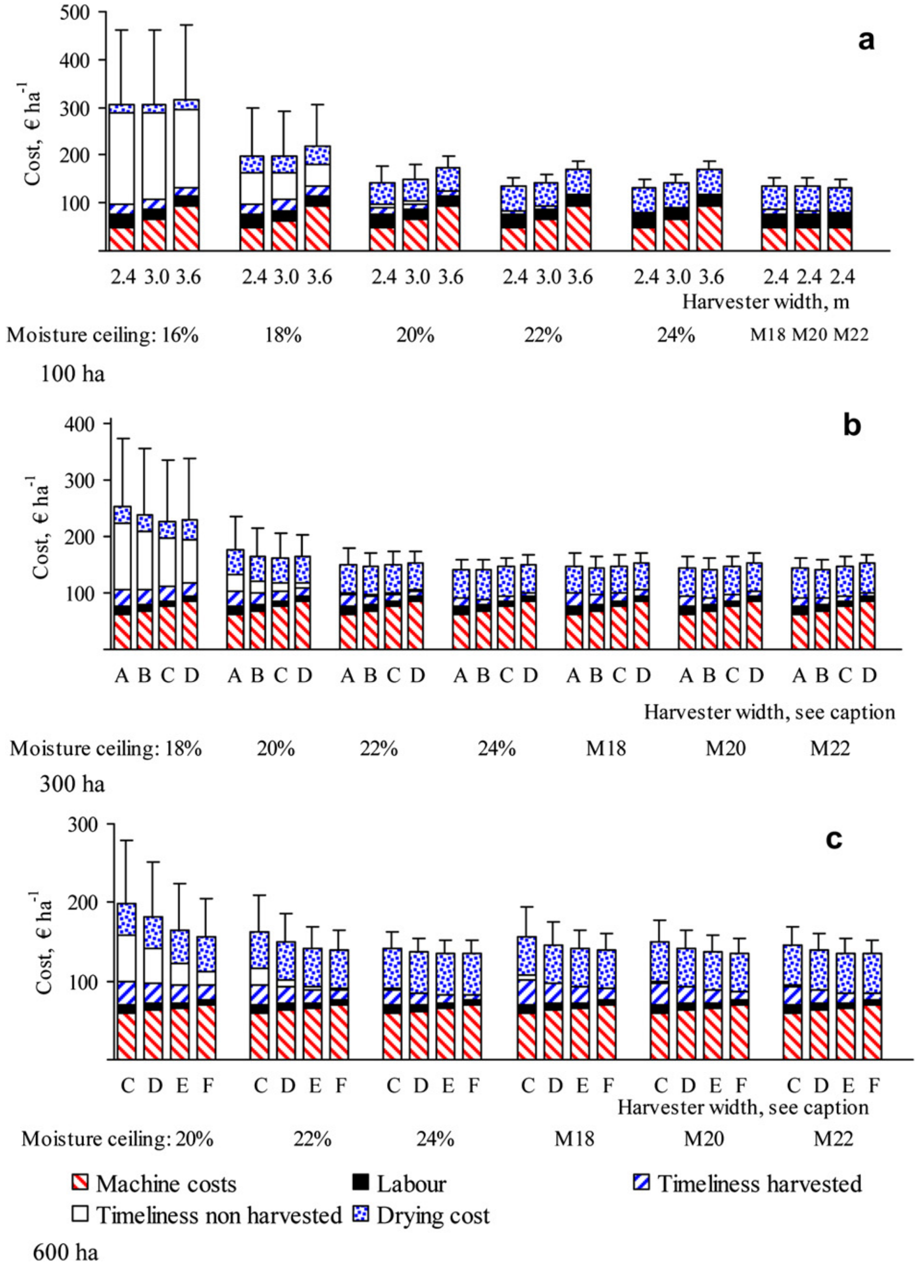

Fig. 7 – Estimates based on 30-year simulations for machine (harvester), labour, timeliness for harvested and non-harvested area and drying costs for cereal harvesting operations in the Stockholm region with various combinations of harvester sizes and moisture ceilings on an area of (a) 100, (b) 300 and (c) 600 ha. The error bars indicate one standard deviation of the annual timeliness and drying costs ($n = 30$ years). The legends 'M18', 'M20' and 'M22' refer to the options where the grain moisture ceiling to operate was gradually increased from 18, 20 and 22%, respectively, in early August to 24% by late September. Harvester width *A*, *B*, *C*, *C*, *D*, *E* and *F* refers to a real harvester width of 4.5, 5.4, 6.3, 7.5, 9.0 and 10.5 m, respectively.

obtained with a moisture ceiling of 22–24% and a daily harvesting capacity of 4–5% of the area, in other words a harvesting capacity large enough to complete harvesting operations in about 150 h or 20 days. The low cost systems also showed a smaller annual cost variation, and hence they were subject to lower risks.

Similarly, the systems gradually increasing the moisture ceiling from 18% at the beginning of August to 24% at the end of September also performed well in terms of the overall costs and annual variations in costs, but with some restrictions on harvester size for the 600 ha cereal farm (Fig. 7).

3.6. *Annual timeliness and drying costs*

The main source of annual cost variations were those items affected by weather, firstly the timeliness costs and secondly the drying costs. Fig. 8 illustrates a harvesting system where the annual timeliness costs varied much more than the drying costs.

The average drying and timeliness costs over 30 years for those systems performing relatively well ranged from €55 to some €70 ha^{-1}. However, the annual variation was much larger, from about 15 to some €60 ha^{-1}, mainly due to the higher timeliness costs during some years (Fig. 9). This was particularly the case for the systems with low daily harvesting capacity and/or operating with a moisture ceiling below 22%, where considerable areas were left unharvested during the years with poor weather conditions, leading to higher costs on average and large annual variation.

The harvesting moisture ceiling affected the moisture content of the harvested grain, particularly at a fixed ceiling, as shown in Fig. 10(a). A lower ceiling was related to lower moisture content of the harvested grain and consequently lower drying costs. Decreasing the ceiling from 24% to 20% reduced the moisture content of the harvested grain from 18.4 to 17.1%, but the available combining time was reduced considerably, from 75 to 45%.

For certain combinations of moisture ceilings-combine sizes, the latter parameter had a low effect on the moisture of the harvested grain [Fig. 10(b)]. A high harvesting capacity led to a considerable amount of grain being harvested at moisture contents close to the operating ceiling before the cereal reached its ‘long-term average moisture’ (17–18%), resulting in higher moisture contents for those systems compared with those employing smaller machines.

4. Discussion

4.1. *Grain moisture model*

Potential evapotranspiration was used as the main term to represent the drying/wetting power of the atmosphere, excluding precipitation. It seemed appropriate to use this variable as it incorporates weather, crop and soil factors influencing the drying process. However, its estimation requires data on weather variables that are not always available from standard weather records. If data are available, the computation may be facilitated by programmes obtainable on the internet (e.g. Ref-ET, 2011, internet source).

The grain moisture time proportion estimates give a good picture of the expected available time for harvesting operations at different moisture ceilings during the month of August in the Stockholm region [Fig. 5(a)]. No corresponding information for the region was found in the literature with which to compare these results. In general, reducing the ceiling led to lower moisture content of the harvested grain, but at the expense of less available harvesting time. Sørensen (2003) arrived at a similar conclusion under Danish conditions, and also found small differences in available harvesting time for wheat and barley.

4.2. *Available combining times and harvesting moisture ceiling*

Available combining time was highly dependent on the harvesting moisture ceiling (Fig. 6). Several studies report similar conclusions (Abawi, 1993; Nawi et al., 2010; Philips & O’Callaghan, 1974; Sørensen, 2003). At a higher harvesting moisture ceiling, more time is available for harvesting operations but higher drying costs can also be expected. Philips and O’Callaghan (1974) reported that most growers in southeast England wait until the moisture content falls below 18% before starting to harvest, while Nawi et al. (2010) cited a figure of lower than 20% in the case of Australia. In the Stockholm region, farmers usually operate at a moisture ceiling of some 23% ($n = 135$ days, statistic based on the 90th percentile of the moisture content of wheat delivered to the drying plant in Västerås during the period 2008–2010, M. Johansson, pers. comm.).

However, the expected average moisture content of the harvested grain was estimated to be 17 to 18% in the region of Stockholm [Fig. 10(a)]. Abawi (1993), in a comparable study in Australia, observed the same pattern. He explained that the grain moisture content of the standing cereal tends to fluctuate around a certain average, determined by the prevailing climate conditions of the zone. Weather variability contributes to this fact with a mixture of ‘good’ and ‘bad’ days during

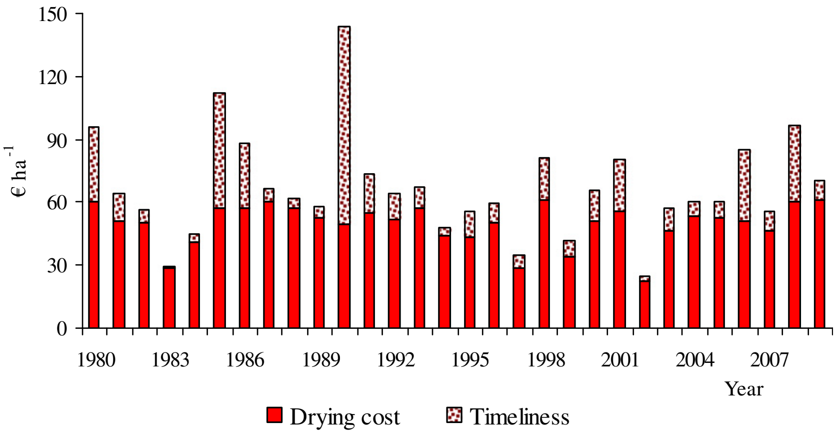

Fig. 8 – Annual timeliness and drying cost estimates for a series of years for a 5.4 m combine harvester operating a 300 ha cereal acreage at a harvesting moisture ceiling of 22% (w.b).

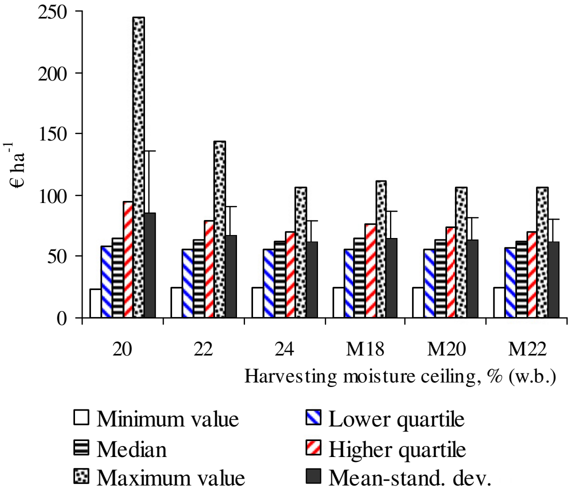

Fig. 9 – Quartile distributions and mean – standard deviation (error bars, $n = 30$ years) of the annual drying + timeliness cost estimates for harvesting operations on a 300 ha cereal farm in the Stockholm region at various moisture ceilings. The legends 'M18', 'M20' and 'M22' refer to the options where the harvesting moisture ceiling was gradually increased from 18, 20 and 22%, respectively, in early August to 24% by late September.

most harvesting seasons, making the annual moisture variation in the harvested grain much lower [Fig. 10(a) and (b)]. Naturally, the same variability of weather brings the risk of extreme conditions during some periods.

Data on undried wheat delivered to the drying plant in Västerås (59°37'N, 16°32'E) for the period 2008–2010 confirmed the moisture estimations obtained by simulation in this study (Fig. 11).

4.3. *Overall harvesting costs*

The timeliness costs were the most important source of annual cost variation and were closely related to the available operating time, which in turn was linked to the moisture ceiling during harvesting operations. As farmers do not know the weather conditions in advance, they have to operate at a higher ceiling than needed during an 'average' year in order to be sure that nearly all the cereal area is harvested, including those years with poor weather conditions. Otherwise, the penalties for non-harvested fields would offset any other savings in the system. Some efforts have been made to assess the value of 'knowing weather conditions in advance' on harvesting operations and thus taking advantage of weather forecasts (Atzema, 1998).

4.4. *Timeliness and drying costs*

In order to complete harvesting operations in nearly all years, it was necessary to operate at moisture ceilings of 22–24% in the region studied. This constraint demands a drying capacity large enough to match the harvesting capacity if the system does not include aerated bins for temporary storage of the wet grain. For a 6.3 m harvester with a daily capacity of about 20 ha day^{-1}, the corresponding daily drying capacity should be about 15 m^3 water in order to dry some 120 000 kg cereal from 23.5% to 14%. However, this drying capacity will only occasionally be required, as the expected average moisture content of the harvested grain was estimated to be much lower, about 17–18%.

A larger combine may allow harvesting at a lower moisture ceiling, leading to lower drying and labour costs, in addition to lower timeliness costs during the operation. Nevertheless, the time needed for the standing cereal to reach lower moisture involves risks, which should be accounted for in terms of

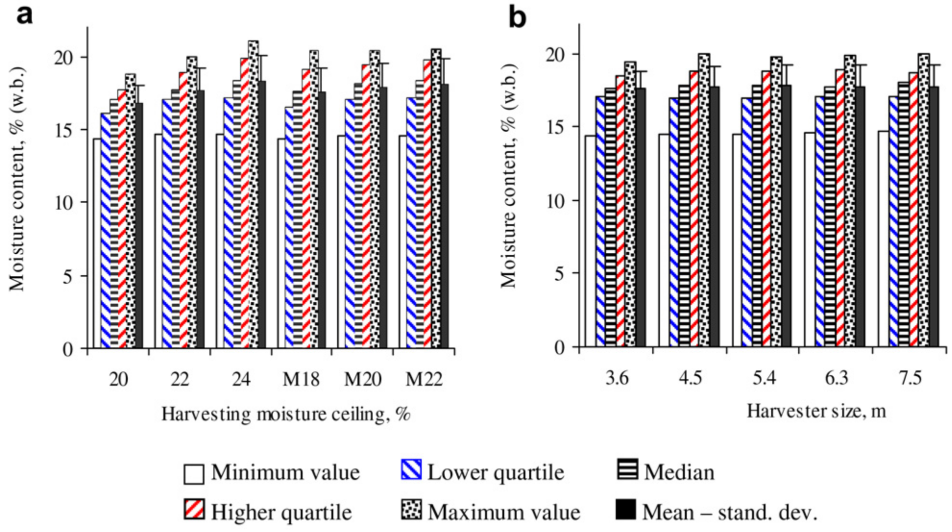

Fig. 10 – Quartile distributions and mean – standard deviation (error bars, $n = 30$ years) of the moisture content estimates for the harvested grain (a) at various harvesting moisture ceilings with a 6.3 m harvester and (b) combined with various harvester sizes at a moisture ceiling of 22% (w.b.) on a 300 ha cereal farm in the Stockholm region. The legends 'M18', 'M20' and 'M22' refer to the options where the harvesting moisture ceiling was gradually increased from 18, 20 and 22%, respectively, in early August to 24% by late September.

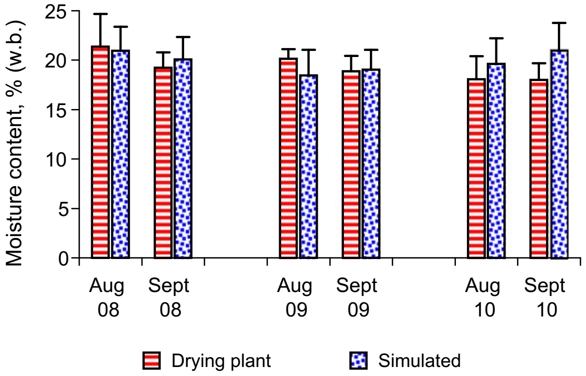

Fig. 11 – Grain moisture content of undried wheat delivered to the Lantmännen drying plant in Västerås (59°37′N, 16°32′E) during August and September 2008–2010 (M. Johansson, 2011, pers. comm.) and simulated mean moisture content during daytime (11.00–19.00 h) when the moisture content did not exceed 25% (harvesting constraints). The error bars denote one standard deviation based on daily averages for 21–26 days for the drying plant, and 162–288 h for the simulated values.

higher timeliness costs during the ‘additional drying’ period. Hence, a larger combine would allow drying and labour costs to be reduced, in addition to the timeliness costs during the operation, but at the expense of higher specific machine costs and timeliness costs due to the delay for the cereal to reach a lower moisture content under the implicit risks of inclement weather.

4.5. *Validity of results*

Considering the complexity of the drying and wetting processes affecting pre-harvested ripe grain, the weakest link of this study was the prediction of changes in grain moisture content in the pre-harvested cereal. Weather, and biological and soil factors influenced the process in a complex way, making it difficult to elucidate their individual influence, while it was still more difficult to predict the result of their interactions. The different approaches to solve the question (see ‘Introduction’ section) reflect the problem and there is still no conclusive methodology on the issue.

The similarity of the estimated moisture contents for harvested wheat to the moisture contents of the wheat delivered to a large drying plant in the region (Fig. 11) increases the confidence in the findings of this study. In addition, many of the conclusions arrived at by Abawi (1993) and Nawi et al. (2010) in Australia were applicable to the present study, as cereal harvesting operations have many features in common world-wide.

5. Conclusions

The main results of this study based on 30-year simulations, which may also be valid for regions with similar climate and agricultural conditions to Stockholm, were:

- The average grain moisture content of wheat during harvesting hours (11.00 to 19.00 h) in August was estimated at 19%, but variation was large ($n = 8370$, s.d. = 5%). Considering only the time when the cereal moisture content did not exceed 24%, the mean moisture content was lower (17.4%, $n = 6892$ h, s.d. = 3.1) for the same period.
- The available combining time was highly dependent on the grain moisture ceiling and the annual variation was considerable, e.g. a moisture ceiling of 21% (w.b.) was associated with a 65% combining time and a standard deviation of 24% ($n = 30$ years).
- In order to complete harvesting operations in most years, it was necessary to operate at a relatively high moisture ceiling (22–24%, w.b.) with a reasonable harvesting capacity. However, the average moisture content of the harvested grain for 30 years was much lower (about 17–18%). Similarly, options of gradually increasing the ceiling from 18 to 20% in early August to 24% by late September produced good results.
- Overall harvesting costs (labour + machine + timeliness costs + drying), which are specific to the conditions and zone studied, were estimated at €140 ha^{-1} for those systems operating relatively well, i.e. at a moisture ceiling of 22–24% (w.b.) and a daily harvesting capacity of 4–5% of the cereal area. The major cost components for these systems were the machine and drying costs.
- Several combinations of daily harvesting capacity and moisture ceiling had equally low costs. Higher machine costs for the larger harvesters were offset by lower timeliness costs.
- The main sources of annual cost variation were firstly the timeliness costs and secondly the drying costs.
- The most uncertain item in the study was prediction of changes in grain moisture content for the standing cereal, due to the complexity of the drying process.

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